October 8, 2025
Public Comments of Benjamin G. Kaldunski
TO: City of Madison Urban Design Commission
RE: Dane County Landfill #3/Sustainability Campus

I am a Madison resident and 2015 graduate of the UW-Madison Nelson Institute (M.Sc., Energy Analysis and Policy) with a strong desire for Madison to support development of a circular economy through deployment of innovative technologies. Planning activities for the Dane County Landfill **Sustainability Campus** present a unique opportunity for implementing a suite of complimentary technologies that could leverage Federal and State grant funding. My comments provide an overview of several promising technologies that should be explicitly included in zoning, land use, and permitting activities related to development of the Sustainability Campus. Doing so would support Madison's ambitious goal to achieve 100% Renewables and **Net Zero Carbon by 2030**.

The three technologies that should be evaluated in DNR's feasibility study are:

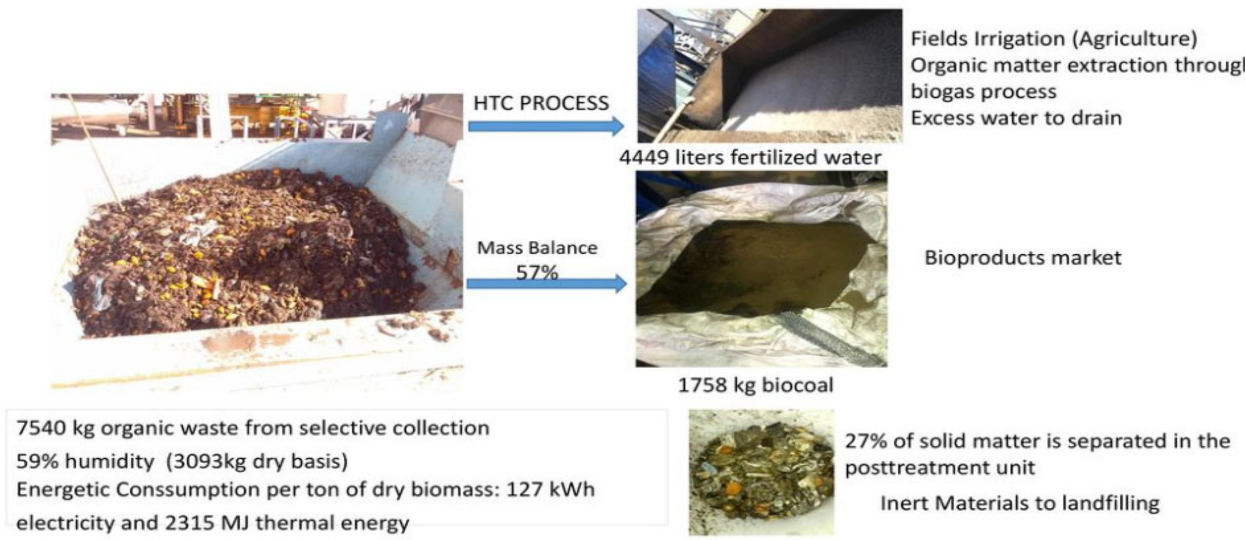
1. **Hydrothermal Carbonization (HTC):** HTC bioreactors have been deployed in several European countries by the **Spanish firm Ingelia Spa**, and in Phoenixville by U.S. company **SoMax Circular Solutions**. These bioreactors can convert a wide variety of organic waste feedstocks into a net zero carbon solid biofuel with energy content similar to fossil coal (8,600-15,000 Btu/lb);
2. **Advanced Steam Boiler & Engines**: Technology developed by **Mackwell Locomotive Co**., of New Zealand that use waste biomass (or HTC-produced biocoal) as a carbon neutral fuel for farm tractors, waste collection trucks, street sweepers, snow plows and other fleet vehicles;
3. **Modular Combined Heat and Power (CHP)**: Systems developed by **Uniflow Power Ltd**., and **Village Industrial Power** are capable of utilizing a wide variety of carbon neutral biomass feedstocks as fuel to power high efficiency steam engines that produce electricity, heat, and hot water. Siemens is also a leader in small steam turbine technology used in many commercial and industrial applications.

I will describe each of the three technologies listed above in greater detail beginning with the HTC bioreactor developed by Ingelia and SoMax. The Ingelia HTC reactors have been undergoing development since 2007 and have now been deployed at commercial scale in Belgium, Italy, Spain, and the UK. The bioreactors are capable of processing a wide variety of organic waste feedstocks including agricultural waste (plant and animal), food waste, pulp and paper byproducts, and even municipal wastewater sludge. Each reactor measures approximately 4' square and 40' tall with a maximum inflow capacity of 770 lb/hour (dry), and output of 440 lb/hour. Ingelia or SoMax HTC systems could be installed at the Sustainability Campus to process agricultural waste from local farms and/or food waste from UW-Madison cafeterias, restaurants, and other food service companies. Brewery spent grains and coffee grounds have been found to produce biocoal with high energy content through HTC processing These waste streams would be diverted from the landfill.

Notably, HTC bioreactors can process solids leftover from anaerobic digesters while increasing the amount of biomethane produced from a digester(s). They could be paired with Dane County's existing **community manure digester** facilities to generate additional value-added products. MMSD could also utilize the HTC system to compliment their existing anaerobic digestion facilities at the **Nine Springs WWTP**, This could be especially valuable during winter months when the MMSD's Metrogro fertilizer product must be stored onsite rather than distributed to local farms. MMSD could utilize the HTC system to produce solid biofuel for use in process heating, on-site CHP, or municipal fleet vehicles. A commercial scale project using ten Ingelia HTC bioreactors cost 27.3 million Euros (about $30.2 million USD). Ten bioreactors would be able to produce ~19,310 tons of solid biofuel whose energy content of about 350,000 MMBtu is equivalent to ~2.5 million gallons of diesel worth $7.5 million assuming $3/gallon. The 10-reactor system was shown to have a payback period of 5.3 years (see **IEA Report**), compared to 15-20 years for solar photovoltaic systems.

Producing net zero carbon biofuel from organic waste is directly aligned with Madison's goal to achieve 100% renewable energy and net zero carbon emissions by 2030. The SoMax HTC system is capable of processing ~15,000 tons of feedstock per year yielding 1,500 – 2,000 tons of solid biofuel (depending on moisture content) with energy content of 25,000 – 50,000 MMBtu depending on the feedstock. The thermal requirements of the SoMax HTC system can be satisfied by the additional biomethane produced at anaerobic digesters paired with the HTC technology. Economic viability depends on the utility cost of electricity, natural gas (both as inputs and avoided costs), and avoided tipping fees. Avoided tipping fees are a net benefit for the landfill as well, as it extends the life of the landfill in future years when tipping fees will likely be higher than they are today.

Figure 1: Summary of HTC Demonstration Project



Solid biofuel produced from organic waste feedstocks could then be used to power advanced steam boiler/engine units for stationary and mobile applications. Steam power may be considered a defunct and obsolete technology from the 19th century, but startup companies like Mackwell Locomotive Co., Uniflow Power Ltd., and Village Industrial Power (see **DOE ARPA-E slides**) have developed highly efficient and versatile pilot units that are well suited for use at the Sustainability Campus as on-site sources of electricity and thermal energy. Most importantly, modern steam engines can use many types of solid biomass or liquid biofuels to displace the use of traditional fossil fuels. Steam engines are relatively simple with fewer moving parts compared to internal combustion engines, and do not rely on rare earth metals used in lithium-ion batteries that power most hybrid and all-electric vehicles. In short, use of advanced steam technology for on-site energy and municipal fleet vehicles like garbage trucks, street sweepers, and snow plows, would transform waste streams with disposal costs into a net zero carbon fuel to reduce gasoline/diesel costs. The Sustainability Campus could serve as the fueling and maintenance hub for advanced steam fleet vehicles powered by biofuel.

For example, the **Mackwell AgLoco** utilizes a two-cylinder steam engine rated at 150HP and 5,800 lb-ft of torque with a towing capacity of 66,000 lbs. At that towing capacity, the AgLoco has an estimated range of 128 miles using 1,100 lbs. of solid fuel (equivalent to about 80-85 gallons of diesel assuming 137,000 Btu/gallon and 10,000 Btu/lb of solid biofuel). Cummins diesel engines commonly used in city buses are rated at 200-350HP and 500-1,000 ft-lbs or torque. The Mackwell AgLoco boiler and steam engine could be adapted to better suit the needs of on-road fleet vehicles to improve fuel and water economy. In fact, **Madison resident Charles Keen** built a modern steam-powered automobile in the early 1960's whose 4-cylinder 100 cubic inch engine was rated at 130HP and 2,500 lb-ft of torque with fuel economy of 10-15 miles per gallon (or about 1.2 miles per pound of solid biofuel).

The ultra-high torque provided by steam engines at low RPM is ideal for slower speed operations like snow plowing and waste collection/hauling by City and County fleet services. Lastly, the ultra-efficient combustion of solid biofuel results in zero smoke emissions and lower air pollution than diesel engines (**Advanced Steam**). California tested several steam-powered buses in the 1970's and British Sentinel steam-powered trucks were manufactured from the early 1900's through 1950 (see Attachments 7-8).
Another leader in advanced steam technology is Uniflow Power Ltd., whose modular CHP units are based on Australian engineer **Ted Pritchard** who developed a steam automobile in the 1960's. Pritchard's 25 cubic inch steam engines were rated at 45HP and 340 lb-ft of torque with fuel economy of 20-25 miles per gallon (or about 1.5-2 miles per lb of solid biofuel). Water use of just 170 miles per gallon was achieved by utilizing the existing automobile radiator as a condenser to capture exhaust steam for re-use in the closed-loop system.

Most impressive, the Pritchard steam generator and engine were capable of meeting 1990's era emissions standards when it was tested by major U.S. automakers in the early 1970's. While the steam automobile never went in production, Pritchard continued to develop his design into the S5000 engine (Steam 5,000 Watt) whose patents serve as the basis for Uniflow Power's modular CHP units. These CHP units could be used at the Sustainability Campus as the primary source of electricity, steam, and hot water for waste handling equipment and buildings. Larger models for commercial/industrial applications could be developed in the future as part of a demonstration project based at the Sustainability Campus with support from UW-Madison Engineering and the **Great Lakes Bioenergy Research Center**. Finally, the U.S. EPA's recently proposed revisions to the Renewable Fuel Standard (RFS) creates a pathway for electricity produced by biomass to generate "eRINs" with a potential value of $3 per gallon, further improving the financial viability of utilizing Uniflow Power modular CHP units at the Sustainability Campus.

Madison's commitment to zero waste and 100% renewable energy goals, as well as the long history of public/private partnerships involving UW-Madison and other public agencies present the ideal conditions for demonstration and deployment of HTC bioreactors to produce fuel for advanced steam boilers/engines being developed by Mackwell, Uniflow Power, and others. I would love for Madison and Dane County to achieve their ambitious sustainability goals through partnerships with these firms, or other companies offering similar technological solutions to our environmental challenges. The in flux of federal funding from the Infrastructure Investment and Jobs Act (IIJA) and the Inflation Reduction Act (IRA) could also be leveraged to support innovative partnerships to deploy the technologies summarized above.

Funding Opportunities for HTC Bioenergy Projects:

- IRA transferrable tax credits offer up to 40-50% of total project costs
- U.S. EPA Solid Waste Infrastructure & Recycling Grants Program (**website**)
- Section 11403 State Carbon Reduction Program (**website**)
- Section 11511 Emerging Alternative Fuel Vehicle Study (**website**)
- Section 11401 Community Alternative Fuel Infrastructure Grants (**website**)
- U.S. EPA Proposed RFS Revisions for Biomass eRINs (**Penn State Extension**; **EPA Website**)

HTC Options for the Dane County Sustainability Campus, Dane County Digesters, or MMSD

The figures immediately following my written comments provide illustrative examples for how HTC could be paired with other equipment (dryers, CHP, and gasification) to deliver additional revenue from the Sustainability Campus. The figures contemplate siting HTC with different combinations of complimentary technologies at the Dane County landfill, existing Dane County digesters, or the MMSD Nine Springs wastewater treatment plant (WWPT) to take advantage of existing capital investments and HTC feedstocks.

The four main technology combinations are:

1. Stand-alone HTC without dryer(s) to produce hydrochar at ~50% moisture;
2. HTC with dryer(s) to upgrade hydrochar to biocoal with low moisture content for sale to off-takers like electric power plants, steel mills, or heritage steam railroads;
3. HTC with dryer(s) and CHP where biocoal is used to generate on-site hat and electricity;
4. HTC with dryer(s) and gasification to reduce 50% moisture hydrochar to 15-25% moisture for use a feedstock in gasification systems that produce renewable natural gas;

Stand-alone HTC would have the lowest upfront capital cost, but would deliver limited additional revenue since the only byproduct would be high moisture hydrochar. HTC paired with a rotary dryer could be used to upgrade the hydrochar to low moisture biochar (15% to 25%) as an interim feedstock for gasification to produce RNG, or produce biocoal (1% to 5% moisture) as fuel for on-site energy production with a CHP unit, or for sale to other end use customers as a carbon neutral alternative to fossil fuel. Any combination of these technologies could be sited at the Dane County Sustainability Campus to leverage existing waste hauling partnerships with large volume waste producers such as UW-Madison, food/beverage processing facilities, and local agricultural operations. Commercial programs that focus on high energy HTC feedstocks like coffee grounds or spent brewery grains could also be explored. Supplemental HTC feedstock could also provided from Dane County digesters and/or biosolids from the Nine Springs WWTP that exceed the capacity of existing storage facilities.

Notably, projects that pair HTC with CHP would qualify for IRA tax credits because hydrochar upgraded to biocoal would be used to generate renewable electricity and thermal energy. Pairing a standalone HTC system with an existing Dane County digester may also qualify for IRA tax credit because the HTC system would increase biomethane production and renewable energy production. Pairing HTC with gasification at the Dane County landfill would leverage existing biomethane processing facilities and pipeline interconnections. The thermal energy requirements of dryers needed to support an HTC-plus-CHP or HTC-plus-gasificaiton project could be met by diverting a modest portion of landfill or giester gas prior to pipeline injection.

Dane County may also consider partnership scenarios where an HTC system is jointly owned/operated by MMSD at the Nine Springs WWTP. The HTC system would be paired with existing anaerobic digester and rotary drying equipment, and optional CHP or gasification technology. Dane County coordinate waste hauling to divert organic waste from the landfill to the WWTP for co-processing with post-digester biosolids. The increased biomethane production resulting from HTC could offset the system's themal energy needs and produce additional energy for use at an on-site CHP system resulting lower utility bills for the WWTP. Co-processing diverted landfill waste with WWTP biosolids would increase the energy content of biocoal produced by the HTC system because agricultural and food waste feedstock have higher carbon content than WWTP biosolids. MMSD and Dane County would see mutual benefits from landfill waste diversion, reduced utility expenses, and additional revenue from the production and sale of excess biocoal. Companies like Ingelia, SoMax, Carbon2H and Genifuels (additional information in Attachments 1-6) can further refine the collaborative business model if MMSD and/or Dane County support a feasibility study.

Request of Madison Urban Design Commission

Given the potential benefits of the advanced technologies summarized in these comments, I respectfully request that the Madison Urban Design Commission issue guidance clearly stating that:

1) HTC, gasification, anaerobic digestion and other technologies are eligible as permitted activities at the Sustainability Campus compositing facility (as defined on page 372 of the DNR Feasibility Study); and

2) HTC, gasification, anaerobic digestion and other organic waste processing technologies are eligible as approved/permitted activities within the Sustainable Business Park (as defined on page 373 of the DNR feasibility Study).
3) HTC, gasification, anaerobic digestion and other organic waste processing technologies are eligible as approved/ activities in future zoning, land use, and permitting activities related to the Sustainability Campus project development.

I also respectfully request that the Madison Urban Design Commission issue an addendum to the DNR's Feasibility Report project summary document (issued May 21, 2025) to clarify the following:

1) Page 21 description of "a new landfill gas treatment system for RNG other beneficial uses" should be amended to specifically include references to HTC, HTL, gasification and other advanced organic waste processing technologies as permissible developments at the new landfill site; and
2) Page 38 description of the "sustainable business park north of the proposed landfill" should be amended to include specific references to HTC, HTL, gasification, biomass CHP and other advanced organic waste processing technologies as permissible activities under the broader description of "new waste management technologies."

Concluding Remarks

Thank you for providing the opportunity to submit comments on this important project. I look forward to continued engagement with City of Madison, DNR, and Dane County staff. These comments were previously submitted to DNR staff in May 2025, and the City of Madison Sustainability Committee ahead of its meeting held on February 27, 2023. A list of attachments and additional reference materials is included on the following page.

Sincerely,

Ben Kaldunski
Madison Resident

List of Attachments:

- Attachment 1: Village Industrial Power 10-40 CHP Unit Overview
- Attachment 2: SoMax HTC at the Phoenixville Wastewater Treatment Plant
- Attachment 3: SoMax HTC Feasibility Study for Gardner, Massachusetts
- Attachment 4: IEA Bioenergy Evaluation of Ingelia HTC Pilot Project
- Attachment 5: EU Commission NEWAPP Report on Ingelia HTC Pilot Project
- Attachment 6: Carbon2H Product HTC Overview
- Attachment 7: CHAR Technologies Overview
- Attachment 8: HTL Research at WWTPs (PNNL and Great Lakes Water Resource Authority)
- Attachment 9: Mackwell & Co., Advanced Steam Product Specification Sheets
- Attachment 10: Uniflow Power Ltd., & Pritchard Advanced Steam Engine Materials
- Attachment 11: Keen Steam Car Reference Materials
- Attachment 12: British Sentinel Steam Truck Reference Materials
- Attachment 13: SAE Report on California Steam Bus Program
- Attachment 14: Modern Steam Locomotive Economic Analysis by Roger Waller

Attachment 1 provides high level information about the steam engined CHP product developed by Village Industrial Power (VIP). Attachments 2-7 include detailed information on HTC (CHAR, Ingelia and SoMax) and gasification (Carbon2H) technologies referenced in my written comments. Attachment 8 provides information on hydrothermal liquefaction (HTL) technology and research being conducted by Pacific Northwest National Laboratory (PNNL) at wastewater treatment plans in collaboration with Genifuels and the Great Lakes Water Resource Authority (GLWRA). Attachments 9-10 provide information about modern steam engine/boiler and CHP technologies developed by Mackwell Engineering and Uniflow Power Ltd., that are referenced in my written comments.

Attachments 11-14 provides background information on various steam powered vehicles to demonstrate the potential for biocoal produced by HTC to power fleet vehicles. Selling biocoal to heritage railroads operating steam locomotives (such as the Mid-Continent Railroad Museum near Baraboon, Wisconsin) would be another opportunity to derive additional revenue from HTC systems at the Dane County Sustainability Campus, Dane County community digesters, or MMSD Nine Springs WWTP. Modern steam boiler and engine technology could power waste collection rucks and other fleet vehicles that build upon successful steam vehicles like the British Sentinel steam trucks, Keen and Pritchard steam cars, and the California Steam Bus Program from the early 1970's.

Contacts for Technology Partners:

Organization & Location	Name & Email	Web & YouTube Links
SoMax (Pennsylvania)	Dan Spracklin (dan@somaxhtc.com) Jeremy Taylor (jeremy@somaxhtc.com)	SoMax Phoenixville YouTube
Ingelia SpA (Spain)	Marisa.hernandez@ingelia.es	Ingelia HTC Overview YouTube
CHAR Technologies (Canada)	Andrew Friedenthal (Business Develoment) afriedenthal@chartechnologies.com	CHAR Thorold Project YouTube
Carbon2H (Germany)	Philip Michael (info@carbon2h.com)	Carbon2H Overview YouTube
Village Industrial Power (Vermont)	Carl.Bielenberg@villageindustrialpower.com	VIP Project in Benin YouTube
Mackwell & Co., (New Zealand)	Sam.Mackwell@mackwell.co.nz	Mackwell A35 Tractor YouTube
Uniflow Power (Australia)	Michael.McCann@uniflowpower.com	Cobber CHP Overview YouTube
Genifuels (Utah) and PNNL (Washington)	**James Oyler (jim@genifuel.com)** Daniel.Santosa@PNNL.gov	HTL Overview by Metro Vancouver

Additional References:

1. Advanced Steam, "Emissions from Modern Steam Locomotives." Available at https://advanced-steam.org/5at/5at-project/5at-and-the-environment/emissions/
2. Dane County Department of Waste & Renewables, "Community Manure Digesters." Accessed at https://lwrd.countyofdane.com/what-we-do/community-manure-management
3. Dane County Department of Waste & Renewables, "Sustainability Campus." Accessed at https://landfill.countyofdane.com/projects/WastandRenewableProjects/Sustainability-Campus
4. Friday Off Cuts (2022). "Solid Biofuel Powered Tractor Being Developed." Accessed at https://fridayoffcuts.com/dsp_article.cfm?id=959&date=%7Bts%20%272022-04-01%2000:00:00%27%7D&aid=12165
5. IEA Bioenergy (2021), "Valorization of Organic Waste and Sludges for Kandinsky Hydrochar Production of Biofertilizer." Accessed at https://www.ieabioenergy.com/wp-content/uploads/2021/10/HTC-Valorisation-of-organic-wastes-and-sludges-for-hydrochar-production-and-biofertilizers-Full-Report.pdf
6. Mackwell Locomotive Co., "21st Century Boiler Secrets" accessed at https://www.youtube.com/watch?v=BLRNaIkxL2s&t=1190s
7. Mackwell Locomotive Co., "Boilers" accessed at https://mackwelloco.com/locomotive-boilers/
8. Mackwell Locomotive Co., "LOCO - The AgLoco Documentary" accessed at https://www.youtube.com/watch?v=tuf4BbxNmoE&t=317s
9. McCann, Michael (2011). "Big Market for Small Steam Engines." Accessed at https://www.ecoinvestor.com.au/Stories/Eco-Investor/June-2010/Big_Market_for_Small_Steam_Engines.htm
10. NEWAPP Report Summary – New Technological Application for Wet Biomass Waste Stream Products," accessed at https://cordis.europa.eu/project/id/605178/reporting
11. Rex Research, "Ted Pritchard Steam Powered Automobile." Accessed at http://www.rexresearch.com/pritchardsteam/pritchard.html
12. Bowen, Tyson (2022). "Australian Designed Car Built to Steamroll the Establishment." *The Drive.* Accessed at https://www.drive.com.au/caradvice/the-australian-designed-car-built-to-steamroll-the-establishment/
13. Uniflow Power Ltd., "Technology" accessed at https://www.uniflowpower.com/technology/
14. Village Industrial Power, "Biomass Fueled Power Plants." Accessed at https://www.villageindustrialpower.com/energy-generation

Summary of HTC Ownership & Deployment Options

HTC Site	Dane Co. Landfill	Dane Co. Digester	Nine Springs WWTP
HTC System Owner	Dane County	Dane County	MMSD or joint ownership with Dane County
Feedstock Sources	Organic waste collected from all customers OR - Targeted organic waste collection from large customers (i.e.,, food processors, breweries, ag residuals) Supplemental Feedstock – MMSD wastewater sludge otherwise land applied	Organic waste sorted at Dane Landfill and trucked to digester site. OR - Targeted organic waste collection from large customers trucked directly to digester site Supplemental Feedstock – MMSD wastewater sludge and excess manure from existing digester collection system	WWTP sludge that exceeds storage capacity Supplemental Feedstock – Trucked to WWTP from Dane Landfill after sorting/processing optimal organic wastes OR target large customer collection program (UW, breweries, coffee ground) trucked directly to MMSD
HTC Equipment	HTC Reactor (SoMax) Dryer (Feeco / Baker Rullman) to convert hydrochar (50% H2O) into biocoal (1-10% H2O) Steam CHP Unit (VIP, Mackwell Ltd., or Uniflow Power Ltd.) can produce electricity and heat for on-site use (buildigs or EV fleet vehicles) Gasification Unit: Convert biochar (10-20% H2O) into biogas for pipeline injection or on-site fleet vehicle fueling station	HTC Reactor (SoMax) Existing Dryers convert hydrochar (50% H2O) into biocoal (1-10% H2O) Steam CHP Unit (VIP, Mackwell Ltd., or Uniflow Power Ltd.) can produce electricity and heat for on-site use (buildigs or EV fleet vehicles) Gasification Unit: Convert biochar (10-20% H2O) into biogas for pipeline injection or on-site fleet vehicle fueling station	HTC Reactor (SoMax) Existing Dryers convert hydrochar (50% H2O) into biocoal (1-10% H2O) Steam CHP Unit (VIP, Mackwell Ltd., or Uniflow Power Ltd.) can produce electricity and heat for on-site use (buildigs or EV fleet vehicles) Gasification Unit: Convert biochar (10-20% H2O) into biogas for pipeline injection or on-site use
Biochar/Biocoal End Use	Hydrochar: Landfill top layer, soil amendment etc. Biocoal: Used in on-site CHP or sold to ELC utility as zero carbon fuel	Hydrochar: Landfill top layer, soil amendment etc. Biocoal: Used in on-site CHP or sold to ELC utility as zero carbon fuel	Hydrochar: Landfill top layer, soil amendment etc. Biocoal: Used in on-site CHP or sold to ELC utility as zero carbon fuel
Notes	HTC+Gasification could utilize existing RNG injection facilities at the landfill.	HTC+Gasification could utilize existing RNG injection facilities at the landfill.	HTC+Gasification could boost WWTP digester CH4 production and meet on-site heating needs

Dane County-1) HTC Only: Landfill

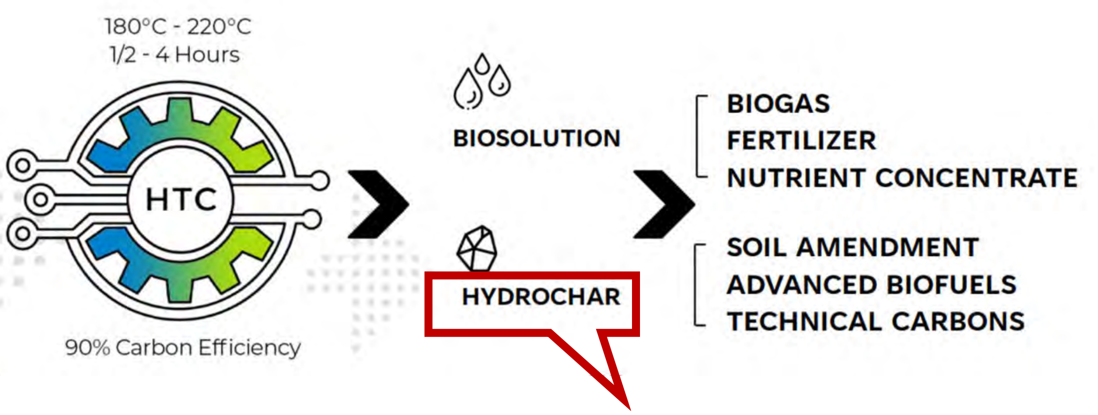
Feedstock Sources: Madison MSW organics/compost collection program OR large waste producer organic collection programs such as UW-Madison (food waste), area breweries (spent grains), coffee grounds. MMSD biosolids could also be trucked to the Dane County landfill or Community Digester for HTC processing at a lower tipping fee than what MMSD pays for land application of Metrogro.

HTC Output: Hydrochar is dried from ~50% to 10-20% moisture content to be sold as a biocoal solid fuel for electricity generation at coal/biomass plants or other industrial heating purposes.

Feedstock Source 1: UW-Madison Organics

Feedstock Source 2: Coffee Grounds and Spent Brewery Grains

Feedstock Source 3: MMSD Biosolids



Dane County-2) HTC with Dryer: Landfill or Community Digester

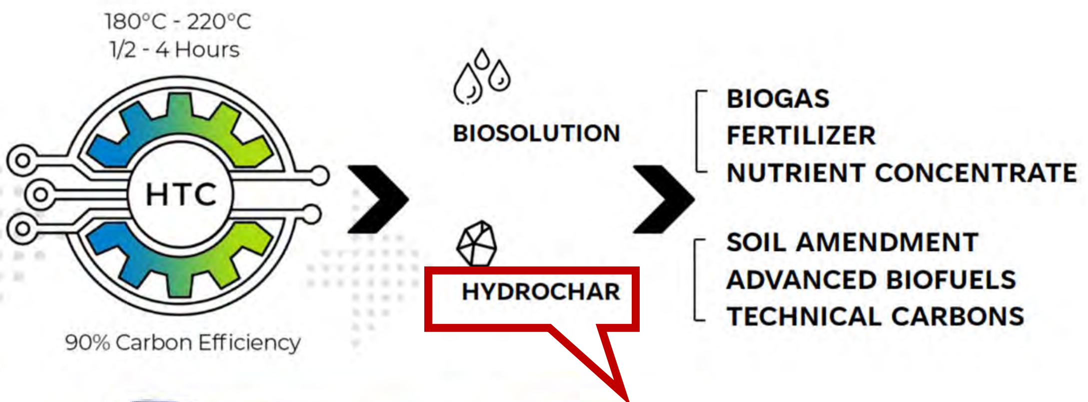
<u>Feedstock Sources</u>: Madison MSW organics/compost collection program OR large waste producer organic collection programs such as UW-Madison (food waste), area breweries (spent grains), coffee grounds. MMSD biosolids could also be trucked to the Dane County landfill or Community Digester for HTC processing at a lower tipping fee than what MMSD pays for land application of Metrogro.

<u>HTC Output</u>: Hydrochar is dried from ~50% to 10-20% moisture content to be sold as a biocoal solid fuel for electricity generation at coal/biomass plants or other industrial heating purposes.

<u>Feedstock Source 1</u>:
UW-Madison Organics

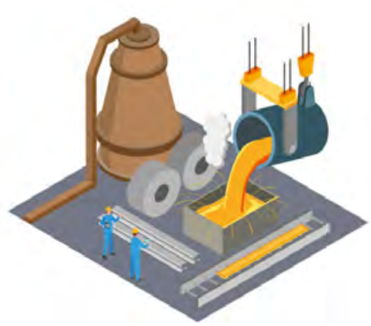
<u>Feedstock Source 2</u>:
Coffee Grounds and Spent Brewery Grains

<u>Feedstock Source 3</u>:
MMSD Biosolids



FEECO / Baker-Rullman Rotary Dryer
OR Existing Digester Dryer

Dryer is needed to reduce hydrochar with 50% moisture to biocoal with 1-5% moisture that can be sold to electric utilities other industrial users, or heritage railroads as zero carbon fuel. On-site CHP is needed to produce electricity for buildings or EV fleets.



Dane County-3) HTC with Biomass CHP: Landfill

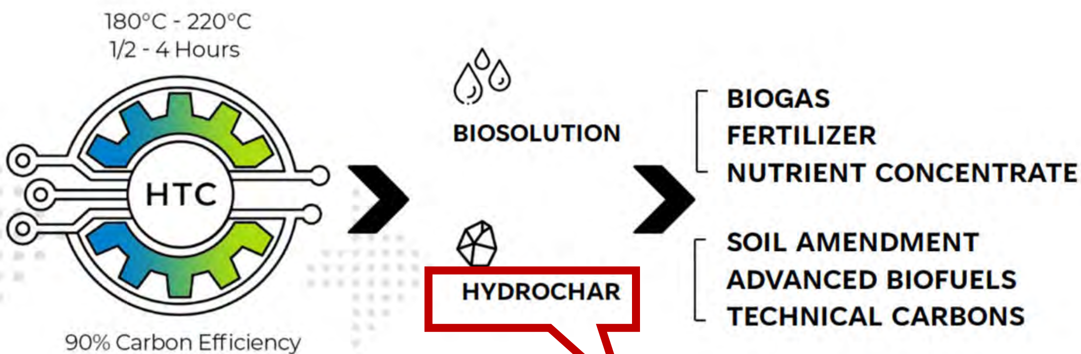
Feedstock Sources: Madison MSW organics/compost collection program OR large waste producer organic collection programs such as UW-Madison (food waste), area breweries (spent grains), coffee grounds. MMSD biosolids could also be trucked to the Dane County landfill or Community Digester for HTC processing at a lower tipping fee than what MMSD pays for land application of Metrogro.

HTC Output: Hydrochar is dried from ~50% to 10-20% moisture content to be sold as a biocoal solid fuel for on-site CHP to power buildings or electric fleet vehicles. Biosolution boosts digester CH_4 production.

Feedstock Source 1: UW-Madison Organics

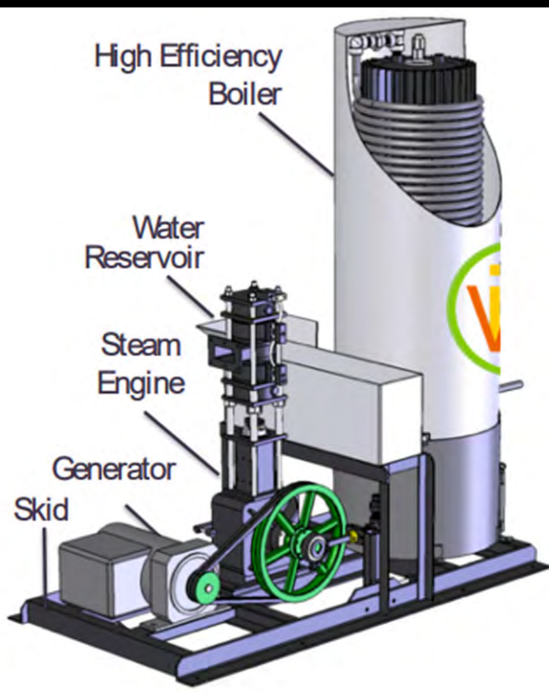
Feedstock Source 2: Coffee Grounds and Spent Brewery Grains

Feedstock Source 3: MMSD Biosolids



FEECO / Baker-Rullman Rotary Dryer
OR Existing Digester Dryer

On-site CHP unit burns biocoal to produce electricity for buildings or EV fleet vehicles.



VIP 10 kWe / 40 kWt Steam CHP Unit

Dane County-4) HTC with Gasification: Landfill or Community Digester

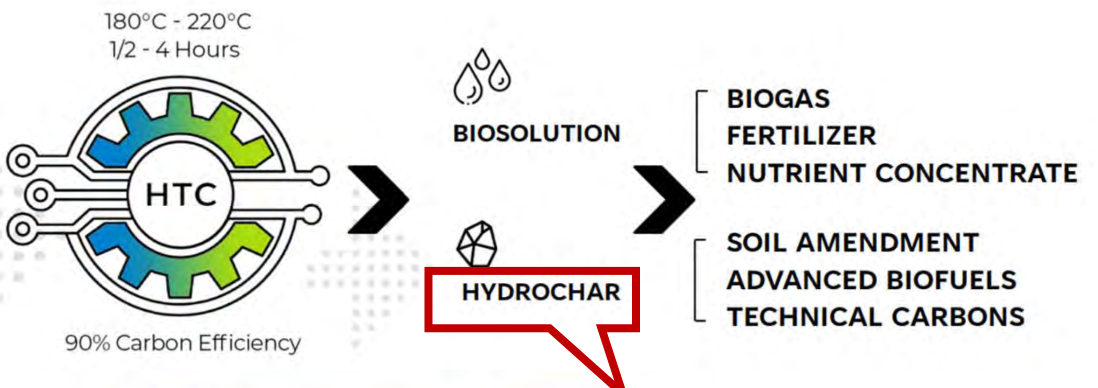
<u>Feedstock Sources</u>: Madison MSW organics/compost collection program OR large waste producer organic collection programs such as UW-Madison (food waste), area breweries (spent grains), coffee grounds. MMSD biosolids could also be trucked to the Dane County landfill or Community Digester for HTC processing at a lower tipping fee than what MMSD pays for land application of Metrogro.

<u>HTC Output</u>: Hydrochar from HTC is fed into gasification systems to produce biogas that is then upgraded to pipeline quality for sale. Biosolution boosts digester CH4 production.

<u>Feedstock Source 1</u>:
UW-Madison Organics

<u>Feedstock Source 2</u>:
Coffee Grounds and Spent Brewery Grains

<u>Feedstock Source 3</u>:
MMSD Biosolids



FEECO / Baker-Rullman Rotary Dryer

Rexwood Modular Biomass Gasification Unit

Biogas Compression, Upgrading & Injection

MMSD-1) HTC with Dryer: Nine Springs WWTP

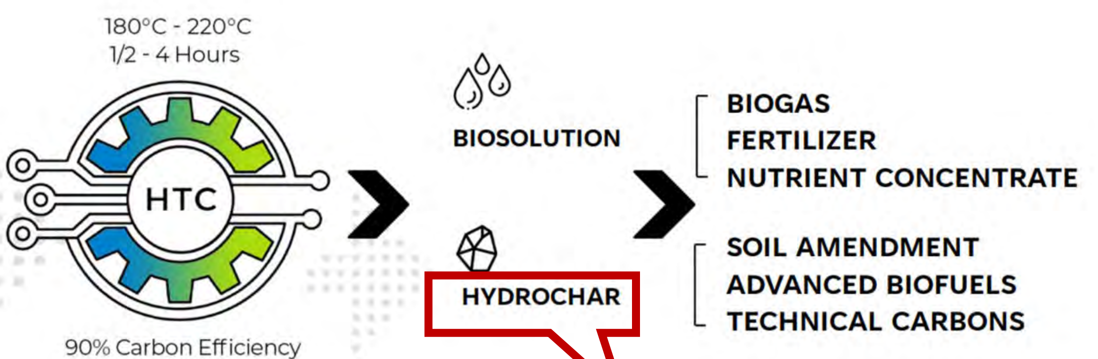
Feedstock Sources: MMSD wastewater sludge is primary HTC feedstock that could be supplemented by Madison MSW organics/compost collection program; OR large waste producer organic collection programs such as UW-Madison (food waste), area breweries (spent grains), coffee grounds. MMSD could earn additional revenue by charging tipping fees for these organic waste streams.

HTC Output: Hydrochar is dried from ~50% to 10-20% moisture content to be sold as a biocoal solid fuel for electricity generation at coal/biomass plants or other industrial heating purposes.

Feedstock Source 1:
WWTP Biosolids

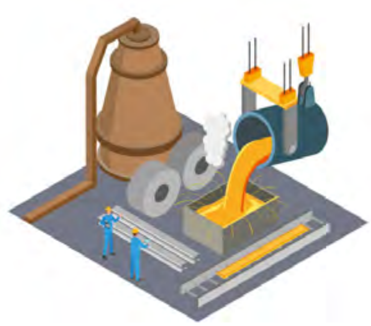
Feedstock Source 2:
Coffee Grounds and Spent Brewery Grains

Feedstock Source 3:
UW-Madison Organics



Existing WWTP Rotary Dryer

Dryer is needed to reduce hydrochar with 50% moisture to biocoal with 1-5% moisture that can be sold to electric utilities other industrial users, or heritage railroads as zero carbon fuel. On-site CHP is needed to produce electricity for buildings or EV fleets.



MMSD-2) HTC with Biomass CHP: Nine Springs WWTP

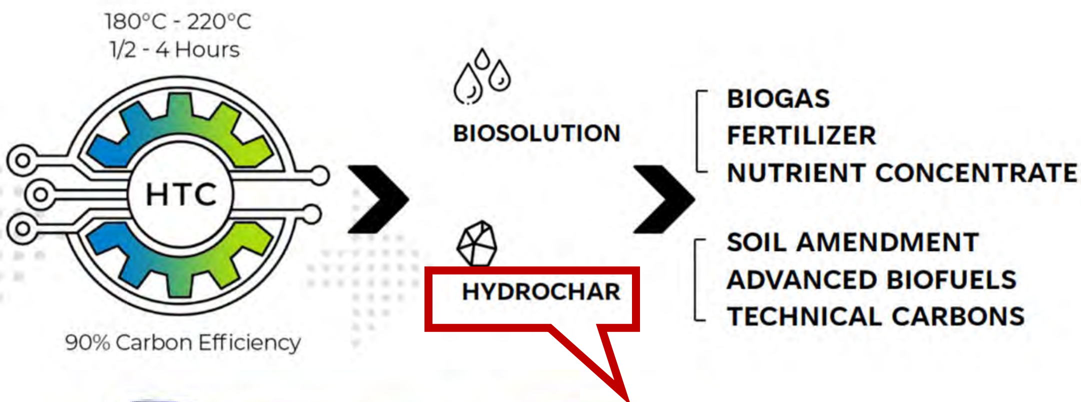
Feedstock Sources: Madison MSW organics/compost collection program OR large waste producer organic collection programs such as UW-Madison (food waste), area breweries (spent grains), coffee grounds. MMSD biosolids could also be trucked to the Dane County landfill or Community Digester for HTC processing at a lower tipping fee than what MMSD pays for land application of Metrogro.

HTC Output: Hydrochar can be used onsite for landfill cover, or sold to other entities for upgrading into biocoal for electric power generation. Biosolution can boost anaerobic digester methane production.

Feedstock Source 1:
WWTP Biosolids

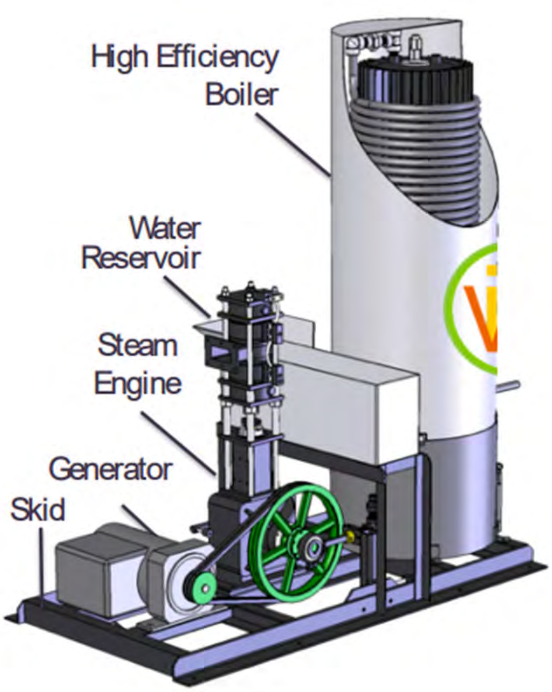
Feedstock Source 2:
Coffee Grounds and Spent Brewery Grains

Feedstock Source 3:
UW-Madison Organics



Existing WWTP Rotary Dryer

On-site CHP unit burns biocoal to produce electricity for buildings or EV fleet vehicles.



VIP 10 kWe / 40 kWt Steam CHP Unit

MMSD-3) HTC with Gasification: Nine Springs WWTP

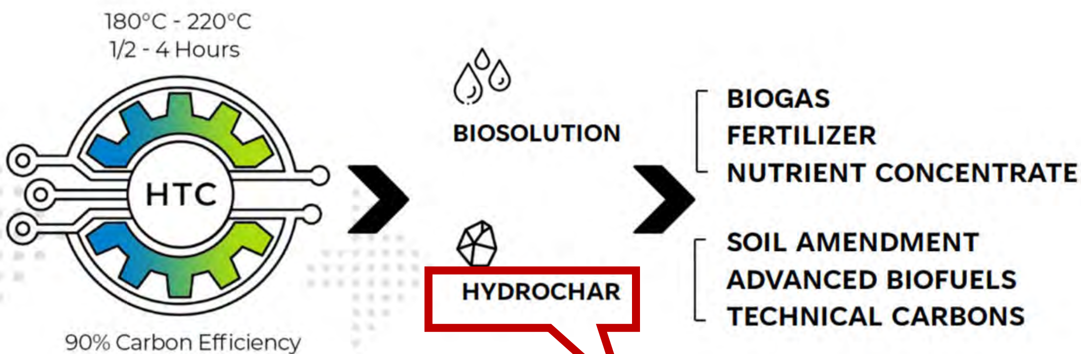
<u>Feedstock Sources</u>: Madison MSW organics/compost collection program OR large waste producer organic collection programs such as UW-Madison (food waste), area breweries (spent grains), coffee grounds. MMSD biosolids could also be trucked to the Dane County landfill or Community Digester for HTC processing at a lower tipping fee than what MMSD pays for land application of Metrogro.

<u>HTC Output</u>: Hydrochar can be used onsite for landfill cover, or sold to other entities for upgrading into biocoal for electric power generation. Biosolution can boost anaerobic digester methane production.

<u>Feedstock Source 1</u>:
WWTP Biosolids

<u>Feedstock Source 2</u>:
Coffee Grounds and Spent Brewery Grains

<u>Feedstock Source 3</u>:
UW-Madison Organics



Existing WWTP Rotary Dryer

Rexwood Modular Biomass Gasification Unit

Biogas Compression, Upgrading & Injection

ATTACHMENT 1

Updated on **December 16, 2023** · Created on **June 30, 2016**

VIP 10-40 Steam Engine

UPCOMING UPDATE

Using agricultural waste as fuel, the VIP 10-40 supplies thermal, electrical, and mechanical power.

DEVELOPED BY

- Village Industrial Power

TESTED BY

- Village Industrial Power

CONTENT PARTNERS

Unknown

AUTHOR

packleader

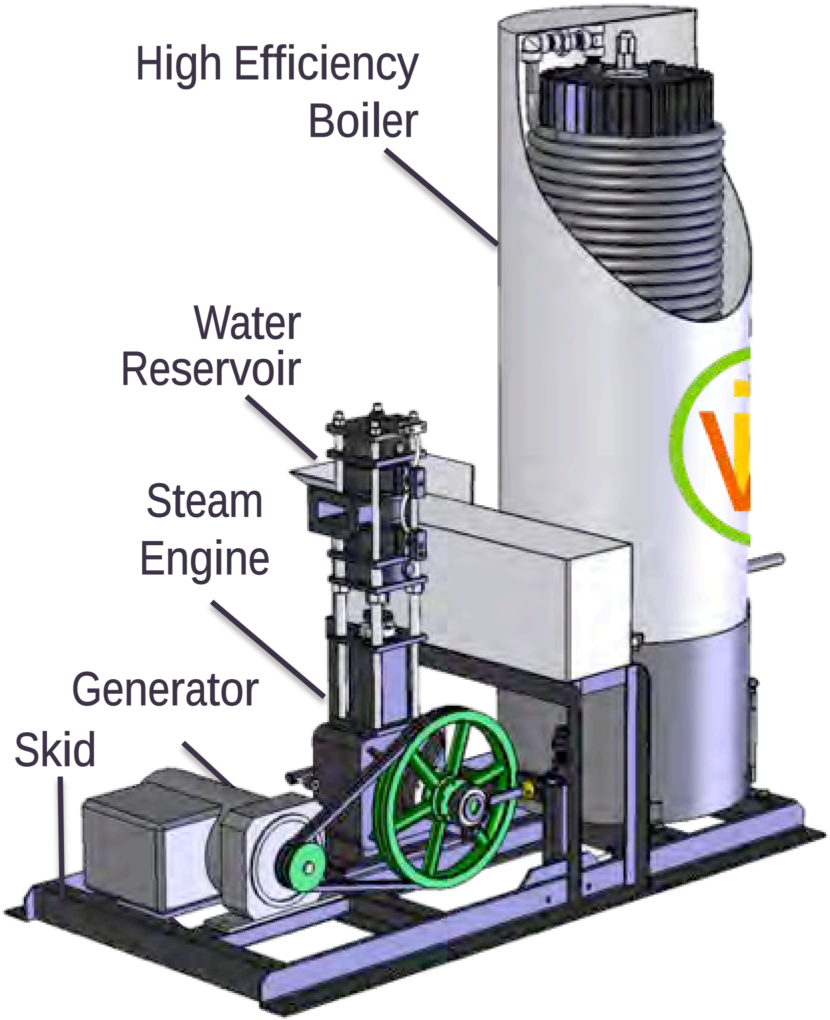
PDF CSV

Snapshot | Manufacturing & Delivery | Performance & Use | Research & Standards | Feedback

Product Description

The Village Industrial Power V-10-40 steam engine produces heat that can be used either to produce hot air or hot water, depending on the agricultural application required. Functionalities include transforming biomass into heat for opportunities such as crop drying, and powering various equipments. It is clean-burning and able to run on numerous biomass feedstocks. V-10-40 was previously named as V-10 steam engine. Village Industrial Power is located in Bradford, Vermont with additional operations in Nairobi, Kenya and Maharashtra, India.

10kWe/50kWt - Village Industrial Power(VIP) / 50kWe - AgWatt



Patent Pending

Unique features:

- Fuel Flexibility, Oil-less Steam Cylinder

Capabilities: Co-Generated Heat (low pressure steam), ease of use cooking

Technical Details – 10 to 50kW range

- 10kWe, 50kWt power/ 50kWe,
- Weight: 2,000- 10,000 lbs
- Size: 2m x 1m x 2m, Efficiency; (fuel to e): 10%
- Emission: min visible; CO < 500 ppm
- Boiler Exhaust = 300 C
- Engine exhaust = 120 C (saturated steam)
- Inlet temp; 300 C (superheated steam, 20 bar)
- Durability (10 plus years; run time insufficient for verification)
- Cost; (projected cost, US manufacture: $20,000; overseas: $10 –15,000)
- Noise; currently est. 80 db at full output, potentially much lower

AgWatt VIP

AgWatt/Village Industrial Power (VIP)

Development Needs

- Build and Test Integrated 50 kW plant
- Adapt to AgFuel Energy Crop Burner; test varied fuels
- Endurance testing; Optimization (pressure-displacement data logging, heat transfer analysis, speed increase to 1800 rpm)
- Cost reduction
- Feasibility – tailor the system to 1 to 5 kW range (specific cost)
- Automation
- Code approval for commercial and residential use

AgWatt VIP

ATTACHMENT 2

SoMax

Hydrothermal Carbonization at the Borough of Phoenixville WWTP

Jeremy Taylor
Chief Sustainability Officer
SoMax Circular Solutions

NORTH EAST RESIDUALS & BIOSOLIDS CONFERENCE
Sponsored by NEWEA AND NEBRA
2022 SPECIALTY CONFERENCE & WORKSHOP SERIES
NEWEA WORKING FOR WATER QUALITY
25th Anniversary 1997–2022 nebra North East Biosolids & Residuals Association

Agenda

- Intro to SoMax
- Fundamentals of Hydrothermal Carbonization (HTC)
- Hydrothermal Carbonization and the Status Quo
- Development of SoMax HTC at the Borough of Phoenixville WWTP

SoMax Circular Solutions

2015
Partnered with Villanova Sustainable Engineering

2018
3rd Generation Reactor Design

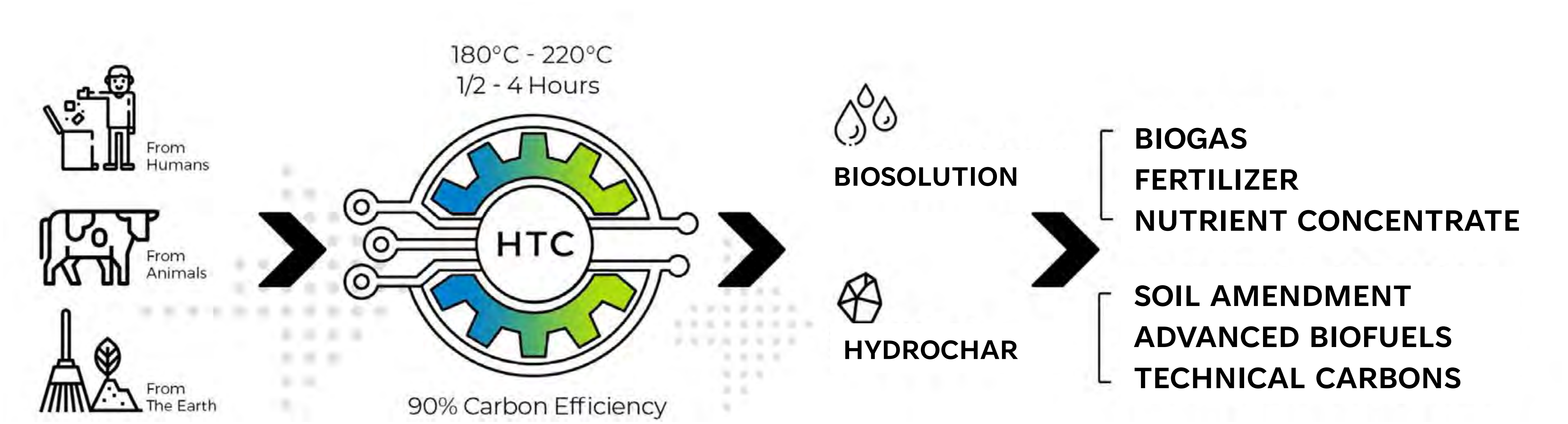
2019
Awarded design-build contract for 1st HTC plant in North America

2019
Finalist – The Manure Challenge
The Yield Lab Institute

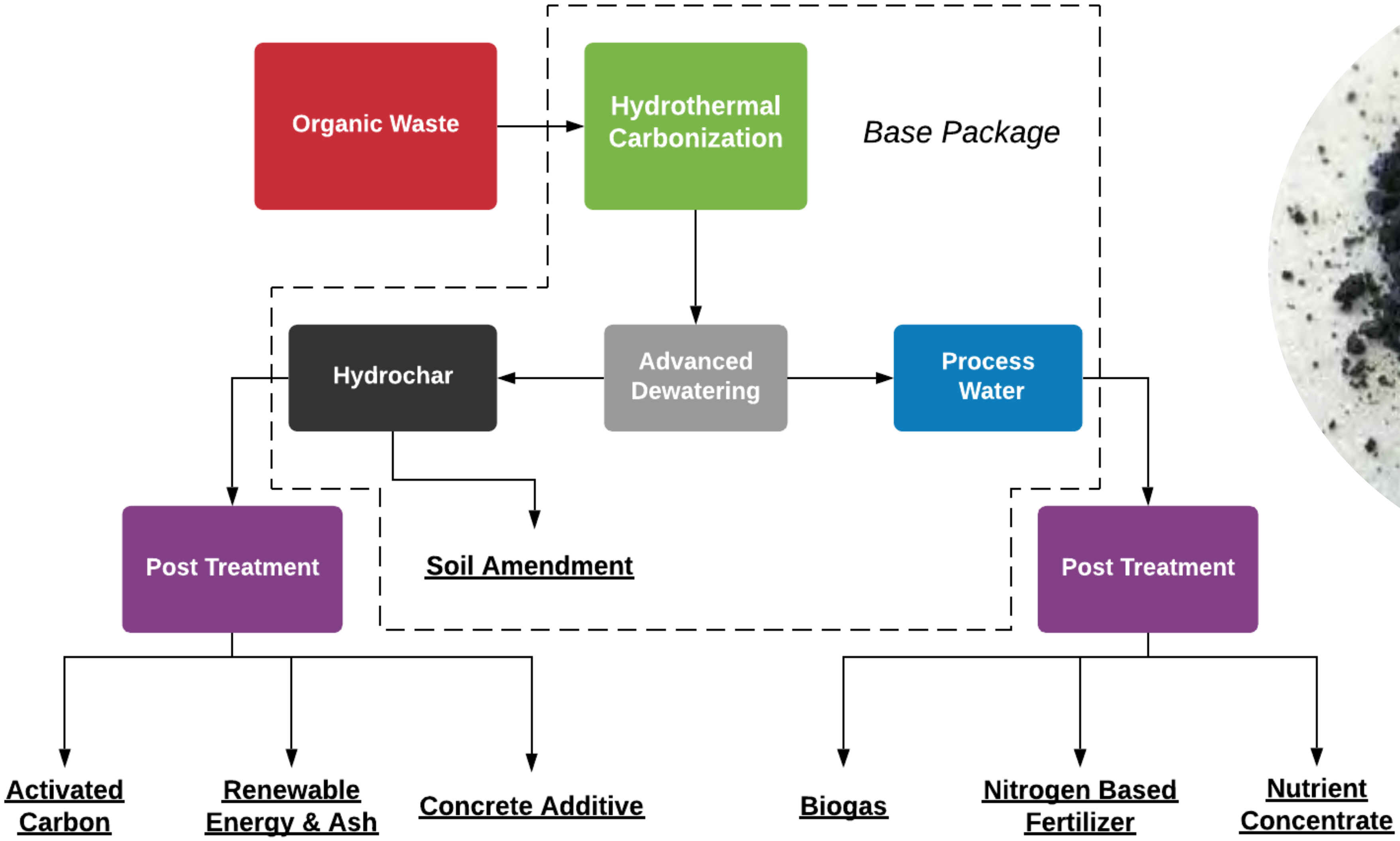
2021
Winner – Water Resource Recovery Prize
U.S. Department of Energy
Seeking scalable and repeatable solutions for implementation at WWTP across U.S.

2021
Winner – Diageo's Low Carbon Heat Challenge
Integrating Hydrothermal Carbonization as a closed loop solution for Spent Distillers Grains

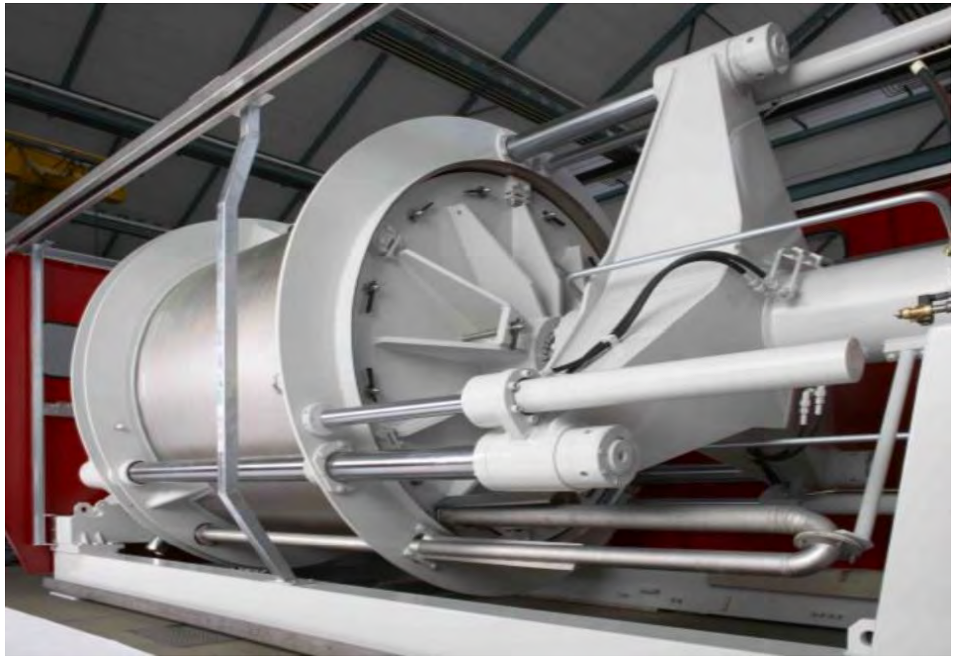
Hydrothermal Carbonization

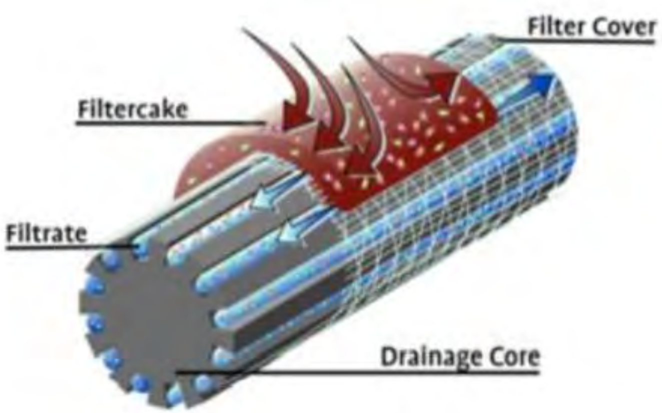


Commercial Process Overview



Advanced Dewatering – Bucher Press





- Slow Rotating Body – Hydraulic Filter Press
- **Polymer Free Dewatering**
- > 99% solids capture with <100mg/L TSS in the filtrate
- 50-65% TS hydrochar dewatering
  - 70%+ TS from pilot unit w/acid addition

HTC's Impact on Sludge and Biosolids

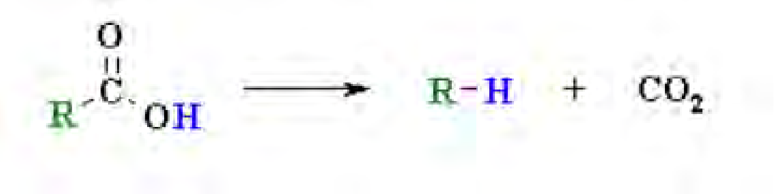
Pre HTC
~20% TS Primary Sludge

Post HTC
Hydrochar Product Slurry

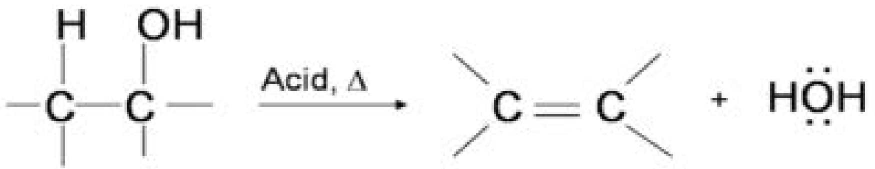
- 70 – 80% Sludge Reduction
- Improves Dewatering Efficiency
- Increases Energy Density and Carbon Concentration
- No Sticky Phase
- Pathogen Free
- Pharmaceutical and PFAS Reduction

Reaction Mechanisms – Carbon

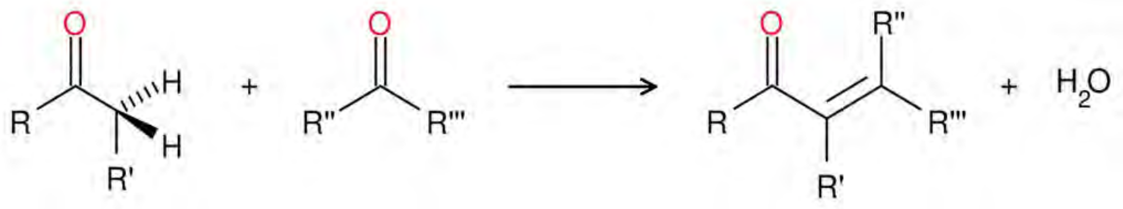
Hydrolysis – Cleaves large molecules



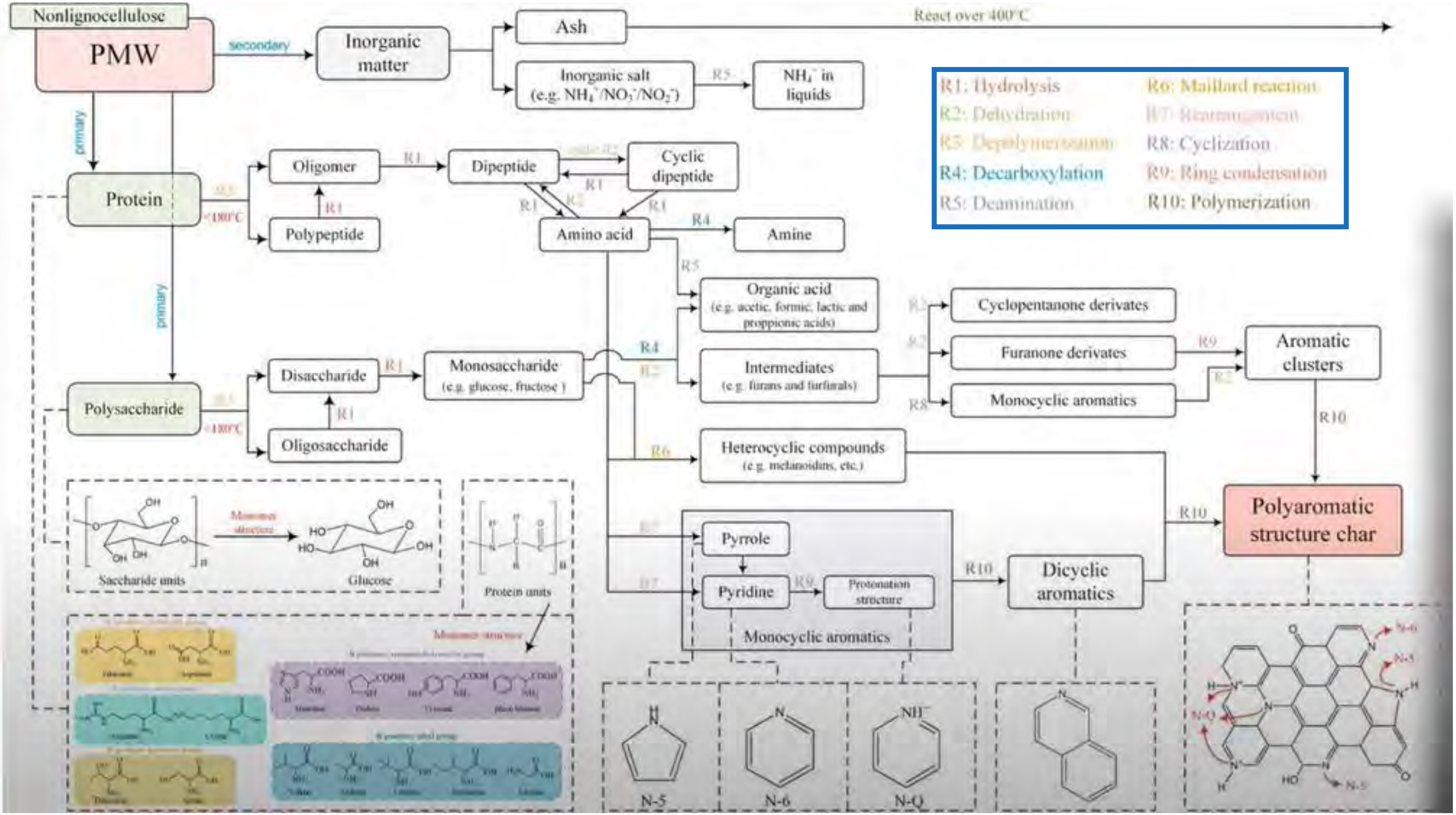
Decarboxylation – Creates CO_2 gas



Dehydration – Creates water

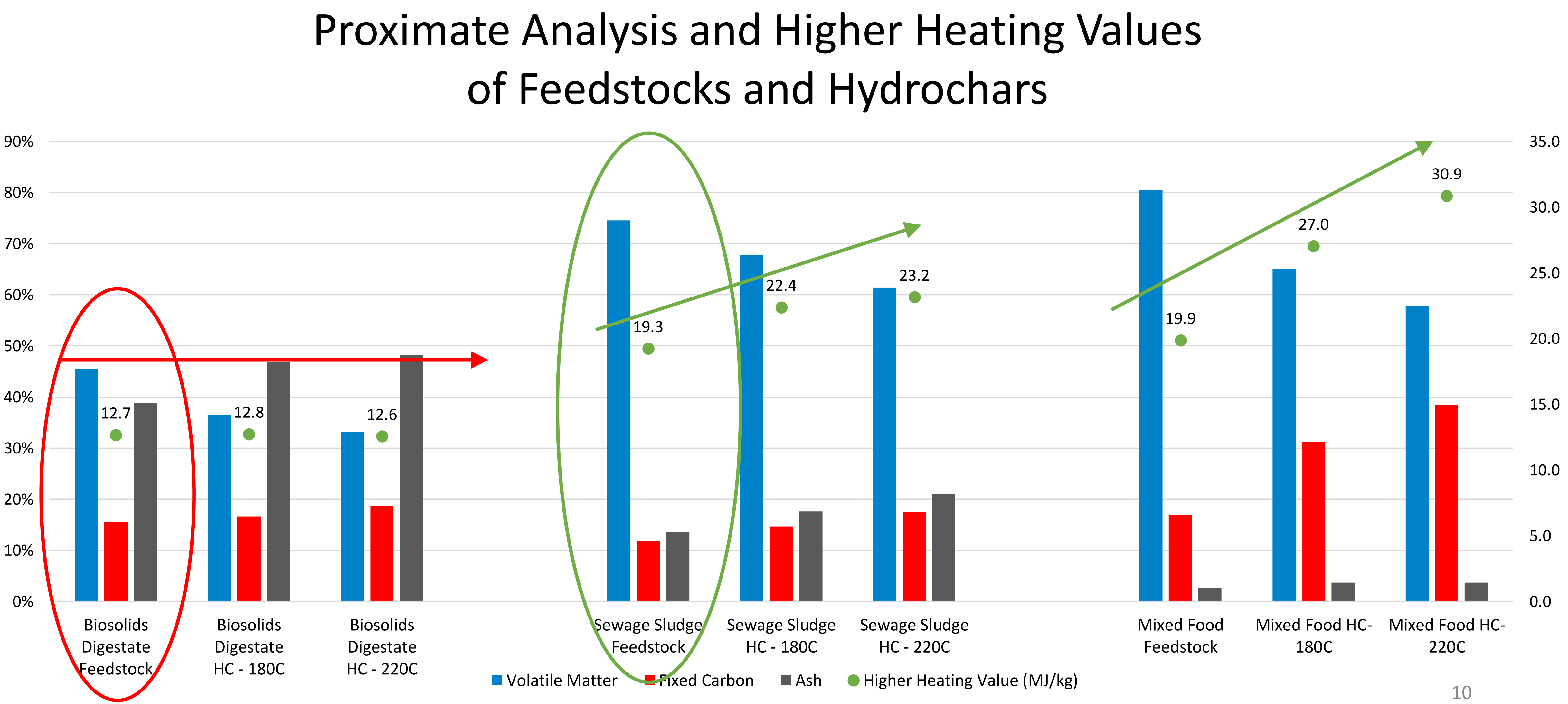


Condensation – Creates larger molecules and water



https://www.youtube.com/watch?v=QX2A95eSv9I – Prof. Stergios Vakalis

Reaction Trends - TGA and HHV



Hydrochar aka Bio(*genic*) Coal

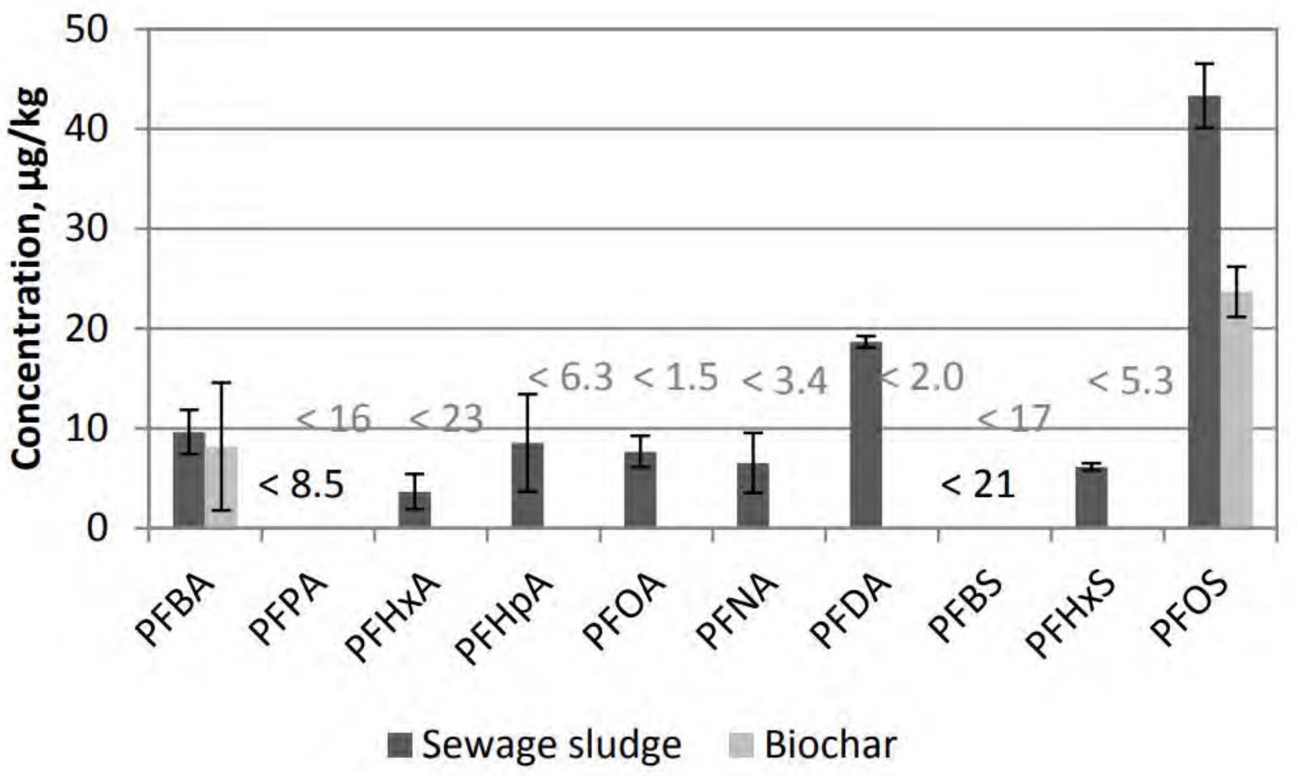
	BioCoal (Spent Grain)	Anthracite	Bituminous	BioCoal (Mixed Food)	Sub-Bituminous	BioCoal (Raw Sewage)	Lignite
Heat Content (BTU/lb)	14,000 - 16,000	13,000 - 15,000	11,000 - 15,000	11,500 - 13,300	8,500 - 13,000	9,000 - 10,300	4,000 - 8,300
Fixed Carbon	20 – 30%	85 – 98%	45 – 85%	30 – 40%	35 – 45%	15 – 20%	25 – 35%
Ash	0.5 – 1.5%	10 – 20%	3 – 12%	2 – 5%	<10%	15 – 20%	10 – 50%
Formation Time	3 Hours	350,000,000 Years	300,000,000 Years	2 Hours	100,000,000 Years	1 Hour	60,000,000 Years

BioCoal heating values range between 9,000 – 16,000 BTU/lb and has a **Net Zero** Carbon emission factor.

https://www.purdue.edu/discoverypark/energy/assets/pdfs/cctr/outreach/Basics8-CoalCharacteristics-Oct08.pdf

HTC and PFAS

- HTC parameters of 210°C and 4 hours
- Sum of all PFAs in Sewage Sludge: 104 µg/kg_{DM}
- Sum of all PFAs in Hydrochar: 32 µg/kg_{DM}
- **2/3 reduction in total PFAs**
- Complete removal of PFOA
- HTC process water/filtrate not tested



Behavior of Micropollutants during Hydrothermal Carbonization of Sewage Sludge. Claudia vom Eyser, 2016

HTC and Pharmaceuticals

- HTC parameters of 210°C and 4 hours
- Decomposition Temperature not indicative of removal
- Concentrations of 6 of the tested pharmaceuticals were below LOQ
- HTC process water not tested

	Measured concentration in spiked sewage sludge µg/kg_{DM}	Concentration after HTC µg/kg_{DM}	Removal during HTC %
Ibuprofen	350 ± 33	130 ± 15	63
Phenazone	210 ± 33	230 ± 6	No removal
Carbamazepine	560 ± 23	< 20	> 98
Bezafibrate	180 ± 8	< 40	> 89
Fenofibric acid	340 ± 23	< 20	> 97
Metoprolol	650 ± 96	400 ± 23	39
Propranolol	360 ± 120	70 ± 14	81
Clarithromycin	220 ± 55	< 20	> 95
Roxithromycin	190 ± 63	< 10	> 97
Erythromycin	180 ± 24	< 10	> 98

Behavior of Micropollutants during Hydrothermal Carbonization of Sewage Sludge. Claudia vom Eyser, 2016

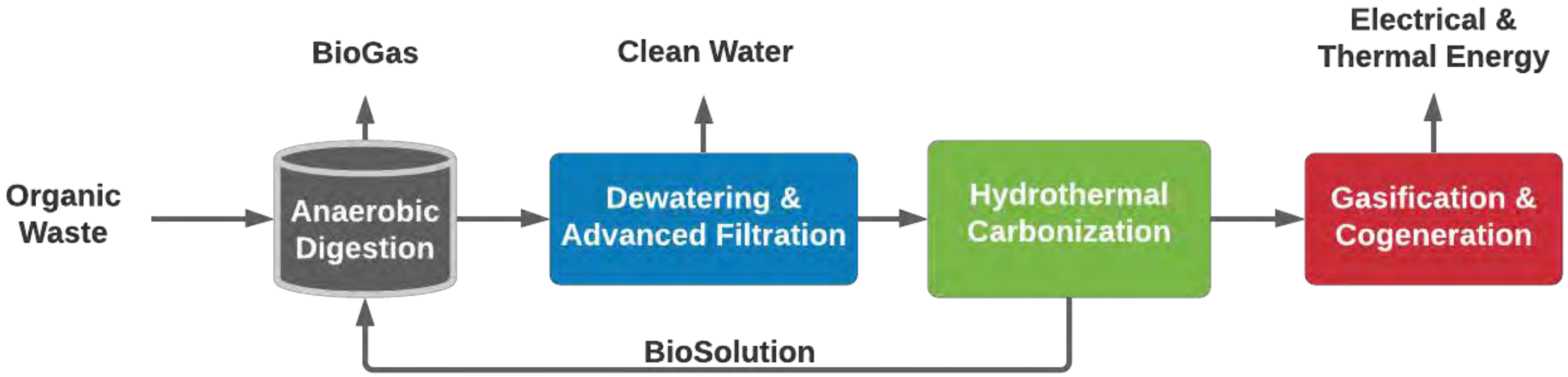
HTC vs. Standard Organic Waste Solutions



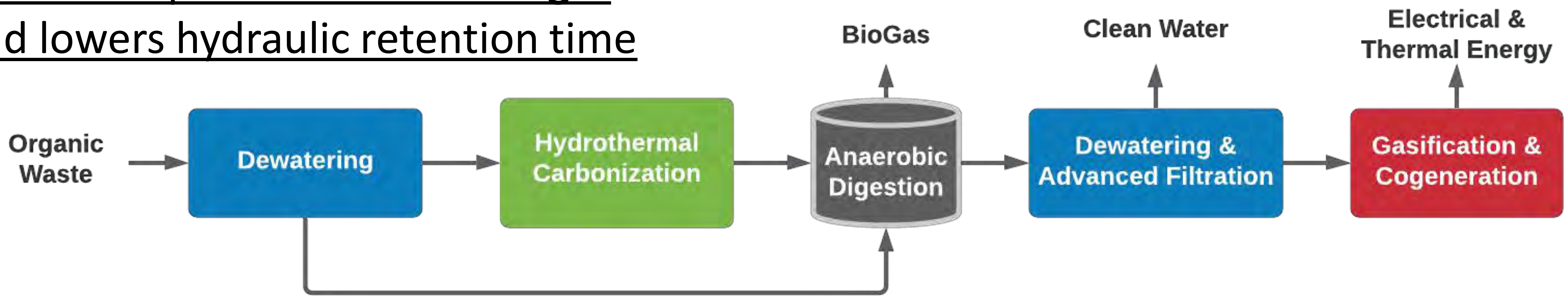
Process	Carbon Efficiency	Process Duration	Final Product
Landfill	0%*	Months-Years	Landfill Gas, Leachate
Composting	10%	12 Weeks	Soil Amendment
Anaerobic Digestion	50%	15-40 Days	Biogas – 60% Methane, 40% CO_2
Hydrothermal Carbonization	**Up to 90%**	**30 Minutes – 4 Hours**	**Hydrochar**

HTC + Anaerobic Digestion

Produces up to 30% more Biogas



Produces up to 300% more Biogas and lowers hydraulic retention time

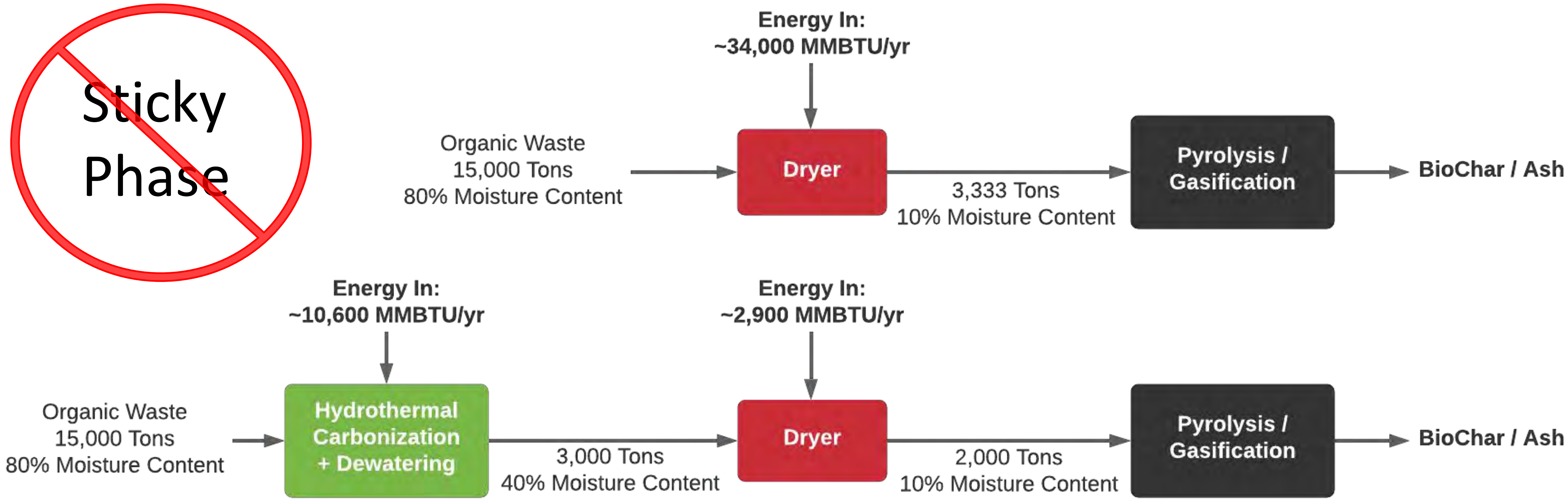


Lucian, M. et al (2020)

HTC + Pyrolysis/Gasification

HTC + Drying uses **60% less** energy of drying of wet waste for Pyrolysis/Gasification

HTC + Drying reduces the dryer unit size by **80%** and Pyrolysis/Gasification unit size by **40%**



PXVNEO

PHOENIXVILLE NEW ENERGY OPTIMIZATION

HYDROTHERMAL CARBONIZATION FACILITY

www.PXVNEO.com

Borough of Phoenixville, PA

First Municipality in Pennsylvania to pledge 100% Clean and Renewable Energy Goal by 2035

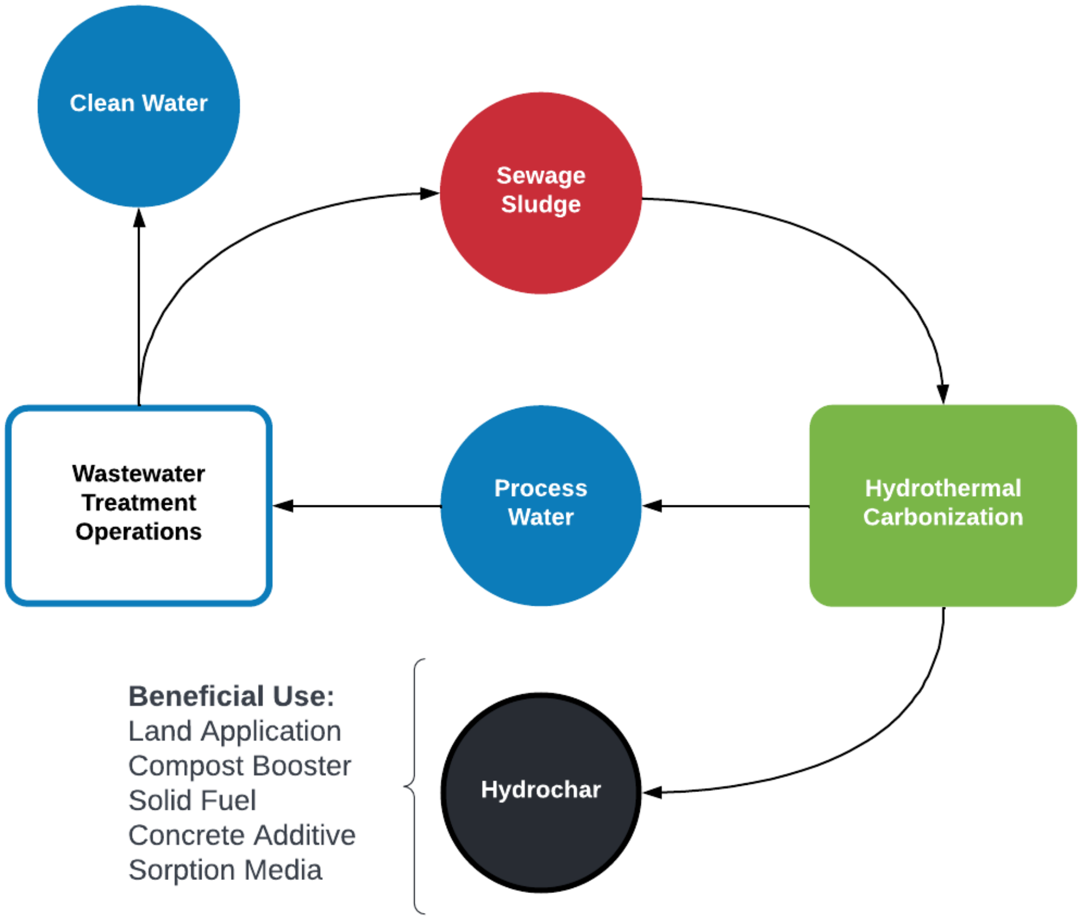
Borough of Phoenixville WWTP

Population:	~17,000
Rated Cap.:	4 MGD
Ave. Cap.:	1.75 MGD
Product:	Class B Biosolid
Method:	AD
Volume:	1618 tons @ 25% TS
Disposal Cost:	$46.90/ton

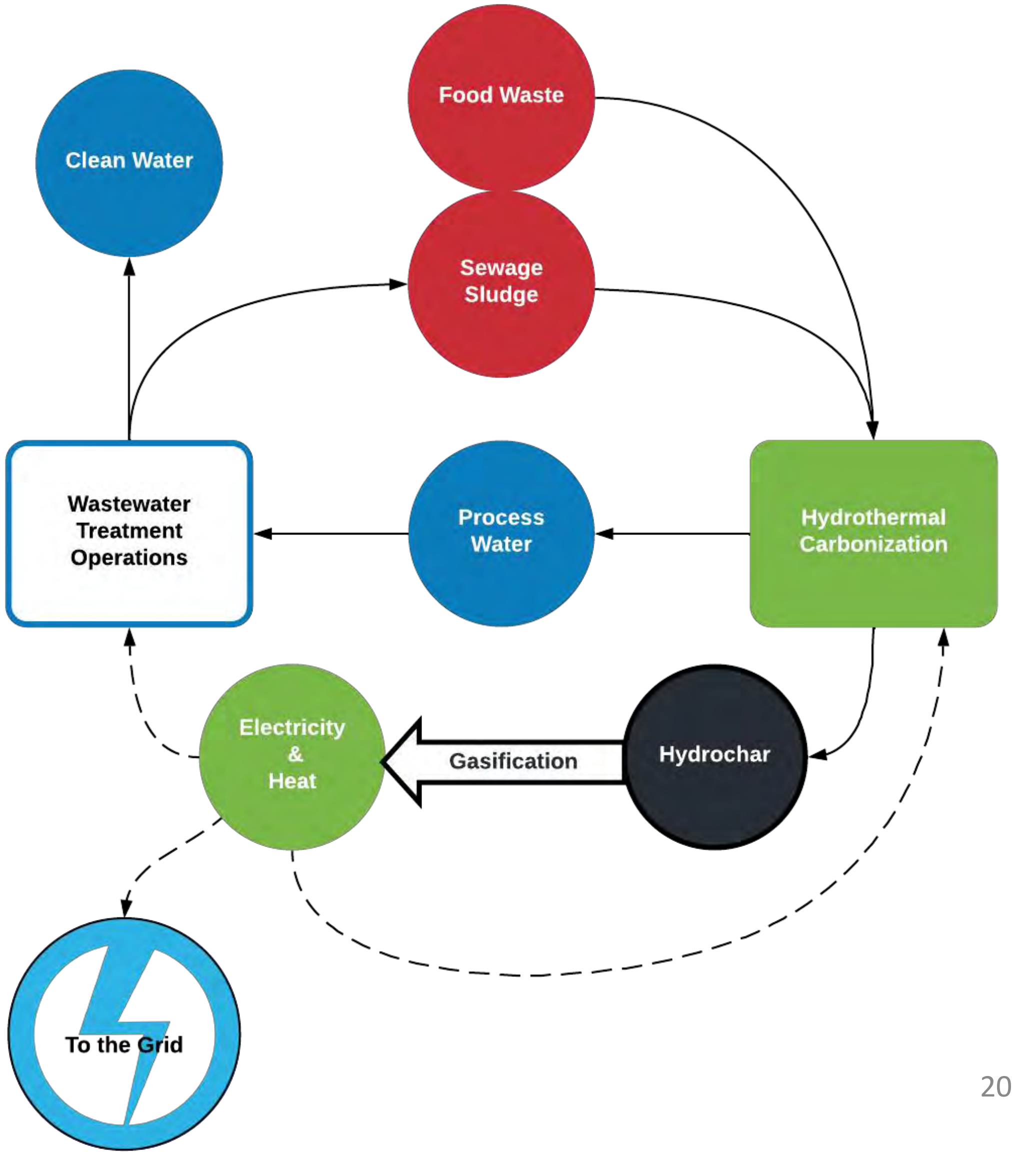
Phoenixville HTC Project Timeline

- April 2019 – HTC Engineering and Design
- May 2021 – Present – Greenhouse Slab Upgrades
- June – August 2021 – Equipment Purchasing
- Q1/Q2-2022 – Equipment Arrival and Construction
- Q1 2023 – HTC Process Commissioning
- 2023 – Prove and Permit Beneficial Use Cases & Apply for a PA General Permit
- 2024/2025 – Phase 2 – Combine Food Waste as a feedstock and include Gasification for Carbon Neutral Electricity Generation

Phase 1 – HTC



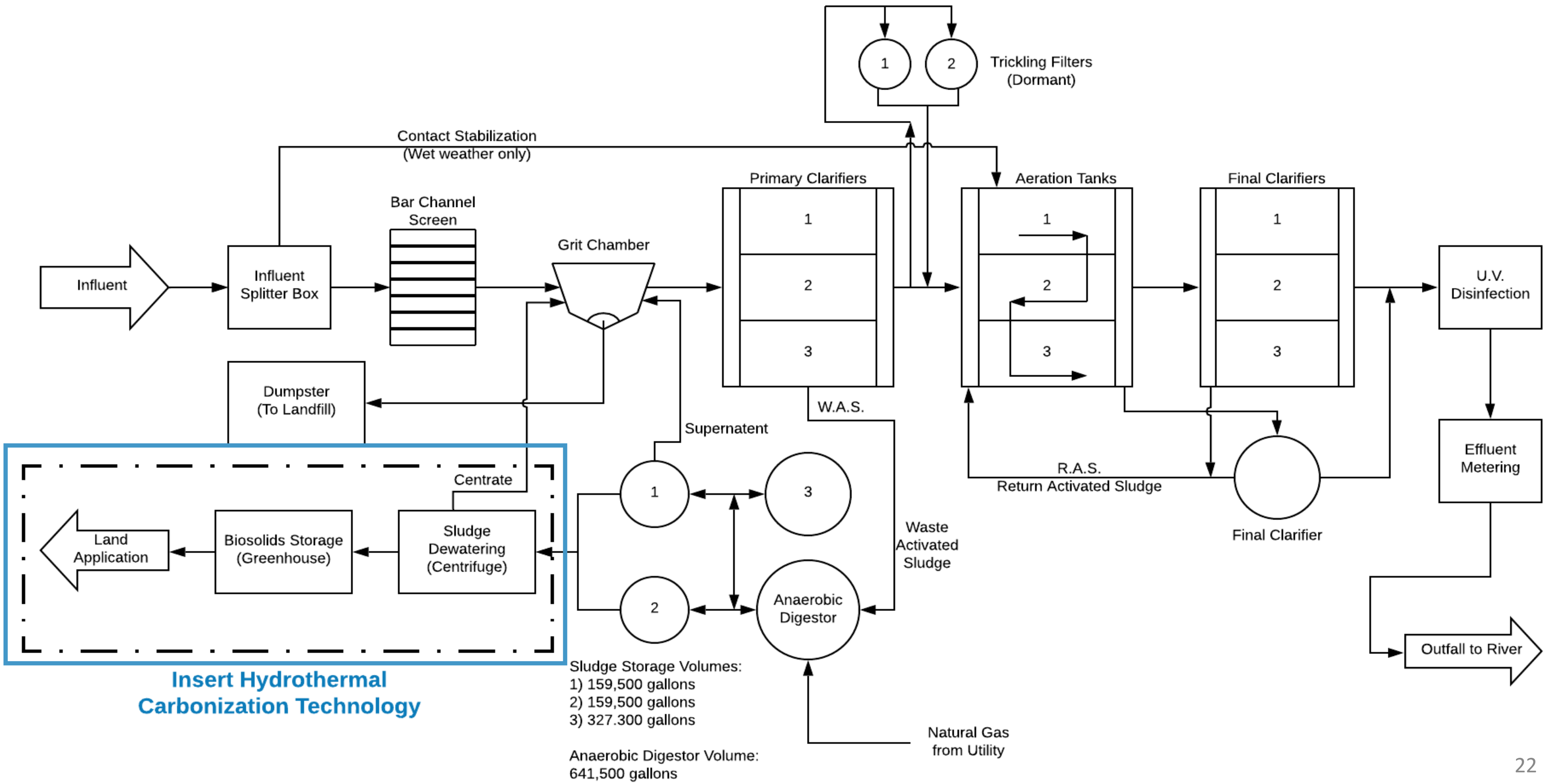
Phase 2 – HTC + Gasification



PA DEP Permitting

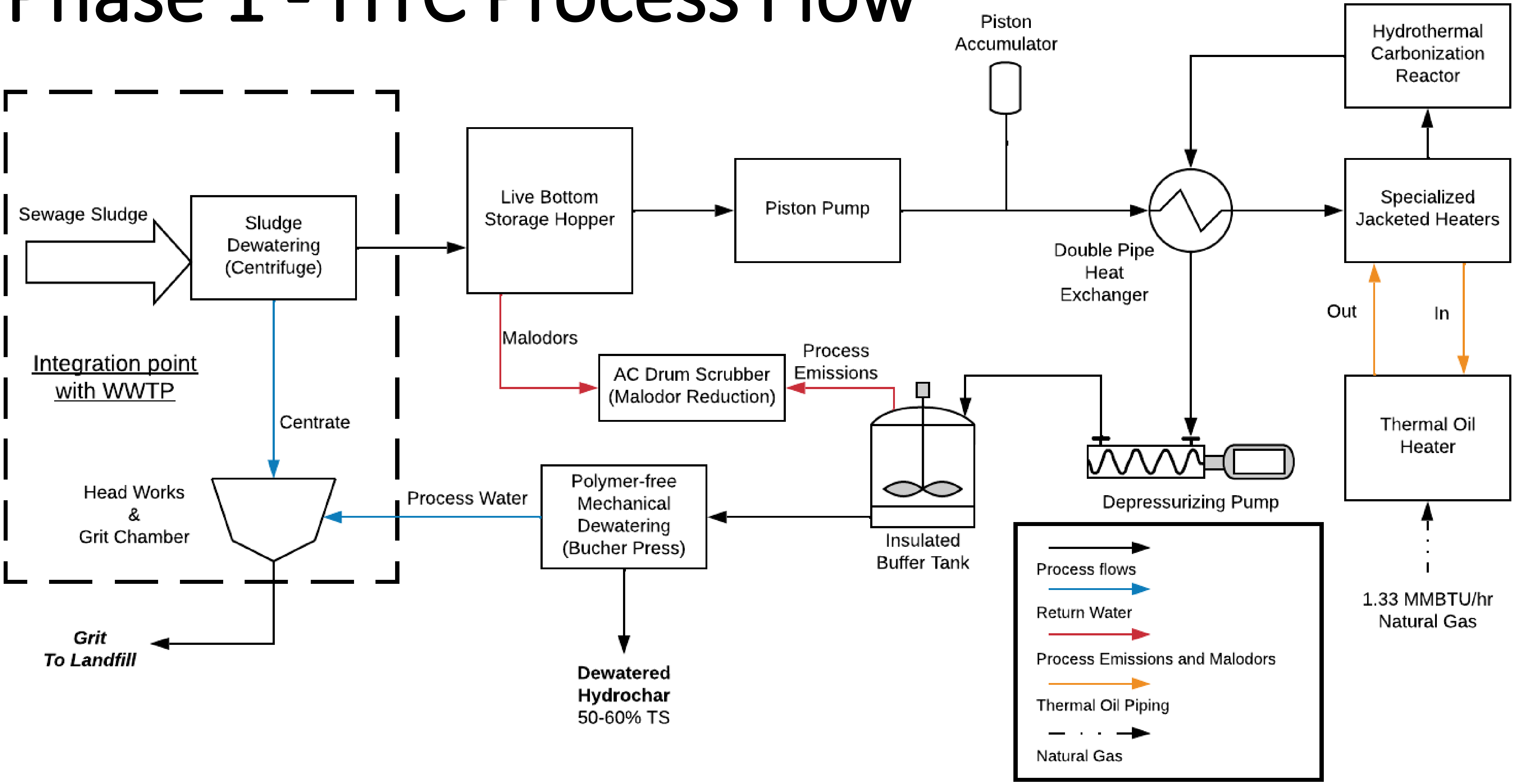
- February 10, 2022 – Approved as a Permit-By-Rule (PBR) captive municipal waste processing facility
- Initially hydrochar is **WASTE** and must be stored on site
- Landfill and land application will need to be approved
  - Goal is Class A EQ improving from Class B
- Solid fuel requirement easily met at 5,000 BTU/lb
- Beneficial use testing at pilot scale will began for utilizing hydrochar as a concrete additive, asphalt additive, and sorption media
- Hydrochar can be ‘dewasted’ for beneficial use with an Individual or General Permit

WWTP Process Flow Diagram



Insert Hydrothermal Carbonization Technology

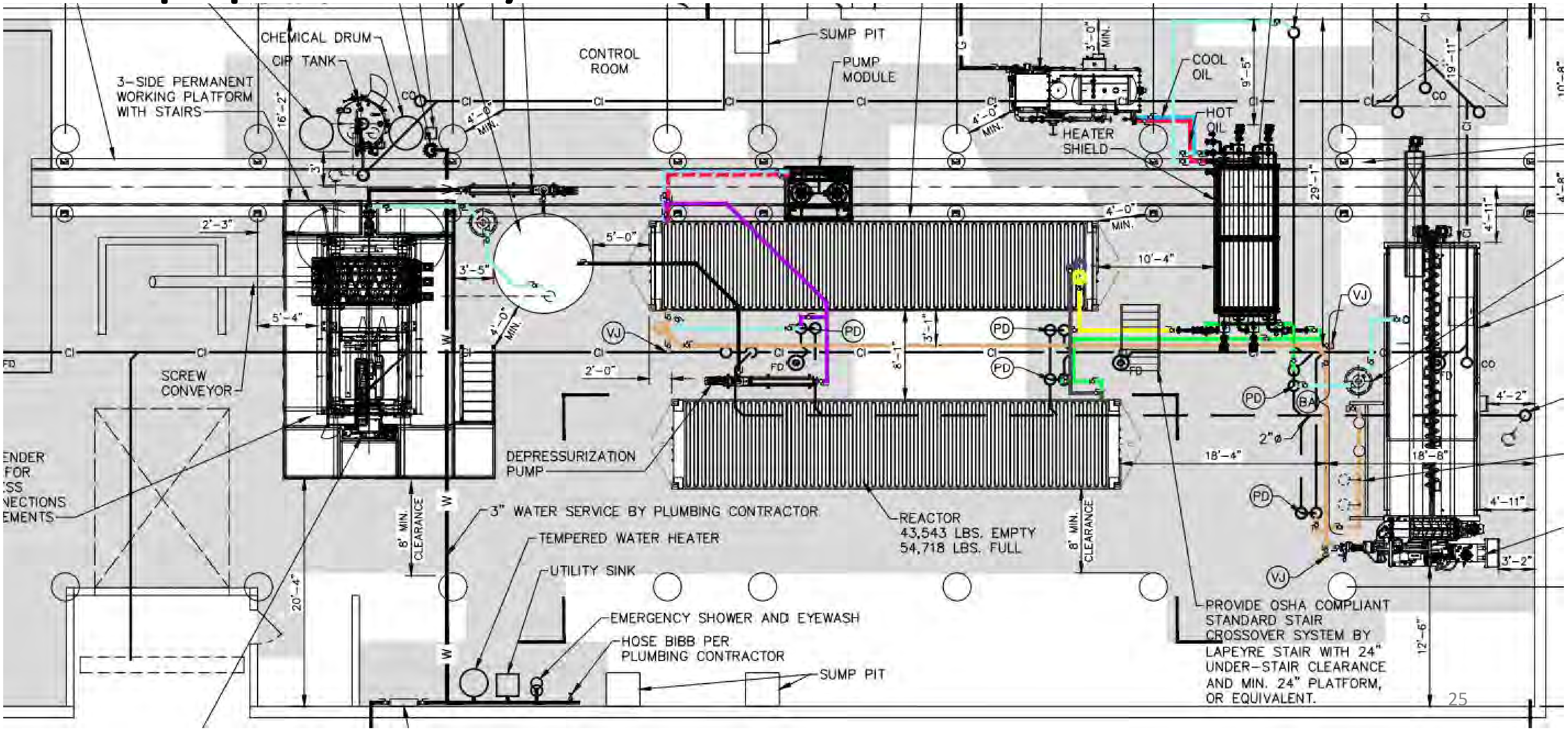
Phase 1 - HTC Process Flow



Equipment placement began April 13, 2022.

The HTC Process will take up ~1/2 of the greenhouse.

Equipment Layout



HTC at the Borough of Phoenixville WWTP

Industry Leading Carbon Efficiency:
- Carbon Efficiency up to 90%
- Lowest GHG emissions of any biomass conversion

Efficient Energy Recovery (w/Phase 2)
- Generates up to 10X more electrical energy than HTC consumes
- Creates up to 150% of the WWTP energy demand

HTC

Barrier Breaking Innovations
- Polymer-free dewatering of hydrochar to over 50% solids
- Source reduction up to 80%

Synergies with other Treatment Processes
- Increases Biogas production
- More efficient drying for pyrolysis/gasification

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25th Anniversary 1997–2022 nebra North East Biosolids & Residuals Association

SoMax

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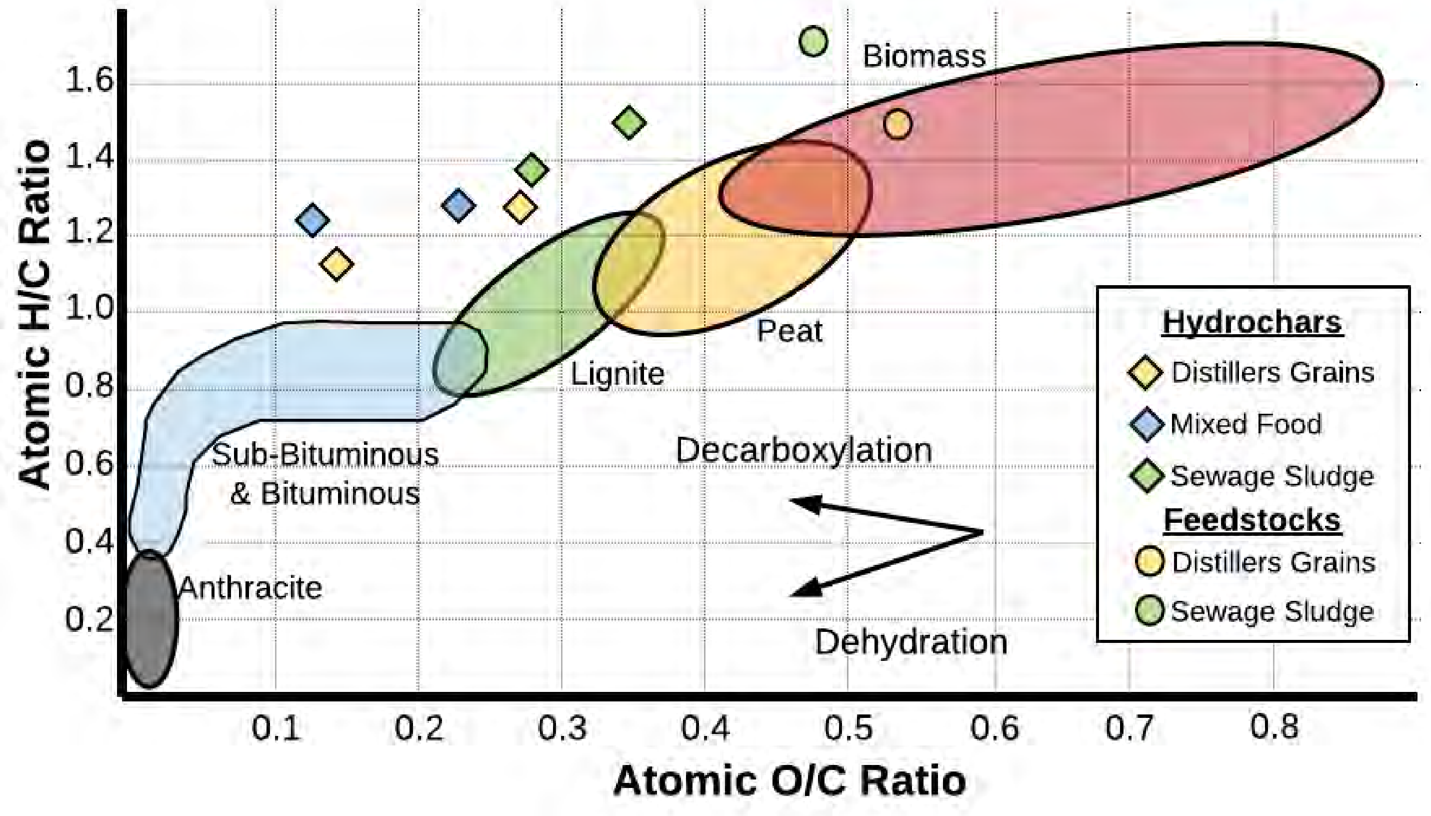
Jeremy@somaxhtc.com
www.SoMaxHTC.com

Appendix

Visualizing HTC Reactions – Van Krevelen



Hydrochars:

Our Hydrochars – $C_{4\text{-}6}H_{6\text{-}12}O_{1\text{-}1.5}$

Typical Literature – $C_{5\text{-}6}H_{12\text{-}14}O$

Coals:

Lignite: $C_{39}H_{35}O_{10}$

Bituminous – $C_{137}H_{97}O_{9}$

High-grade Anthracite – $C_{240}H_{9}0_{4}$

https://www.purdue.edu/discoverypark/energy/assets/pdfs/cctr/outreach/Basics8-CoalCharacteristics-Oct08.pdf

ATTACHMENT 3

Gardner, MA HTC Feasibility Study

Prepared by:

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Jeremy Taylor
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501 S. Main St. Spring City, PA 19475

March 8, 2023

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1. Executive Summary

Project Purpose

The purpose for the feasibility report is to illustrate the impact of implementing hydrothermal carbonization at the City of Gardner Wastewater Treatment plant. By expanding the solids processing capacity through HTC and opening the doors to hauled waste, the Gardner WWTP can become a net energy producer while achieving positive economics.

SoMax's analysis identified the conversion parameters and economic feasibility utilizing biosolids from the City of Gardner Wastewater Treatment Plant as a feedstock for hydrothermal carbonization (HTC). The report will act as a guide for the City of Gardner decision makers when assessing the potential for implementing HTC at the wastewater treatment plant as a sustainable, long-term solution to replace the current practice of landfilling and the expansion of the municipal sludge landfill.

The scope of the project includes assessing the biosolids generated at the Gardner WWTP as a viable feedstock for HTC and analyzing the solid product of HTC, known as hydrochar, for energy production. Additionally, the liquid product of HTC was analyzed through the lens of wastewater characterization to be sent to the headworks of the Gardner WWTP. Multiple scenarios were modeled for economic projections with the assumptions built around Gardner's ability to maximize reactor capacity through hauled waste, including biosolids and food waste. Gardner's stated goal is to produce energy, and the economic projections and modeling were tailored towards energy production through gasification of the hydrochar. Also, a model for product sales was discussed to show a secondary pathway.

The City of Gardner can use the economic models in this report to compare to the economics of the proposed expansion of the municipal sludge landfill.

Project Results

SoMax's analysis resulted in four primary outputs:

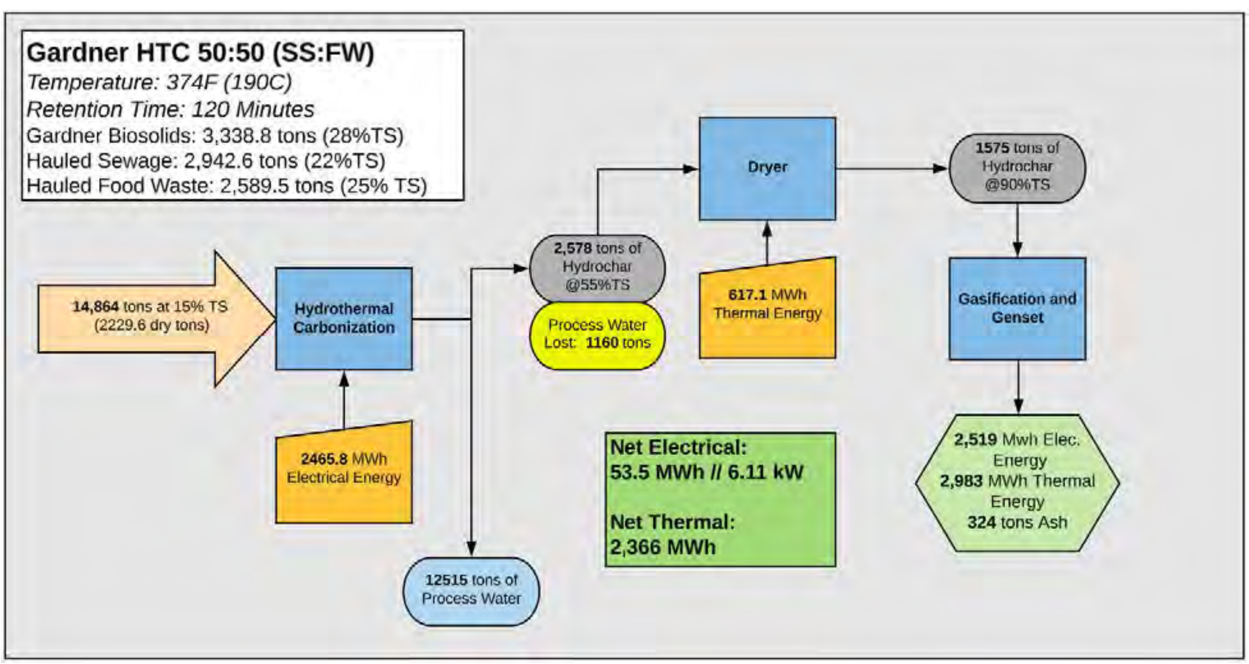
1) Optimized HTC reaction parameters for energy generation
2) Analysis of HTC products
3) Modeling of HTC process
4) Economic analysis and sensitivity study of implementing HTC

The biosolids provided to SoMax from the Gardner WWTP were tested at varying temperatures from 180 – 220°C (356 – 428°F) to identify the reaction parameters that optimized the hydrochar for energy production, analyzing solid yield, carbon recovery and energy recovery. The study resulted in 190°C as the optimized temperature, giving the best combination of solid yield and energy density.

The analysis of the Gardner WWTP hydrochar showed minimal carbonization and increase in energy density. SoMax hypothesizes that the unique hydrochar properties were due to overdosing of ferric chloride and high polymer usage during sludge processing. Compared to other primary sludge SoMax has tested, the energy density in the Gardner sludge-derived hydrochar was ~15% lower. The mineral ash analysis and process water testing highlighted the high ferric chloride use with an excess in iron compared to other sludge samples SoMax has analyzed. The detailed analysis of the hydrochar, including fuel characteristic testing, and process water analysis including fertilizer assessment and wastewater characterization testing, as discussed in the report, did not show other significant abnormalities.

Despite the lower energy density of the Gardner WWTP hydrochar, implementing HTC and filling the remainder of the capacity with hauled waste, such as food waste, surrounding municipalities sewage sludge and biosolids, and septic waste, can allow the City of Gardner to become a net energy producer and reduce the energy load consumed at the wastewater treatment plant. The Gardner WWTP generates between 29 – 42% of the solids capacity of the HTC process, allowing for additional revenue and hydrochar production through hauled waste. Only through additional hauled waste can Gardner become a net energy producer.

The mass and energy balance of the HTC implementation assumed all electric processing as no natural gas utility is on site. The facility becomes net energy positive when hauled waste reaches a ratio of 50:50 food waste: sludge, or greater, producing ~6 – 87 kW of continuous excess energy at the varying flow rates and throughput of the system.



From an economic standpoint, the return on investment for energy generation can potentially be captured in as little as seven years, depending on the tip fees that Gardner can obtain. The state of Massachusetts has a median sludge tip fee $140/ wet ton (22%TS) as stated by a study from NEBRA in 2018. The ‘high’ tip fee economic scenario utilizes this rate, which appears to be obtainable. Market research and regionally available sludge and food waste research is recommended to verify tip fees.

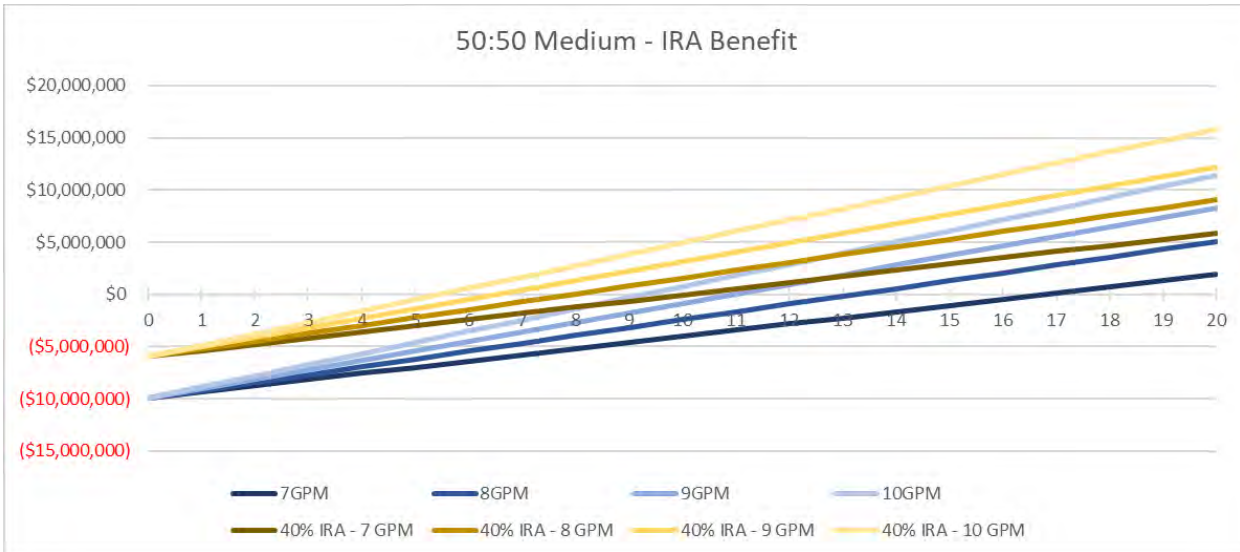
Generating energy opens Gardner and this project to tax incentives not available through the material sales pathway. By becoming an energy producer this project qualifies for federal tax credits under the Inflation Reduction Act (IRA) signed into law on August 16th, 2022.

The IRA establishes a base credit of 6% of the overall project cost and applies bonus credits up to 50% if certain requirements and conditions are met. The bonus credits are covered by 3 main categories:

- 30% bonus credit (6% Base and 24% bonus) for using contractors that pay prevailing wages and meet apprenticeship requirements.
- 10% bonus credit if a project uses domestically produced iron or steel (55% of purchased materials)
- 10% bonus credit for Energy Communities based on retired/closed coal power plants and coal mines.
    - Gardner is not applicable for this bonus credit.

To illustrate the benefits of the IRA tax incentives the project economics were modeled utilizing a 40% tax credit. For the ‘medium’ tip fee scenario, the economics result in an ROI as low as six to eleven years, which will improve if ‘high’, which are the median tip fees in the state of MA, can be obtained. The graph below shows the 20-year project balance with varying flow rates for the ‘medium’ scenario, with and without the IRA tax credits.

Figure 1 - Projected Economics - IRA Benefits - 'Medium' Tip Fee Scenario - Variable Flow Rates



Recommendations and Next Steps

As shown in the figure above, the HTC project can result in positive economics for the City of Gardner with the increase in hauled waste to the wastewater treatment plant. SoMax has outlined recommendations and next steps for implementation of HTC.

- Reassess the usage rates of ferric chloride and polymer at the City of Gardner WWTP
- Assess local and regional market potential for hauled waste availability and applicable tip fees
- Explore and evaluate state and county grants and energy production subsidies through public utility
- Move into formal engineering and design phase for implementation of HTC

As part of a formal engineering and design phase, SoMax can assist in navigating market analysis, and grant and subsidy exploration, as well as beginning the discussion of implementing HTC with the state environmental regulators, MASSDEP. SoMax is uniquely positioned to assist in these areas through utilization of our network of service providers and the experience gained through implementation of this technology for the first time in the state of Pennsylvania.

2. History / Background

The hydrothermal carbonization process (HTC) was first described by Friedrich Bergius in 1913, but its industrial application was not developed due to the rising importance of fossil fuels (coal and oil). With the intervening World Wars, the process was lost to history. In 2006, the HTC process for biomass was rediscovered by Prof. M. Antonietti et. al, at the Max Planck Institute of Colloids and Interfaces (MPI) in Potsdam, Germany. Their rediscovery was published under the title "Magic Coal from the Steam Cooker" in January 2006. The original paper can be found here: http://www.mpikg.mpg.de/1567721/MagicCoal.pdf

"*What is so ingenious about this process is its simplicity*,"
Prof. Markus Antonietti.

Gardner Wastewater Treatment Plant

The City of Gardner has a population of ~22,000 and is in north central Massachusetts. Their wastewater treatment plant is contracted to be operated by Veolia. The WWTP creates a primary and waste activated sludge (WAS) biosolids, that is centrifuged to ~26-28% total solids. The biosolids are mixed with sand and landfilled in a municipal owned sanitary sludge only landfill. The transportation of biosolids to the landfill is completed with municipal owned trucks, and the sand is supplied via municipal quarry. Gardner handles the disposal of biosolids internally, which is rare for a municipality, and keeps outside cost pressure suppressed.

Gardner is facing limited landfill capacity at their sanitary sludge landfill, with the expectation that capacity will be reached in the next 4-6 years. Gardner constituents have brought pressure on city officials to not expand the landfill, increasing capacity. This capacity issue has prompted Veolia, on behalf of Gardner, to reach out to SoMax and assess the viability of HTC as the solution to handle their biosolids.

SoMax is told there is some appetite to expand HTC operations to include biosolids from surrounding communities, as well as other organic wastes. The stated goal of Gardner is to create energy.

SoMax

In 2014, SoMax formed a research and development partnership with Villanova University School of Sustainable Engineering to develop a process for recycling organic waste into renewable fuels, chemicals, and fertilizers. In 2016, initial research identified HTC as the ideal process to meet our goals. From the fall of 2016 though spring of 2019, the focus of this research at Villanova validated HTC as a viable biomass conversion technology. This focus yielded six successful thesis defenses around various stages of the HTC process. These individuals have been granted the degree of Master of Science in Sustainable Engineering by Villanova University.

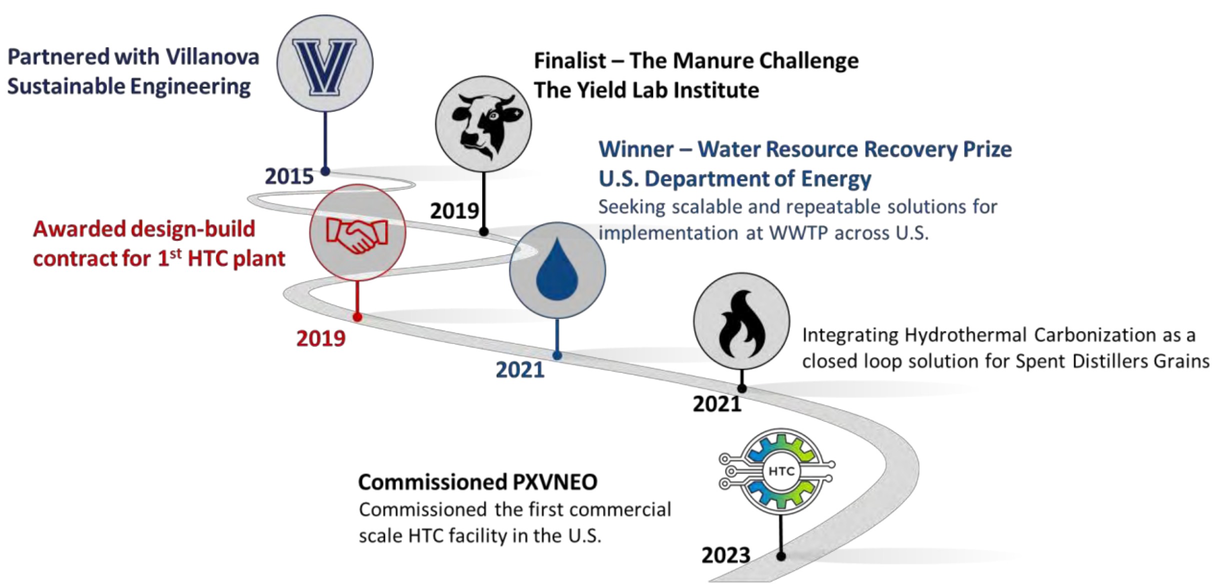
In 2018, based on prior research at Villanova University, SoMax was founded to commercialize HTC technology. SoMax created a network of partnerships with global manufacturers, engineers, and inventors to design a commercial scale HTC system. In April 2019 through a unanimous vote, Phoenixville, PA Borough Council approved the design-build approach to install an HTC Plant onsite at the existing Wastewater Treatment Plant (WWTP). In November 2019 SoMax presented the completed design of the HTC plant to Borough Council with a recommendation to move to the construction and permitting phase.

In 2020, SoMax entered the US Department of Energy's (D.O.E.) Water Resource Challenge. After 18 months of engineering, financial, and technical review, SoMax's HTC technology was selected as a Grand Prize Winner of the Challenge, receiving the endorsement of the US D.O.E and National Renewable Energy Lab (NREL) for technology that should be implemented at WWTP across the country to double the amount of resources recovered from wastewater.

In the spring of 2021, SoMax entered the Low Carbon Heat Challenge presented by Diageo Sustainability Solutions. In the fall of 2021, Diageo selected SoMax's HTC technology as winner of the Low Carbon Heat Challenge and awarded SoMax with a pilot project to examine the application of HTC to distillers' spent grains.

SoMax's expertise in organic waste processing expands beyond wastewater sludge and includes characterization and product development from a wide range of organic wastes, such as animal manures, the organic fraction of municipal solid waste, various food groups, brewing and distillery residuals, algae, and seaweed.

Figure 2 - SoMax History Illustrated



3. Project Overview

This project was executed on behalf of the Gardner WWTP to assess HTC as a potential waste valorization method for their biosolids. The aim of the project is to explore the feasibility of instituting HTC to valorize Gardner's biosolids and create an alternative solution to landfilling the waste stream.

Additionally, the feasibility study will assess the maximizing reactor capacity with regional organic waste, increasing the output of hydrochar, and thus economic benefits to the municipality. The resulting products of HTC present the opportunity to bolster Gardner's bottom line, meet any internal sustainability goals, and most importantly, create value from a waste stream that is currently being landfilled.

Gardner biosolids were shipped to SoMax's laboratory and used as feedstock for HTC reactions. The liquid and solid products of the HTC reaction, called process water and hydrochar, were sent to third party labs for analysis. Generating primary data from individual and unique feedstocks is critical to build to accurate models and assess feasibility.

Project Outputs

SoMax conducted HTC reactions on Gardner WWTP biosolids in their laboratory in Spring City, PA. Third party laboratories analyzed the physical and chemical characteristics of the feedstocks, hydrochar and process water. SoMax utilized the primary data to assess the optimal temperature and retention time to generate a usable hydrochar resource. This data allows SoMax to produce feedstock-specific mass and energy balances and assess the HTC solution at the Gardner WWTP.

This report shares the methodologies used by SoMax and third-party labs when available and the results generated from HTC of sewage sludge and third-party analysis. This data was used to identify the optimal reaction parameter range. The optimized results and detailed analysis of HTC products were used to produce an HTC mass and energy balance model. The model integrated economics, providing capital and operating costs, and varying end use scenarios. While creating energy was the stated goal, it's beneficial to know what other outlets may be available and their economic cases.

Additional scenarios for introducing regional organic waste were also analyzed. Regional organic waste scenarios include filling remaining reactor capacity with neighboring municipalities biosolids, or local food wastes. Accepting waste allows Gardner to manage the throughput of HTC while charging a tip fee, improving project economics, and potentially increasing the energy density of the hydrochar that is generated.

The process water from HTC, which equates to ~80-85% of the volume of the HTC influent, was also a focus of this project. Fertilizer assessment and wastewater characterization analysis were conducted by outside labs and compared with data previously acquired by SoMax. These results are critical parts to understanding the return load back to the treatment plant and establishing ancillary resource recovery potentials.

4. Hydrothermal Carbonization (HTC)

The centerpiece of SoMax's Resource Recovery platform is hydrothermal carbonization, or HTC for short. HTC is a wet thermochemical process that converts organic matter into a carbon dense, solid material known as Hydrochar using moderate temperatures and pressures. Distillery waste is a great feedstock for HTC due to its high moisture content. Unlike traditional thermal processes, HTC converts organic matter with high moisture content without the need for drying prior to conversion. This section discusses HTC from two perspectives: the scaled commercial process and scientific chemical conversion process.

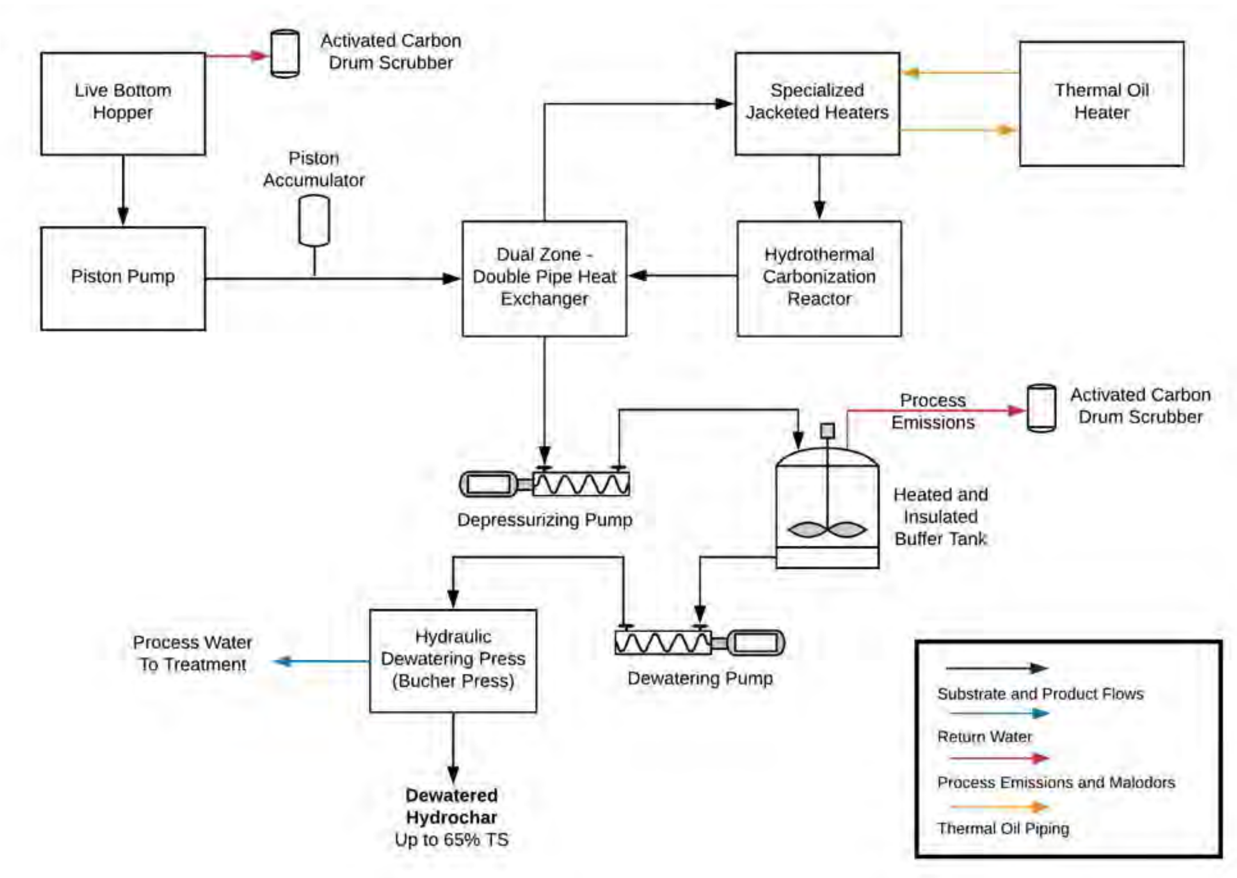
What is Hydrothermal Carbonization? – The Process

The SoMax HTC system can be thought of as an industrial sized, continuous pressure cooker. The figure below illustrates the core HTC process from inlet pump to dewatering press. The standard SoMax HTC system is designed to process ~15,000 wet tons/year. The system design is modular, allowing simple scaling and redundancy.

HTC is a carbon-based conversion process, with the goal of maximizing solids conversion and Hydrochar production. The SoMax HTC system is designed to process feedstocks with a total solids concentration of ~15-20% solids.

Heat recovery, ancillary thermal oil, and electric heating systems regulate process temperature, while the pressure is balanced by the inlet piston and outlet progressive cavity 'depressurizing' pump. Pressure is also buffered by a piston accumulator on the main substrate line. Additionally, the heat exchanger and thermal oil systems utilize bladder accumulators to handle thermal expansion. Water is the medium of heat transfer in the dual-zone double pipe heat exchanger, that transfers heat from the product zone to the substrate zone. The substrate enters the heat exchanger at room temperature and leaves at ~150 – 160°C. The thermal oil jacketed heaters utilize an anti-fouling mechanism that keeps the interior walls of the substrate piping clear of residuals generated from hot boundary conditions. The thermal oil enters the heaters at 250 – 260°C, to bring the substrate to reaction temperature ranging from 180 – 220°C, depending on the feedstock. The reactor acts as a retention vessel to facilitate the desired reaction time and does so by utilizing a series of serpentine pipes, allowing for a continuous process.

Figure 3 - HTC Core Process Flow Diagram



Once the product Hydrochar slurry is cooled to below boiling via the heat exchanger, it exits through the depressurizing pump and into a buffer tank, where it is stored between dewatering cycles. The insulated buffer tank is constantly stirred to mitigate settling of the Hydrochar and it is wrapped in heaters to control temperature leading into the dewatering press. An elevated slurry temperature increases dewatering efficiency.

The dewatering of the Hydrochar slurry utilizes a hydraulic dewatering press that achieves exceptionally low moisture content, as low as 35%. This hydraulic dewatering press is called a Bucher Press and is SoMax's preferred dewatering unit. The Bucher Press has low maintenance and industry-leading dewatering efficiency. If the Hydrochar is used for a solid fuel, it will need to be dried to at least 10% moisture content and this can be accomplished with several 'off the shelf' driers, determined by user preference and operational experience.

The front-end material handling is designed to feedstock characteristics, such as percent total solids, dissolved solids, dewaterability, particle size, and much more. The material handling of feedstock typically consists of dewatering devices, conveyance systems, and storage. Dewatering systems vary based on the feedstock. For instance, sewage sludge requires polymer to increase flocs and particle size, whereas spent grains do not require polymer since they have a structure and relatively large particle size. While food waste will require depackaging, screening, and blending. The storage units must have the ability to feed the HTC system at a consistent rate, mitigate bridging and rat holing, and provide enough storage to handle variable feedstock production. For sewage sludge, SoMax uses a live bottom hopper, which is equipped with a rabble arm in the middle of the unit, and a level screw at the top, but is open to other means of storage.

If gasification is included for energy production from the hydrochar, then a dryer and briquette/pelletizer must be included. Additionally, for electricity generation a genset is required to convert syngas to the energy. The gasification system SoMax recommends has gas scrubbing to remove NOx, SOx, and particulate matter at high efficiencies, so that the when the syngas is combusted the emissions have a much lower pollutant profile.

What is Hydrothermal Carbonization? – The Science

Hydrothermal carbonization (HTC) is the technology centerpiece of SoMax's resource recovery platform. In 2016, the World Energy Council recognized HTC as the technology that emits the lowest amount of greenhouse gases and has the highest carbon efficiency of any biomass-to-fuel conversion process (World Resources, 2016). Anaerobic digestion has a carbon efficiency of ~50%, while HTC has a carbon efficiency of up to 90%. HTC takes place in an aqueous environment at a maximum of 30% solids. All biomasses can be processed by HTC, but in some cases, water must be added to efficiently facilitate the carbonization mechanisms. In HTC, water acts as a reagent that facilitates the reduction reactions that drive the carbonization of the feedstock. The primary end products of HTC are a coal-like solid fuel called Hydrochar and a process liquid that contains organic acids, inorganics, and essential nutrients, among other compounds.

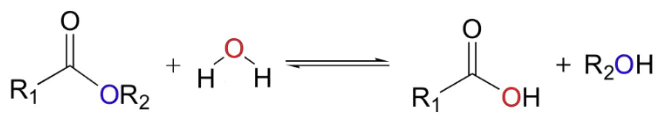
Hydrothermal carbonization takes place in an aqueous environment at temperatures between 320°F-480°F (160°C-250°C) with subcritical pressures that keep the liquid from evaporating and the slurry from drying out (Danso-Boateng, 2015). The subcritical pressures ensure energy is not lost to the evaporation of water, making HTC an energy efficient biomass conversion process. Required reaction temperatures and retention times vary based on feedstock. Retention times can be as short as thirty minutes and up to twelve hours depending on the feedstock and the specifications of the final product.

Due to the moderately high temperatures (> 300 °F) of HTC, the reactants are sanitized during the process (Danso-Boateng, 2015). This creates a pathway for sanitization of pathogenic wastes such as wastewater treatment solids, while upgrading their fuel characteristics. HTC, as shown in the next subsection, reduces the oxygen content of biomass creating a more energy dense product called Hydrochar. HTC also removes nitrogen and sulfur from the biomass during the carbonization process (Chao, 2013). The extent to which oxygen, nitrogen, sulfur, and other various inorganic elements are removed is based on feedstock, reaction temperature, retention time, and potential pre and post treatments.

Reaction Mechanisms

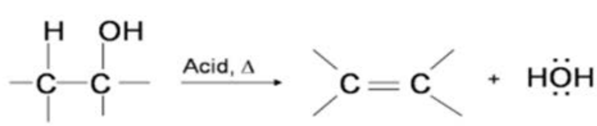
To understand the reaction, consider its name: “hydrothermal carbonization.” It can be assumed that it is a heated reaction in an aqueous environment (hydrothermal) where the input is carbonized or the carbon concentration increases (carbonization). The carbonization process takes place through several different reactions simultaneously. The simultaneous nature of these reactions makes the kinetics of HTC more difficult to model and the chemical complexity of biomass adds to that difficulty. There is consensus to the primary reactions that occur during the hydrothermal carbonization process: hydrolysis, dehydration, decarboxylation, aromatization, and condensation polymerization (Funke, 2010; Reza, 2014; Jain, 2016). The overarching outcome of these reactions is to reduce oxygen concentration and increase carbon concentration. Below are visual examples of each of these simultaneous reactions.

Figure 4 - Generic Hydrolysis Reaction of an Ester



Shown above, the water molecule attacks the ester bond creating a carboxylic acid and an alcohol. This hydrolysis reaction mainly targets the ester carbonyl ether bond. Cleaving larger molecules creates more reaction sites for the other reactions that take place. In the dehydration reaction illustrated below, a water molecule is created from an alcohol creating an alkene. This dehydration reaction is driven by the presence of acid as the H+ ion. The upper temperature range required for the dehydration of primary alcohols is between 338°F – 356°F (170°C – 180°C) (Hoang, 2013). Secondary and tertiary alcohols give rise to more stable carbocations in acid-based dehydration and are easier to dehydrate at lower temperatures. In general, dehydration is the elimination of hydroxyl groups creating water molecules.

Figure 5 - Generic Dehydration Reaction of an Alcohol

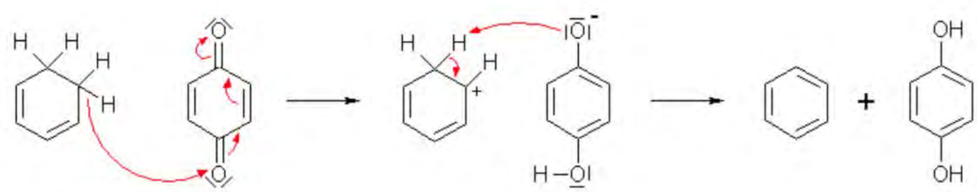


The two previous reactions have synergy in that hydrolysis cleaving leads to alcohols ready to be dehydrated. Decarboxylation, as shown in figure below, is also a complimentary reaction to the hydrolysis of esters as its primary reaction center is also the carbonyl group’s carbon-oxygen double bond. At temperatures above 302°F (150°C), CO_2 and CO are products of the decarboxylation of carboxyl and ketone carbonyl groups respectively (Murray, 1972). Carbon dioxide is the primary gaseous product of the hydrothermal carbonization reaction.

Figure 6 - Generic Decarboxylation Reaction of a Carboxylic Acid

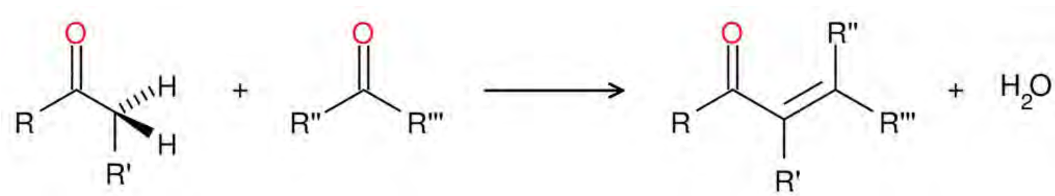
Aromatization, shown in the figure below, illustrates the continual push for stability experienced by hydrocarbons during hydrothermal conditions. An example of aromatization in nature is lignin, which is the most stable of the three main biomass components: hemicellulose, cellulose and lignin (Poletto, 2010). High purity coals in the bituminous and anthracite range also show a high degree of aromatization. The aromaticity of Hydrochar increases with reaction condition severity, which parallels the natural coalification to bituminous and anthracite coal (Funke, 2010).

Figure 7 - Generic Aromatization Reaction



The final reaction that is necessary for Hydrochar formation is condensation polymerization. Unlike the cleaving of large molecules during hydrolysis, condensation reactions combine molecules and remove water. In the reaction mechanism shown below, the most important factor of the condensation reaction is the ability to create carbon-carbon bonds (Hunt, 2013). This is a key component to the construction of carbon dense Hydrochars.

Figure 8 - Generic Aldol Condensation Reaction

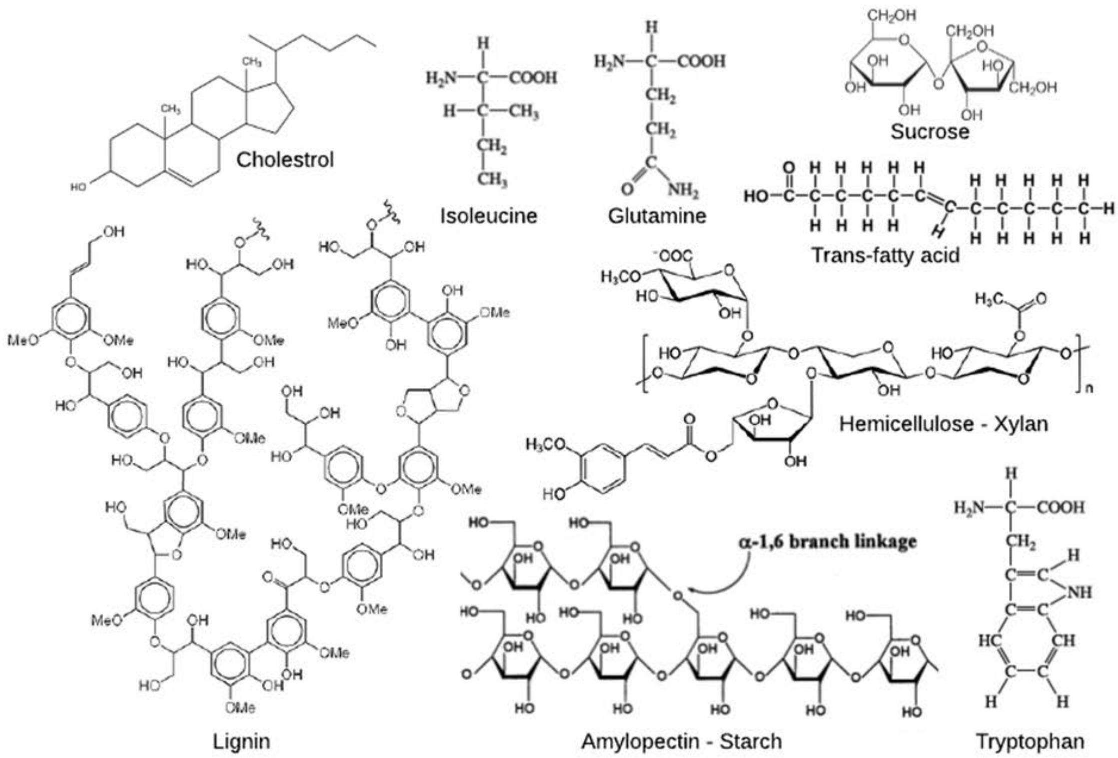


Nitrogen Based Reactions

Nitrogen based compounds are also impacted by hydrothermal processes. Amide formation, deamination, and Maillard reactions all take place simultaneously during the reaction process (Dominik, 2021). These reactions result in ammonia and nitrogen-based compounds migrating to the liquid phase during the HTC process, as well as heterocyclic nitrogen containing compounds that may become part of the solid Hydrochar matrix (Alhnidi, 2020). Maillard reactions are in the same family of reactions that take place when grilling meat. The caramelly, burnt, nutty, meaty, roasted flavors that are generated are all under the umbrella of products made from Maillard reactions (Compound Interest, 2015).

These mechanisms are simple to explain on a reaction-by-reaction basis, however, when the large chemical makeup of food waste, wastewater solids, and biomass is combined, the exact reactions and their kinetics are much harder to pinpoint. Most compounds in wet organic biomasses are carbon, hydrogen, oxygen, and nitrogen based, but their individual composition and structure dictates the potential and degree of carbonization at various process conditions. For instance, hemicellulose breaks down below 392°F (200°C); cellulose breaks down between 446°F – 442°F (230°C – 250°C); and lignin above 500°F (260°C) (Reza, 2013; Lu, 2014). The figure below shows a composite image of typical molecular compounds found in organic biomass: cellulose, hemicellulose, lignin, starch, proteins, lipids, sugars. This image only shows a fraction of the compounds in organic biomasses.

Figure 9 - Compounds in Biomass



Trends of Hydrothermal Carbonization

In understanding the fundamentals of HTC, it's necessary to know the overarching trends of the reaction. The HTC process in general, deoxygenates, increases carbon content, increases hydrophobicity (dewaterability), increases energy density, while reducing solid mass yield. All of which create a solid product with better fuel characteristics than the initial feedstock. The degree to which these trends take place is dependent upon process parameters and initial feedstock characteristics. This section will address the trends associated with reaction temperature, retention time, and inorganic transport.

Reaction Temperature

HTC takes place between temperatures of 320°F – 480°F (160°C – 250°C) with retention times as low as thirty minutes. Carbonization continues to take place above 480F, but a bio-oil byproduct becomes more pronounced at higher temperatures. As temperature increases solid conversion yields decrease due to increase removal of oxygenated functional groups and inorganics (Idowu, 2017). Solid yields range from 40% - 80% and are highly dependent on process temperature and feedstock (Danso-Boating, 2015; Idowu, 2017; Reza, 2013). The chemical composition of the feedstock determines its ability to be carbonized at a specific temperature range. For instance, a high lignin content woody biomass will have a higher solid yield than a high starch-based food waste at lower temperatures because of the high temperature at which lignin decomposes (Kang, 2012; Lu, 2014). As for biosolids and sewage sludge, the solid yields are on the higher end of the spectrum, at 71-80% and 60-70% respectively, due to their higher inorganic content compared to food waste and biomass (Bhatt, 2018). The overarching trend of reaction temperature and solid yield is that as reaction temperature increases solid yield decreases.

As reaction temperature increases, the carbon content of the Hydrochar also increases relative to that of the feedstock, which in turn increases the energy density, and the higher heating value (Smith, 2016; Reza, 2013). The energy density of woody biomass can double with process temperatures of 482°F (250°C). While some feedstocks, such as the anaerobic digestate of sewage sludge, decrease in energy density at higher temperatures 482°F (250°C), this trend does not hold true with high ash content feedstocks, like digested biosolids (Smith, 2016). They are the lowest grade of feedstock for solid fuel production via HTC and the carbonization process fails to increase HHV at certain temperatures due to the increased ash content of the Hydrochar.

One important facet of HTC centers around the dewaterability of Hydrochar. The Hydrochar product slurry is much easier to dewater than raw sludge, digestate, or wet biomass. The final dewatered Hydrochar will have a much lower moisture content than the maximum dewatered feedstock. This feature of Hydrochar plays a large role in the total energy consumed to dry the final product. Depending on the feedstock, HTC plus drying of the Hydrochar uses less than energy than thermal drying alone. The greater the carbonization, the better the dewaterability. Therefore, more severe reaction conditions will yield a Hydrochar slurry that is easier to dewater, thus reducing dewatering operational costs, and energy needed to dry the dewatered Hydrochar.

Retention Time

Retention time is defined as the time held at the desired reaction temperature. Long retention times are less impactful than higher reaction temperatures, but each feedstock does have a minimum retention time for effective carbonization. There is a maximum reaction time that corresponds to a consistent minimum solid yield, but that reaction time is highly feedstock dependent. One study shows biosolids are finished carbonizing after only thirty minutes, while another shows a decline in yield for up to two hours (Bhatt, 2018; Danso-Boateng, 2015). Wood waste can take up to 72 hours to reach a consistent solid yield.

At longer retention times a higher carbon content Hydrochar may be obtained, but long retention times are constrained by process design. Capital costs for large, or many reactors, and operational costs to keep the reactor at temperature are economically prohibitive when considering very long retention times.

Inorganic Transport

In this case, inorganic transport includes everything but carbon. As mentioned with temperature and retention time, the degree of inorganic transport will vary based on feedstock and reaction parameters, but there are overarching trends.

Nitrogen is an element of concern when considering using Hydrochar as a solid fuel due to the potential for NOx emissions when combusted, but also a nutrient of focus for recovery. When any biomass goes through hydrothermal carbonization the nitrogen content in the solid phase decreases, making Hydrochar from biomass a more attractive fuel than the original feedstock. This is due to the breakdown of the proteins in the biomass. Nitrogen, a primary component in proteins, is released through the hydrolysis of proteins into lower molecular weight polypeptides and amino acids into the liquid phase, but repolymerization and condensation reactions of these amino acids takes place with polysaccharides creating N-containing heterocycles in the Hydrochar phase (Wu, 2018). Protein breakdown is shown to happen as low as 302°F (150°C) and as temperature increases the ammonium-nitrogen (NH_4-N) to organic-nitrogen (Org-N) ratios in the liquid phase increases (Inoue, 1997). The higher concentration of ammonium-nitrogen in the process liquid presents an opportunity for resource recovery in the form of a nitrogen-based fertilizer, ammonium sulfate.

Other inorganics in Hydrochars range from essential nutrients, to minerals, to metals and toxic heavy metals, and the concentration of which are dependent on the feedstock. Municipal solid wastes and sewage sludges will have higher metal concentrations than biomass or clean streams of food waste. Each element transports at different ratios to the solid Hydrochar product and process liquid streams, which again, is dictated by the feedstock composition. Some general trends that have been observed in multiple research efforts are that metals, heavy metals and phosphorus tend to stay in the Hydrochar phase while water soluble inorganics, like sodium and potassium, are primarily transported into the liquid phase (Wu, 2018; Smith, 2016; Liu, 2018). At low pH's (< 3) phosphorus, and other metals, can be leached from the solid phase to the liquid phase, allowing for phosphorus recovery and better fuel characteristics of the Hydrochar. This is the first step for struvite formation and phosphorus fertilizer recovery.

Lui (2018) addressed heavy metal transport during HTC and concluded that over 90% of manganese and lead, over 80% of mercury, cadmium, zinc, copper, and nickel, and over 70% of chromium stay in the Hydrochar phase, while over 50% of potassium and sodium move to the liquid phase (Liu, 2018). This research also focused on the health risks associated with the heavy metals after the HTC process. They concluded that HTC reduced the exchangeable/acid-soluble and reducible fraction of heavy metals, thus reducing the potential risk of mobile heavy metals. While heavy metal concentration in spent grains and biomass-based feedstocks is very low, this highlights an additional benefit of utilizing Hydrochar as a soil amendment.

5. Methodology

Hydrothermal Carbonization (HTC) reactions of Gardner's biosolids were conducted in SoMax's lab in Spring City, PA. Material handling and qualitative assessments of the feedstocks were also conducted in the SoMax's lab while all characterization testing was completed in outside, third-party labs.

SoMax approached the testing of feedstocks and HTC products in four phases:

- Optimization via initial analysis of feedstock, Hydrochar and HTC reaction parameters
- Detailed analysis of HTC products
- Utilization of carbon product
- Characterization and resource recovery via process water

The data obtained from the four phases of analysis give SoMax a comprehensive view of product utilization, treatment, and valorization potential. The methodology was created in accordance with the literature and researched already established within the HTC field, specifically those concerning sewage sludge as HTC feedstock. The section will cover the methodology used during the four phases.

Initial Analysis

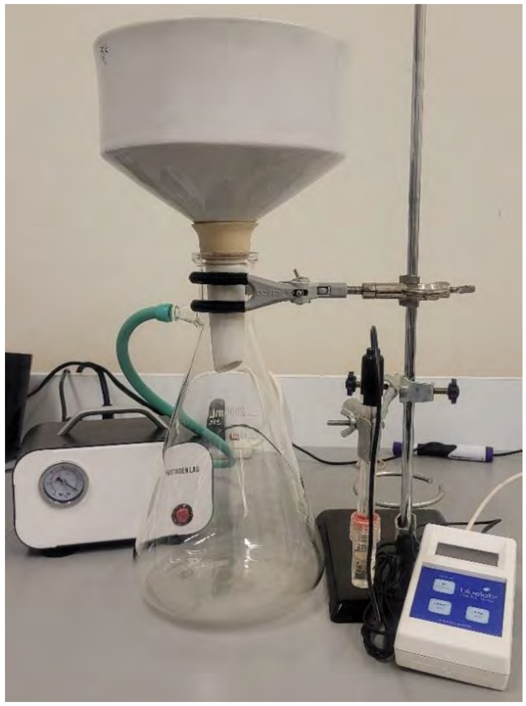
Initial analysis included material handling, optimization testing, and high-level characteristics of the Hydrochar such as proximate analysis, elemental analysis, and energy density. The optimization of the sludge began with the intention of created a solid fuel and later focused on other valorization pathways.

The sludge arrived by mail in three 3-gallon buckets over a period of two weeks. The sludge did not require any further straining as it was fairly dewatered upon arrival. The sludge was transferred to dry over night (up to 24 hours) on aluminum baking trays in a 105°C in an oven (Fisher Scientific Isotemp). Weights were taken before and after drying, with the weight loss used to determine the percent total solids of each sample.

The HTC reactions were conducted at ~15% TS, with ~200g of dried sludge and ~1100g of water. The dried sludge and water were combined and allowed to rehydrate before loading into the HTC reactor. The HTC reactions were conducted in a 2L Parr 4530 reactor with a 4848 controller, shown below. The reaction parameters such as heating and cooling rate, retention time, and temperature were set using SpecView software.

Figure 10 - 4530 Parr Reactor with 4848 Controller

Figure 11 - Buchner funnel vacuum filtration setup and pH ComboBlue meter



The cooled HTC product slurry was filtered using a 20cm Buchner vacuum filter setup, shown above, with 20–micron filter paper. The pH of the filtered process waste was measured using the ComboBlue meter.

The filtered process water was collected, sampled for percent total solids, and stored in the refrigerator for later analysis. The Hydrochar in the filter was rinsed with wash water and transferred to a baking sheet for drying. The Hydrochar was dried at 105°C in the oven until mass loss ceased. Weights were taken before and after drying, documenting the filterability/dewaterability of the Hydrochar at various temperatures.

The Hydrochar yield or solid yield calculation for Hydrochar yield is determined using the total solids into the reactor, and the Hydrochar accounted for after reaction. HTC runs were conducted at ~15% total solids. The calculation for solid yield is shown below.

$$\frac{Total\ Hydrochar\ (g)}{Dry\ Solids\ Content\ In\ (g)} = \%\ Solid\ Yield$$

Out of house, or third-party analysis results were used for the initial analysis phase to determine the optimized parameters for valorization of sludge. The initial third-party analysis package includes proximate analysis, ultimate analysis (basic elemental analysis), and bomb calorimetry. Sulfur testing was included for the initial analysis to better understand the possible use of hydrochar as a solid fuel. The table below outlines the tests completed in the Initial Analysis phase. Two outside labs were used to verify the analysis results, reduce the possibility of outliers and average results.

Table 1 - Initial Analysis Outline

Lab Test	Company	Result
HTC of Sludge	SoMax Labs	Hydrochar and Process Water
Thermogravimetric Analysis (Proximate Analysis)	Galbraith Laboratories Intertek	Moisture content, volatile matter, fixed carbon, ash percentages
Bomb Calorimetry	Galbraith Laboratories Intertek	Energy density (Higher heating value)
Ultimate Analysis (elemental analysis)	Galbraith Laboratories Intertek	Carbon, Nitrogen, Oxygen, Hydrogen
Specific Elemental Analysis	Galbraith Laboratories Intertek	Sulfur

Optimization

A range of temperatures, 180°C – 220°C, at a retention time of three hours were selected for the first iteration of testing. Based on the first round of results, the data was assessed for optimization, analyzing energy recovery, carbon recovery, dewaterability, and overall carbonization. The reaction temperature that displayed optimal results was then tested with varying retention times, at one, two and three hours. The resulting hydrochar data was again compared for optimal carbonization.

Detailed Analysis

The detailed analysis phase included the HTC process water analysis, wastewater characterization, and fuel characteristic analysis of the hydrochar. The process water analysis was conducted using the liquid product from the optimized HTC parameters, allowing for targeted results from what may be generated at scale.

Following the procedures described in the previous section, process water and hydrochar were collected from HTC reactions at the optimized parameters and sent to third-party laboratories for analysis. The fuel characteristic analysis required a significant volume of hydrochar and was supplemented with hydrochar generated near optimal parameters from the initial analysis.

The framing of the process water analysis was built on the core data required by the Pennsylvania Department of Environmental Protection (PA DEP). The liquid analysis yields information required for understanding the valorization potential, available resources to be recovered and required treatment for various end uses. The table below highlights the liquid analysis and results completed in the detailed analysis phase.

Table 2 - Process Water Analysis Outline

Lab Test	Company	Result
Liquid Fertilizer Assessment	J.R. Peters	EC, pH, Alkalinity, Total N, NO3-N, NH4-N, Urea-N, P, P2O5, K K2O, Ca, Mg, S, SO4, Fe, Mn, B, Cu, Zn, Mo, Na, Cl, Al
Wastewater Analysis	ALS	NH3-N, BOD5, COD, CaCO3 (hardness), Nitrogen as Nitrate or Nitrite, Oil and Grease as HEM, pH, Phenolics, TDS, TKN, TOC, Total P
Metals	ALS	Al, Sb, As, Ba, Be, B, Cd, Cr, Co, Cu, Fe, Pb, Mn, Hg, Mo, Ni, Se, Ag, Tl, Zn
Wet Chemistry	ALS	Br, Cl, SO4
Wastewater Analysis	ALS	COD, BOD, TOC, TDS

The detailed analysis around the hydrochar focused on the fuel characteristics and basic information for boiler and gasification suppliers. The table below outlines the testing methods and results. All tests were completed by Intertek.

Table 3 - Hydrochar Detailed Analysis Outline

Analytical Method	Lab Test	Result
Oxygen Vessel Combustion/ Ion Selective Electrode Method, ICP-MS, XRF (ASTM D4208, D3671)	Halogens	Cl, Fl, Br
Bulk Density (ASTM D 291)	Bulk Density	Bulk Density
ASTM D1857	Fusion Temperature of Ash in Reducing and Oxidizing Environment	Initial Deformation Temp. (IT), Softening Temp. (ST), Hemispherical Temp. (HT), Fluid Temp. (FT)
ASTM D6349	Ash Content	SiO2, Al2O3, TiO2, Fe2O3, CaO, MgO, K2O, Na2O, SO3, P2O5, SrO, BaO, MnO,
ASTM D6357, D6722	Heavy Metals	As, Ba, Cd, Cr, Pb, Se, Hg

6. Results

This section highlights the results of the in-house and third-party testing performed on the feedstocks and HTC products. In-house results include percent solids during material handling, pH, and facilitating the HTC reactions. Third-party analysis results are outlined in the methodology. In this section the results and data will be shared and a more in-depth discussion of the results and impact on modeling and the scaled HTC process will be discussed in latter sections.

The results are broken into three main sections: feedstock, hydrochar, and process water.

Feedstock Analysis

The percent solids of the as received sludge was taken upon receival for all three buckets, averaging at 28.83% solids, before being dried for safe material storage. No additional steps of material handling and preparation was needed beyond the drying. Once dried, the feedstock was ground and stored until needed for HTC reactions.

The tables below, show the results of the material handling/dewatering assessment testing.

Table 4 – Gardner Sludge Feedstock Percent Solids

Sample	Pan Wt. (g)	Wet (g)	Dry (g)	Sample Wt. (g)	% Solids	Average
1	42.72	1098.32	330.82	288.10	27.29%	28.83%
2	42.78	1129.36	343.39	300.61	27.67%	
3	42.77	1058.63	323.00	280.23	27.59%	
4	42.82	1063.75	321.56	278.74	27.30%	
5	42.73	1144.45	367.32	324.59	29.46%	
6	42.70	1215.02	390.46	347.76	29.66%	
7	42.18	1097.94	379.00	336.82	31.90%	
8	45.88	1189.45	386.37	340.49	29.77%	

The pH of the delivered sludge was measured at 4.8, which is the most acidic sludge/biosolids SoMax has tested.

Hydrochar Analysis

The hydrochar analysis is broken into two sections, initial and detailed analysis. Initial analysis includes in-house testing around material handling and optimization for energy production. Detailed analysis includes comprehensive fuel characteristic testing.

Initial Analysis

Initial analysis includes conducting optimization of hydrothermal carbonization reaction parameters with a focus on utilizing the Hydrochar as a renewable solid fuel. Retention time and reaction temperature of the HTC process were varied and Hydrochar yield, proximate analysis, ultimate analysis, and energy density were analyzed.

To determine the optimized HTC temperature and retention time two core metrics were used:

1) Energy Recovery – total energy in the Hydrochar as a percentage of original embodied energy of the feedstock
2) Carbon Efficiency – total carbon in the Hydrochar as a percentage of carbon in the feedstock.

Additionally, the reaction temperature is considered, as a higher reaction temperature for similar results of energy recovery and carbon efficiency will require additional process heat to achieve. The table below shows five reaction temperatures ranging from 180°C to 220°C with a three-hour retention time and the optimized temperature at one, two, and three hours and their corresponding energy density, carbon concentration, energy recovery, and carbon efficiency.

Surprisingly, HTC trends did not hold true for this feedstock and the product hydrochars. It was expected that there would be a reduction in solid yield and increase in energy densities and carbon concentrations, with higher reaction temperatures and longer retention times, but the change in energy density and carbon concentration changes were negligible.

The negligible change in results with varying temperatures has yet to occur during SoMax's large portfolio of tested feedstocks. Several duplicates were completed, and the results were confirmed. SoMax does not know the exact reasons for the off-trend results but assumes the overdosing of $FeCl_3$ and high level of polymer could have impacted the carbonization reactions. Previous primary sludge tests from other treatment plants have held to trend.

$FeCl_3$ catalyzed HTC reactions show an increase in the decarboxylation reaction mechanism, which can be seen in the elemental analysis results, with the steady reduction in oxygen concentrations, and a reduction in carbon to a lesser degree due to the reduction in solid yield (Lu et al., 2022). Recognizing that catalyzing the HTC reaction directly vs. using ferric in the wastewater treatment process are different, the presence of $Fe(OH)_3$ in the sludge will be similar, as well as the acidic nature of the H^+ ions, which is shown with the pH of the sludge.

The HTC trends that did hold are a reduction of solid yield, volatile matter, and oxygen concentration with increasing reaction severity. The volatile matter and oxygen data are shown in the following sections.

Proximate and Ultimate Analysis

The proximate and ultimate analysis are simple tests to determine the level of carbonization and quality of solid fuel. Proximate analysis identifies moisture content, volatile matter, fixed carbon, and ash percentages. Ultimate analysis identifies core elemental concentrations of carbon, nitrogen, oxygen, and hydrogen. Sulfur was also included in the ultimate analysis as solid fuel use was a potential outcome, and the sulfur concentration can indicate potential emissions.

The table below shows the proximate and ultimate analysis data, while the table titled *Gardner Sludge Initial Analysis – Energy Density and Proximate Analysis* shows select data to highlight the trends of HTC. The proximate and ultimate analysis results are shown on a dry basis.

Table 5 -Proximate and Ultimate Analysis – Gardner Sludge

Gardner Biosolids	**Prox. Analysis (%)**				**Elemental Analysis (%)**				
	Ash	**V.M.**	**F.C.**		**C**	**H**	**O**	**N**	**S**
Raw	22.4	72.4	5.27		42.3	6.13	24.5	4.16	0.54
3 Hours									
180C	31.4	65.1	3.57		41.4	5.57	19.3	1.92	0.47
190C	31.9	63.8	4.33		41.4	5.77	18.2	2.23	0.47
200C	33.1	61.7	5.20		41.3	5.54	17.5	2.03	0.50
210C	33.7	62.3	4.03		41.9	5.70	16.0	2.24	0.55
220C	34.7	60.6	4.67		42.3	5.70	14.6	2.17	0.58
Optimized Temperature varying retention time									
190C – 1	30.1	64.2	5.77		42.0	5.34	20.2	1.89	0.50
190C – 2	30.7	63.9	5.35		41.7	5.42	19.7	1.90	0.51
190C – 3	31.9	63.8	4.33		41.4	5.77	18.2	2.23	0.47

These data highlight some of the trends of increasing temperature and retention times. As reaction severity increases, volatile matter decreases, ash concentrations increase, and oxygen concentration decrease. These data break HTC trends by not exhibiting an increase in fixed carbon, or carbon concentration. The carbon concentration showed some fluctuations as it increased with reaction severity but was still a decrease from the feedstock. The nitrogen concentration is also reduced from feedstock to hydrochar. Nitrogen is typically an issue with biomass fuels generating NOx emissions during combustion. The same issue is present for sulfur and SOx emissions. NOx and SOx emissions are largely avoided by utilizing gasification with cold gas scrubbing, as opposed to the common biomass or coal boiler that use direct combustion.

Ash content, as shown in the proximate analysis results, is used for modeling the mass of ash generated at scale. The increase in ash content from feedstock to hydrochar is typical of HTC, since the hydrochar primarily maintains metal content in the solids matrix.

The proximate and ultimate analysis results are also a good data check for energy density data inconsistencies. The lack of significant changes from feedstock to hydrochar regarding carbon concentration and fixed carbon are consistent with the lack of energy density change.

Optimized Reaction Parameters

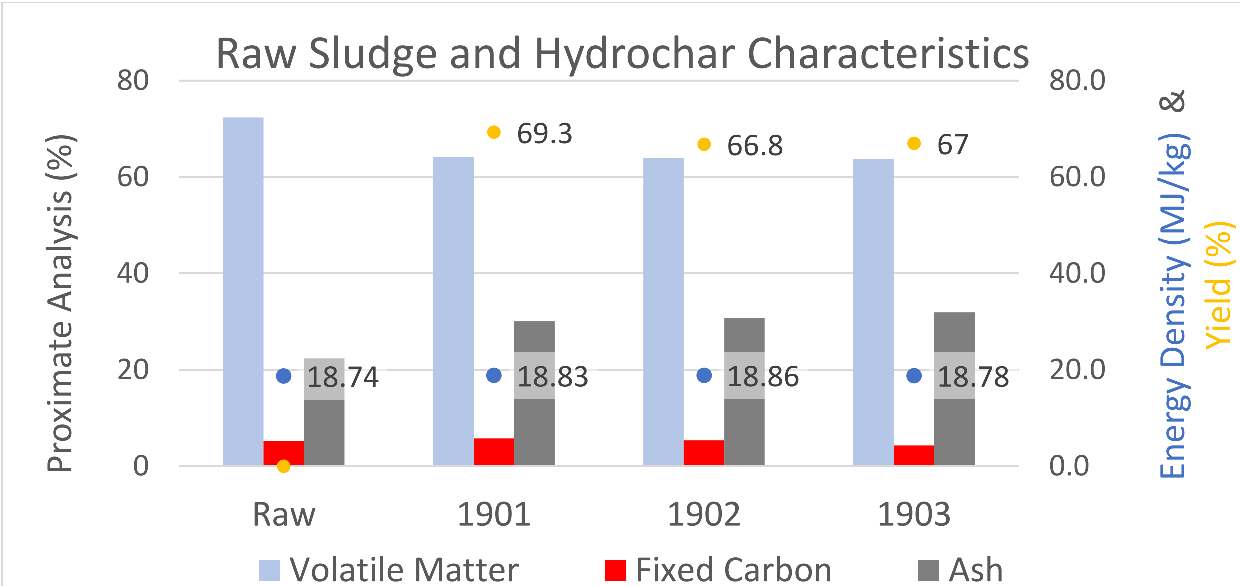
Based on the study, the optimized temperature for the Gardner sludge is 190°C. The higher yield at this temperature was the deciding factor for optimization. The higher yield led to the highest energy and carbon recovery.

Table 6 - Optimization Data

	Energy Density		**Yield**	**Optimization**		
Gardner, MA Sludge	**BTU/lb**	**MJ/kg**	**Solid Yield**	**Carbon**	**Energy Recovery**	**Carbon Recovery**
Raw Sludge	8057	18.7		42.32%		
3 Hours						
180C	8202	19.1	65.7%	41.4%	66.9%	65.0%
190C	8076	18.8	67.0%	41.4%	67.2%	66.3%
200C	8039	18.7	65.2%	41.3%	65.1%	64.4%
210C	8136	18.9	63.7%	41.8%	64.3%	64.0%
220C	8376	19.5	61.7%	42.3%	64.2%	62.6%
Optimized Temperature at 1/2/3 hours						
190C – 1hr	8087	18.8	69.3%	42.00%	69.7%	70.6%
190C – 2hr	8120	18.9	66.8%	41.72%	67.2%	67.6%
190C – 3hr	8076	18.8	67.0%	41.39%	67.2%	66.3%

The graph below shows core characteristics of the feedstock and three subsequent Hydrochars within the optimized range. There are no significant differences between the hydrochars and the feedstock beyond an approximate 10% decrease in volatile matter and an approximate 5% increase in ash. This further cements the Hydrochar inefficiency as a solid fuel source.

Figure 12 Gardner Sludge Initial Analysis – Energy Density and Proximate Analysis



There are tradeoffs to be made when assessing an optimized temperature, the main one being the energy input into the HTC system to obtain the higher reaction temperatures and higher degree of carbonized hydrochar. Additionally, at higher reaction temperatures the hydrochar becomes more easily dewatered, which is a function of the degree of biomass transformation. The dewatering efficiency directly impacts the amount of water that is needed to be removed via drying prior to energy generation. Utilizing HTC, dewatering with a Bucher Press, and drying, will consume less thermal energy than just dewatering and drying using traditional means.

The table below shows how the increasing temperatures impact the percent solids of the Hydrochar once filtered via vacuum filtration. The increase in temperature shows an increase in dewaterability. With the exception of the 2-hour run at 190°C, which appears to be an outlier, the retention time did not have much effect on dewaterability. While these values are not representative of the percent solids of SoMax's preferred dewatering press at scale, the Bucher Press, they do indicate the trend of dewaterability with increasing reaction temperature. SoMax expects 50% TS hydrochar exiting the Bucher press.

Table 7 - Dewatering Efficiency

Initial 3 hour Runs	
Reaction Temp. (°C)	**Hydrochar % Solids**
180	46.97%
190	41.96%
200	48.85%
210	52.27%
220	50.69%

Optimized Temperature		
Hours	**Reaction Temp. (°C)**	**Hydrochar % Solids**
1	190	41.74%
2	190	63.63%
3	190	41.96%

Determining the optimized retention time also has nuance to it and has different impacts at commercial scale. Due to the type of reactor SoMax uses, retention time has little impact on energy input, but it could impact capital cost. Usually, HTC produces a more significant change in with changing of reaction severity, specifically energy density and carbon concentration. However, the change in energy and carbon recovery results for all the temperatures were muted compared to previously tested feedstocks.

A shorter retention time will reduce the size of the reactor but will have minimal impact on energy use of the HTC system. A shorter retention time shows to be beneficial for energy recovery, which translates to more energy produced from the generated hydrochar. Moderate reaction temperatures are ideal for balancing the energy used to create the hydrochar while generating a high degree of carbonization.

If Gardner were to accept mixed organic waste to fill the reactor capacity it is recommend that the current reactor configuration of ~3-hour retention remain unchanged. Since energy production is goal, it is recommended that food waste is used as a supplemental feedstock to boost hydrochar fuel characteristics. The change in hydrochar characteristics and impacts on scaled processing from supplementing with food waste will be discussed later.

Sludge Based Hydrochar vs. Coal

The sewage-derived hydrochar proximate and ultimate analysis results present a material that is less carbon dense than coal. Anthracite and lignite coals have higher fixed carbon, higher overall carbon concentration, and much lower oxygen concentrations. The hydrochars also have a higher ash content, which is another reason the hydrochar has lower energy density than the coal. The C-H bonds present in hydrochar do offer a high energy density bond, that has degraded in coals.

These data are highlighted below in the data table.

Table 8 - Hydrochar and Coal Energy Density, Proximate Analysis and Elemental Analysis Comparison

	Energy Density	**Prox. Analysis (%)**			**Elemental Analysis (%)**				
	MJ/kg	**Ash**	**V.M.**	**F.C.**	**C**	**H**	**O**	**N**	**S**
Gardner Biosolids	18.7	22.4	72.4	5.27	43.3	6.13	24.5	4.16	0.54
1 Hour / 190C	18.8	30.1	64.2	5.77	42.0	5.34	20.2	1.89	0.50
2 Hours / 190C	18.8	30.7	63.9	5.35	41.7	5.42	19.7	1.90	0.51
3 Hours / 190C	18.8	31.9	63.8	4.33	41.4	5.77	18.2	2.23	0.47

Lignite 1	19.9	17.9	51.4	38.4	50.1	4.1	23.4	0.9	2.1
Lignite 2	25.3	11.3	51.6	48.4	65.9	5.6	23.9	2.0	2.6
Anthracite 1	-	22.5	7.68	69.9	67.0	2.61	5.0	0.80	1.23
Anthracite 2	-	7.91	32.6	59.5	65.6	4.95	13.8	1.13	0.71

The energy density of Anthracite normally ranges from 32-35 MJ/kg (Bowen, 2008). While lignite is lowest grade of coal with energy densities going as low as 16 MJ/kg. The coal samples shown in the table above show that the hydrochar made from Gardner sludge is of low solid fuel quality. SoMax has tested primary sludge from other plants resulting in hydrochar in the low 20 MJ/kg range.

One characteristic of coal that is always higher than hydrochar is the fixed carbon content, which holds true for the Gardner sludge derived hydrochar. Sulfur, a typical issue with coal, is less present in the hydrochar, indicating lower sulfur emissions if combusted. The nitrogen concentration in the hydrochar is slightly higher than coal, which is expected for a biomass derived fuel. The nitrogen levels in the Gardner sludge derived hydrochar is on the lower end of hydrochars generated by SoMax.

An extension of the comparison of Hydrochar to coal takes place in the following section when comparing detailed fuel characteristics.

Detailed Hydrochar Analysis

The detailed analysis of the Hydrochar consisted of advanced fuel characteristic analysis. The analysis was completed by Intertek. The table below displays the results of the detailed analysis of the Hydrochar provided by Intertek.

Table 9 - Detailed Fuel Characteristic Results of Hydrochar

Fusion Temp of Ash Reducing	**Temp. (°C // °F)**
Initial Deformation Temp (IT)	930 // 1706
Softening Temp (ST)	940 // 1724
Hemispherical Temp (HT)	1075 // 1967
Fluid Temp (FT)	1170 // 2138
Fusion Temp of Ash Oxidizing	**Temp. (°C // °F)**
Initial Deformation Temp (IT)	1255 // 2291
Softening Temp (ST)	1270 // 2318
Hemispherical Temp (HT)	1285 // 2345
Fluid Temp (FT)	1370 // 2498
Heavy Metals	**Dry Basis (ppm)**
Arsenic - As	8

Ash Composition	**Ignited Basis (% wt)**
Silicon Dioxide - SiO_2	11.25
Aluminum Oxide - Al_2O_3	5.98
Titanium Dioxide - TiO_2	0.83
Iron Oxide - Fe_2O_3	45.26
Calcium Oxide - CaO	6.52
Magnesium Oxide - MgO	0.87
Potassium oxide - K_2O	0.71
Sodium Oxide - Na_2O	0.3
Sulfur Trioxide - SO_3	0.37
Phosphorus Pentoxide - P_2O_5	24.31
Strontium Oxide - SrO	0.04

Barium - Ba	51
Cadmium - Cd	1
Chromium - Cr	81
Lead - Pb	44
Selenium - Se	<0.1
Mercury - Hg (ppb)	408
Halogens	**Dry Basis (ppm)**
Chlorine (%wt)	0.028
Fluorine	110
Bromine	<20
Bulk Density	**lbs/ft^3**
Uncompacted	21.76
Compacted	28.8

Barium Oxide - BaO	0.13
Manganese Oxide - MnO	0.14
% Undetermined	0.01
% Alkalies	0.33
Base to Acid Ratio	3.12
Silica Value (%)	17.61
T250 F	1140

The Intertek results give insight to how the Hydrochar will function in combustion or gasification settings, the presence of inorganics in the Hydrochar, and the bulk density of the Hydrochar. The detailed analysis was conducted with a mix of Hydrochars from the optimized range.

A comparison of the results to fossil coal in the tables below highlights the differences between the solid energy carriers, by comparing ash composition and heavy metals.

Table 10 - Hydrochar and Coal Ash Comparison

Results on Ignited Basis (% wt)	**Hydrochar**	**Anthracite 1**	**Anthracite 2**	**Anthracite 3**
Ash Composition	SoMax	Lu et al., 2017	Wei et al., 2018	Zhao et al., 2021
Silicon Dioxide - SiO_2	11.25	54.19	55.8	29.17
Aluminum Oxide - Al_2O_3	5.98	27.91	30.88	14.18
Titanium Dioxide - TiO_2	0.83	0.97	1.28	0.46
Iron Oxide - Fe_2O_3	45.26	4.23	4.99	9.5
Calcium Oxide - CaO	6.52	4.87	2.21	25.57
Magnesium Oxide - MgO	0.87	1.08	1.67	1.13
Potassium oxide - K_2O	0.71	1.84	1.27	0.39
Sodium Oxide - Na_2O	0.3	1.89	0.46	
Sulfur Trioxide - SO_3	0.37	2.09	1.79	16.07
Phosphorus Pentoxide - P_2O_5	24.31	0.25	0.3	

There are considerable differences in ash composition between the Hydrochar and anthracite coals assessed in literature. The core differences are the high silicon, aluminum, calcium, and sulfur levels in the coal, while hydrochar has elevated iron and phosphorus concentrations. This makes since with the high dosing of ferric chloride for phosphorus removal from the wastewater and immobilization in the solids.

The metal content of the Hydrochar compared to coals is on the other hand quite acceptable. The table below highlights the minor differences. The data show a range of metal content in various coal samples, which can vary considerably region to region. The hydrochar shows its metal content to be within reason compared to natural coals. Aside from cadmium, the rest of the metals are either below or in range of natural coals, but none of the metals present an issue for land application of other beneficial use.

Table 11 - Hydrochar Heavy Metal Content compared to Coal

	Hydrochar	**Argonne Premium Coal Samples**	**National Coal Quality Inventory**
Metal (ppm)	SoMax	(Palmer, 1997)	(Hatch et al., 2006)
Arsenic - As	8	100 - 350	<1 - 113
Barium - Ba	51	290 - 4700	24.6 - 1260
Cadmium - Cd	1	22 - 32	0.0052 - 0.441
Chromium - Cr	81	5 - 260	6 - 110
Lead - Pb	44	22 - 220	2.48 - 47.3
Selenium - Se	<0.1	9.0 -36	1.5 - 170
Mercury - Hg	0.408		0.025 - 0.77

The ash fusion temperature of the anthracite in Wei et. al is >1581°C, which is ~200°C degrees higher than the fusion temperatures of the hydrochar in an oxidizing environment (Wei, 2018). This is due to inhibitory compounds that reduce the fusion temperatures, such as phosphorus pentoxide. The presence of acidic oxides, like silicon oxide and aluminum oxide increase the fusion temperature, which are both highly present in the anthracite samples, and lower in the hydrochar.

The composition of the ash impacts the fusion temperature, which is a key consideration for the generation of slagging in the boiler or gasifiers. When co-firing with coal, or utilizing Hydrochar as a sole energy source, the fusion temperatures will dictate operational temperatures of the boilers or gasifiers.

The bulk density of the Hydrochar is ~3-4 times lower than that of coal. The hydrochar sample was finely ground before testing. Briquetting or pelletizing the Hydrochar will greatly increase the bulk density and improve handling for fuel use and must be incorporated into hydrochar preparation for gasification.

Process Water Analysis

Third party labs analyzed process water from the optimized range of HTC reaction parameters. The results were used to identify necessary water treatment and potential valorization pathways. The process water analysis is broken into two main parts:

1) Nutrient/Fertilizer Assessment
2) Wastewater Characterization

Fertilizer Assessment

The fertilizer assessment was conducted by JR Peters, a water-soluble fertilizer company, who has experience in the field since the 1940s. The table below shows the optimum range for a basic liquid fertilizer, along with the results of the process water. Results of the different parameters are in parts per million (ppm), unless noted.

Of the essential macro nutrients, NPK (nitrogen, phosphorous, potassium), the process water had optimal amounts of both phosphorous and potassium while the nitrogen content was well above the ideal range. there were also very high concentrations of sulfur, soluble sulfate, and iron, which could prove detrimental to soils and plants. The high iron is again indicative of the overdosing of the ferric chloride.

Table 12 - Process Water Fertilizer Assessment

Parameters	Results (ppm)	Optimum Range	
Soluble Salts (EC)	13.50 (ms/cm)	0.3	2
pH	5.55		
Alkalinity (CaCO3)	NA		
Total Nitrogen	1688.75	15	300
Nitrate	20.49	5	200
Ammonium	1661.15	0	50
Urea	7.11	0	50
Phosphorus	27.90	0	30
Soluble Phosphate	63.92	0	70
Potassium	195.28	0	200
Soluble Potash	235.25	0	240
Calcium	125.67	0	100
Magnesium	48.18	10	50
Sulfur	418.52	5	150
Soluble Sulfate	1255.60	0	300
Iron	568.70	0	3.5
Manganese	1.79	0	2.5
Boron	1.08	0	1
Copper	0.19	0	0.5
Zinc	0.22	0	0.4
Molybdenum	0.11	0	0.2
Sodium	112.90		
Chloride	142.03		
Aluminum	2.48		

The table below shows the Gardner Sludge process water fertilizer results compared to two other water treatment plants as well as mixed food. It is color coded to portray optimal results in green and high results in yellow. Apart from the previously mentioned high concentrations, the Gardner sludge process water is a more desirable fertilizer. The comparative results show that iron concentration is unordinary. Additionally, the low phosphorus could be indicative of the iron in the hydrochar maintaining the phosphorus in the solid matrix.

Table 13 - Process Water Fertilizer Comparison

	Gardner	Phoenixville	Valley Forge	Mixed Food
Parameters	**Results (ppm)**			
Soluble Salts (EC) (ms/cm)	13.50	23.77	29.82	29.82
pH	5.55	7.15	5.52	5.52
Alkalinity (CaCO3)				
Total Nitrogen	1688.75	2952	2414	1661
Nitrate	20.49	0	0	0
Ammonium	1661.15	2940	2399	1649
Urea	7.11	12.1	15.15	11.21
Phosphorus	91.82	186.77	588.3	519.7
Potassium	195.28	334.27	921.88	1904
Soluble Potash	235.25	X	X	X
Calcium	125.67	40.5	67.63	63.86
Magnesium	48.18	58.97	135.71	80.35
Sulfur	418.52	1061	1122	286.24
Soluble Sulfate	1255.60	X	X	X
Iron	568.70	53.76	86.1	1.89
Manganese	1.79	0.87	0.37	1.08
Boron	1.08	4.56	9.78	0
Copper	0.19	0.02	0	0
Zinc	0.22	0.12	2.15	0.54
Molybdenum	0.11	1.69	0	0
Sodium	112.90	220.95	1798	898.07
Chloride	142.03	408.27	2274	1750
Aluminum	2.48	0	5.39	0

Wastewater Characterization

Wastewater characterization was performed by ALS Testing laboratories. SoMax modeled the core analyses after the wastewater characterization after the requirements of Pennsylvania

Department of Environmental Protection for the HTC project in Phoenixville, PA. The results are presented below, followed by a comparison with the Phoenixville, PA results. If results are listed as less than (<), the result is below the reporting limit. The table below shows the results of the wastewater characterization and testing methods used. Metals were tested using EPA 200.7 and are measured in mg/L, with exception to Mercury which used EPA 245.1.

Table 14 - Gardner Process Water Wastewater Characterization

Test	Result	Units	Method
Ammonia as N	1,380	mg/L	SM 4500-NH3G
BOD5	13,400	mg/L	S5210-B11
COD	49,800	mg/L	EPA 410.4
Hardness	487	mg/L	EPA 200.7
N, Nitrate-Nitrite	28.8	mg/L	SW8469056A
Oil and Grease, as HEM	4.4	mg/L	EPA 1664A
pH	5.27		SM 4500-H-B
Phenolics	9.71	mg/L	EPA 420.4
TDS	21,300	mg/L	EPA 300.0
TKN	4,410	mg/L	S4500NH3G-11
TOC	17,600	mg/L	SM5310B-2011
Total P as P	44.3	mg/L	EPA 365.1
Bromide	21	mg/L	EPA 300.0
Chloride	131	mg/L	EPA 300.0
Sulfate	513	mg/L	EPA 300.0
Hexavalent Chromium	<0.5	mg/L	SM3500CrB-2011

METALS

Aluminum	5.1		Iron	562
Antimony	<0.05		Lead	0.02
Arsenic	.016		Manganese	1.6
Barium	0.027		Mercury	<0.0002
Beryllium	<0.01		Molybdenum	<0.05
Boron	1.1		Nickel	0.16
Cadmium	0.009		Selenium	<0.05
Chromium	0.089		Silver	<0.01
Cobalt	0.069		Thallium	<0.05
Copper	<0.025		Zinc	0.25

As indicated in all previous results, the iron is very elevated due to overdosing of ferric chloride. The TDS, TKN, TOC, COD, and BOD5 are all in their expected ranges. The BOD, TOC, and COD concentrations offer the potential to be decreased via anaerobic digestion. SoMax recognizes that Gardner WWTP does not have an AD process, and this presents an opportunity for a small-scale liquid only AD unit that could rapidly digest the process water before sending it back to the headworks for treatment. The biogas could be beneficially used in the post HTC process of either energy production or as fuel for drying of the biogas, and the loading going back to the headworks of the treatment plant would be reduced.

Table 15 - Process Water Wastewater Characterization Comparison

Wet Chemistry	**Gardner**	**Phoenixville**	**Units**
Bromide	21	<100	mg/L
Chloride	131	<500	mg/L
pH	5.27	5.27	
Sulfate	513	1070	mg/L
TDS	21300	30500	mg/L
Ammonia-N, Low Level	1380	1430	mg/L
Total Phosphorus	44.3	44	mg/L
TKN	4410	5730	mg/L
Phenolics	9.71	8.56	mg/L
Oil/Grease	4.4	5.4	mg/L
METALS			
Aluminum	5.1	23.5	mg/L
Arsenic	0.16	0.11	mg/L
Barium	0.027	<0.500	mg/L
Boron	1.1	5.42	mg/L
Cadmium	0.009	<0.020	mg/L
Chromium	0.89	0.236	mg/L
Cobalt	0.069	0.103	mg/L
Iron	562	88.2	mg/L
Lead	0.02	<0.500	mg/L
Manganese	1.6	22.8	mg/L
Nickel	0.16	0.226	mg/L
Selenium	ND	0.109	mg/L
Zinc	0.25	0.544	mg/L

When compared to the Phoenixville process water, the results do not vary too much, aside from the iron and chromium content at 6.5 and 3.5 times higher the concentration of Phoenixville. Interestingly, both process waters showed the exact same pH, a similar chloride and phosphorus content. Phoenixville does not use $FeCl_3$. This supports the dissolution of chloride into the wastewater with the addition of $FeCl_3$. This also supports that phosphorus recovery from $FeCl_3$ addition is being achieved at maximum levels.

The TKN and N as ammonia are key metrics for determining the nitrogen loading going back to the wastewater treatment plant. If the WWTP NPDES permits have limits on ammonia, the impact of implementing HTC on the WWTP nitrogen conversion should be investigated. If TDS, total dissolved solids, is a limiting factor on the NPDES, the impact of circulating the process water to the headworks of the plant should also be checked. Additionally BOD, COD, and TOC illustrate a liquid stream that will be a measurable load on the wastewater treatment plant. While these key characteristics present additional treatment at the wastewater treatment, it is a small fraction of the overall flow of the plant.

While not explored in this feasibility study, SoMax has identified numerous technologies to reduce the load back to the treatment plant and in some cases create a usable a product. Ammonia-Nitrogen can be recovered in the form of ammonium sulfate, a market ready fertilizer, while the remaining TDS is concentrated. The BOD, COD, and TOC can be significantly reduced through a rapid anerobic digestion process while beneficially using the generated biogas to dry hydrochar, preheat the HTC process, or potentially supplement the syngas.

It should be noted that the nitrate and hardness results were excluded for comparison. ALS had difficulty performing their tests and were forced to us different methods, resulting in different units of measurement.

7. Modeling of Results

Modeling Approach and Scenarios

SoMax built the Gardner HTC models with primary data generated from analysis of the primary dewatered sludge provided to SoMax and its HTC products, wastewater treatment plant site specific data, and SoMax's expertise of the HTC process. The core inputs and assumptions used for creating the models are succinctly shared in the Appendix. This section is to provide additional nuance and explanation of the HTC process and design decisions used to generate the Gardner WWTP HTC models.

Gardner has expressed that electricity generation is the core goal of implementing HTC. As shown in the results section, the energy density of the hydrochar generated from Gardner's sludge is not high quality and will present an issue for generating energy. Food waste derived hydrochar has shown to generate higher quality hydrochar, with a higher energy density in the 27-31 MJ/kg range with much lower ash content. If Gardner is to generate electricity, SoMax highly recommends incorporating accepting of food waste to be co-processed with their sludge. Additionally, other sludge can be accepted to reach reactor capacity. The modeled scenarios will explore the impacts on energy generation by showing a mix of hauled waste and it's economic and energy impacts.

In 2021, Gardner generated 3,339.8 wet tons with an average %TS of 28%. The HTC process has a target %TS feedstock of 15% TS, and processes ~15,000 (14,864) wet tons annually at 7 GPM. With this capacity, SoMax highly recommends Gardner accept hauled waste to fill the excess capacity. A smaller system just to meet Gardner's sludge disposal needs is possible but will ultimately handicap Gardner in their goals of energy generation. Capital costs do not scale linearly with throughput, and a smaller system will not only fail to meet Gardner's goal of energy generation, but it will also be less cost efficient and not allow Gardner to benefit financially from hauled waste. For these reasons, modeling of a system with just Gardner's waste will not be included.

The following models will be based on three main variables:

1) Ratio of hauled waste – Illustrating a range of ratios with additional sewage sludge and food waste feedstocks
2) Hydrochar product usage
    a. Electricity generation via gasification
    b. Hydrochar sold as a product
3) Flow rate of the HTC system – Varying flow rate between 7 – 10 GPM
    a. Only applied to the 50/50 ratio of hauled waste

The change in ratio of sewage sludge to food waste will be noticeable with the amount of energy generated as the percentage of food waste increases. Selling the hydrochar as a product will reduce the capital costs of the overall system, but increase the operating costs, since the energy produced via gasification will not offset the HTC system energy consumption. Lastly, during functional commissioning at Phoenixville the HTC system showed promise that it could function at higher flow rates than 7 GPM, while maintaining temperature. Prior to generating primary data from an HTC system at this scale, the energy usage was modeled based on smaller scale systems.

SoMax will provide an updated Gardner mass and energy balance when the system at Phoenixville has functioned continuously with a thickened sludge feedstock. This will allow SoMax to capture real energy use data, impact of increasing flow rates, and update the operating %TS.

Additionally, the tip fee for hauled waste and hydrochar sale price will be varied. The hauled waste tip fee will be based on data from the MA biosolids study performed by NEBRA which identified a mean price of $140/wet ton (22%TS) (NEBRA, 2019). The tip fees will include $60, $100, and $140 per wet ton delivered, and assumed the same fees for food waste. Hydrochar sales price will vary from $50, $100, and $150 per dry ton. The tip fee and hydrochar sales prices will be expressed in low, medium, and high scenarios, moving in tandem.

Capital Costs

Budgetary capital costs were modeled using four equipment scenarios. Introducing food waste as a feedstock increases material handling equipment, such as a depackaging unit, and utilizing hydrochar for gasification and energy production requires a dryer, material handling, and gasification unit. These capital cost scenarios are summarized in the table below.

Additionally, other project costs were included, such as engineering and permitting, and construction. Any land development, or building requirements were not included in the overall project costs.

Table 16 - Estimated Project Costs

Capital Costs (Sewage Only)	$5,370,160
Capital Costs (Food Waste and Sewage)	$5,722,160
Engineering and Permitting	$640,000
Construction	$1,100,000
Gasification + Ancillary Equipment	$2,480,000

The capital equipment captured in the above budgetary costs are as follows:

- Material handling – material conveyors, storage (live bottom hopper)
- Pumps (inlet, outlet, dewatering, heat exchanger)
- HTC specific equipment (heat recovery, ancillary heating, reactor, pressure controls)

- Thermal Oil Heater
- Buffer tank
- Dewatering Press
- Dryer
- Briquette/pelletizer
- Gasification and genset
- Controls and HMI

Operating Costs

The operating costs of the system are estimated from energy use of equipment and annual maintenance costs.

This model was constructed utilizing electrical energy, since natural gas utilities are not present on site. Using a Townsend Light Utility Bill provided to SoMax, the cost of electricity was calculated at $0.09507/kWh. The bill is shown in the appendix with the summary of model inputs.

For material sales, an estimated $40,000 for annual maintenance was included, with an increase to $50,000 with the gasification scenarios.

Savings and Revenue

Savings and revenue are generated via tip fee from hauled waste, product sales, electricity sales/savings, and disposal savings from Gardner derived sludge. It was assumed that Gardner could save $25/wet ton of biosolids disposed of at the Gardner landfill. A low value was used since Gardner handles all disposal internally. The revenue generated from hauled waste is modeled through three scenarios of low, medium, and high using $60, $100, and $140 / wet ton respectively. Hauled biosolids assumed an average of 22% total solids as indicated by the Massachusetts biosolids study (NEBRA, 2019), and 25% TS for food waste. The feedstock mass is adjusted to 15% TS leading into the reactor, and the savings and revenues are accounted for on an as received basis.

The hydrochar product sales are set on a dry basis of $50, $100, and $150, using the same low, medium, and high scenarios. Electricity savings are accounted for utilizing the same price as above, $0.9057/kWh.

Exclusions

Some material flows or energy usage of the models were not accounted for. Ash disposal is accounted for as cost neutral. Gas scrubbing liquid from gasification is assumed to be able to enter the head works of the wastewater treatment. Energy usage around food waste depackaging and preparation was not included. No additional FTEs were included in the operating costs.

8. Model Results

As described in the previous section, three main variables were changed to assess the economic and performance feasibility of implementing HTC at the Gardner WWTP. The following sections show the results of the implementing HTC for material sales and energy production, while changing hauled waste ratios, and flow rates of the system. The first scenario shows hydrochar as a product, followed by energy production, and lastly the impact of variable flow rate on energy production and full system economics.

Hydrochar as a Product

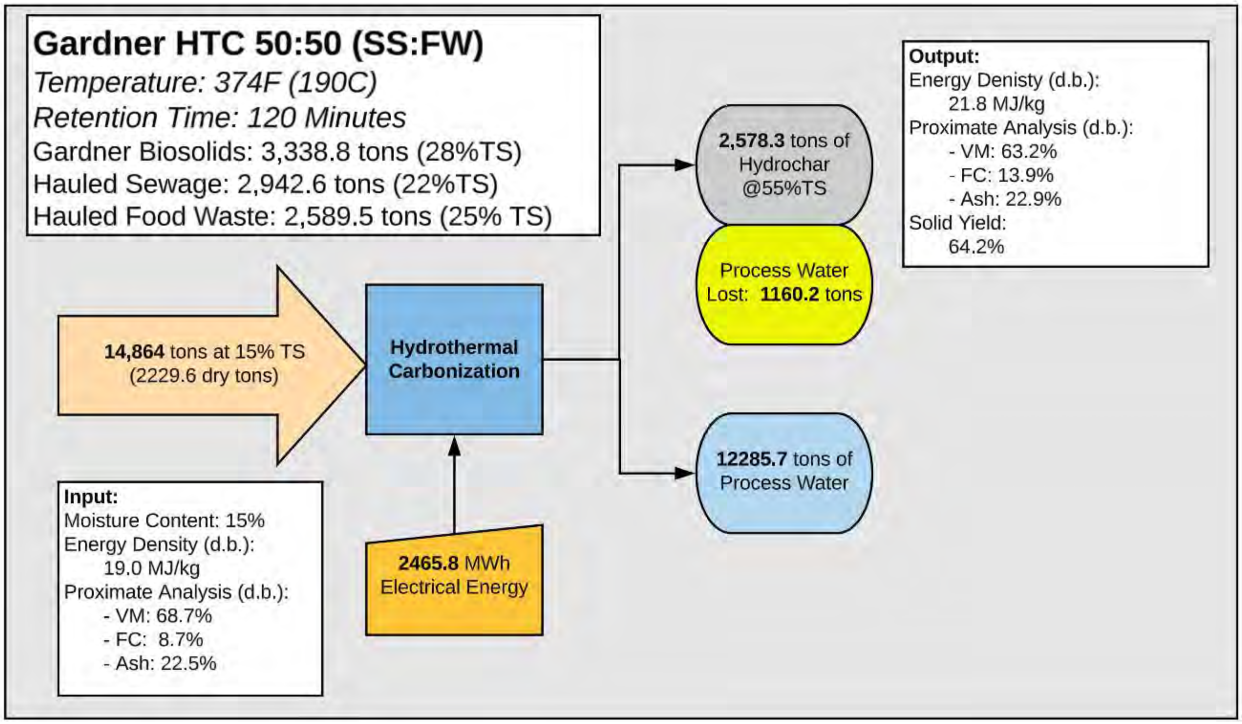
Gardner's stated goal is energy production, but SoMax also modeled hydrochar sales as a product, to show an alternative pathway and potential approach to implementing HTC at the WWTP. Core takeaways and trends from varying ratio of hauled waste feedstock are as follows:

- Food waste has a lower yield through HTC than sewage sludge, therefore lower mass for hydrochar sales.
- Food waste has a higher %TS as received (25% TS), therefore lower tip fees generated from food waste than sewage sludge as modeled.
    - This can be investigated further with what food waste is available locally and models can be updates upon additional data gathered through project development and identifying key suppliers of food waste.
- Hydrochar made with food waste is of higher quality and lends itself to more energy production.
    - Lower ash content
    - Higher heating value
    - Higher carbon concentrations.

The first two takeaways are illustrated in the project economics, showing a reduction in the 20-year project balance and year of returned investment. The last takeaway is clearly shown in the latter energy production scenarios.

Before showing the economic data, below is a high-level mass and energy balance of an HTC system, utilizing a 50:50 (sewage: food waste) ratio for hauled waste at 7 GPM. As shown in the M&E the hydrochar is dewatered to 45% moisture content and sold as is. The hydrochar is modeled as being priced on a dry basis.

Figure 13 - Material Sales - Mass and Energy Balance 50:50 Hauled Waste (7 GPM)



Comparing the results of the hydrochar output to the results of just the Gardner biosolids derived hydrochar shows an increase in energy density, fixed carbon, and decrease in solid yield and ash content. These changes are due to the characteristics of food waste based hydrochar. Hauled waste sewage was modeled after Gardner's results. Depending on the origin of the hauled sewage, the results will vary. For example, digestate has higher ash and lower volatile matter and energy density, than primary sludge.

The graphs below show the project balance with all capital and project costs hit in 'year 0' and in 'year 1' tip fees and product sales begin. Financing can be built into the model as the project develops, on time and material basis. The graphs show the low, medium, and high scenarios which are associated with \$60, \$100, and \$140 per ton (as received) tip fees for hauled waste, and \$50, \$100, and \$150 per ton of hydrochar (dry basis) sales price.

The first graph shows all sewage sludge hauled waste and increases in ratio of food waste to the last graph which is all food waste hauled waste filling the remaining capacity of the system. No annual increases were applied to tip fees, energy prices, or product sales. Additionally, no carbon credits have been accounted for with hydrochar production. The 25:75 and 75:25 scenarios are shown in the appendix.

Figure 14 - Projected Economics - Material Sales 0:100 (FW:SS)

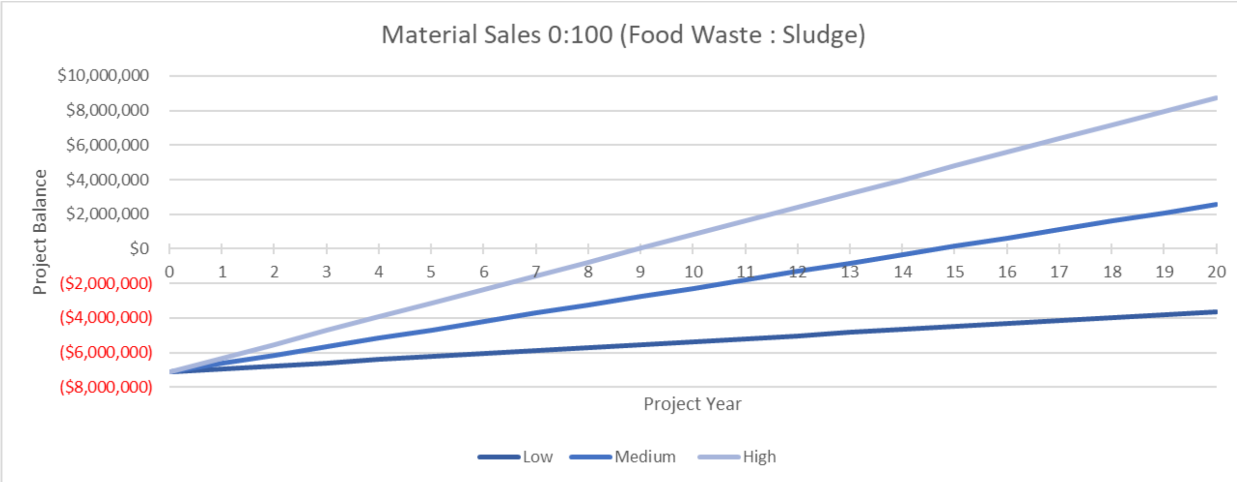


Figure 15 - Projected Economics - Material Sales 50:50 (FW:SS)

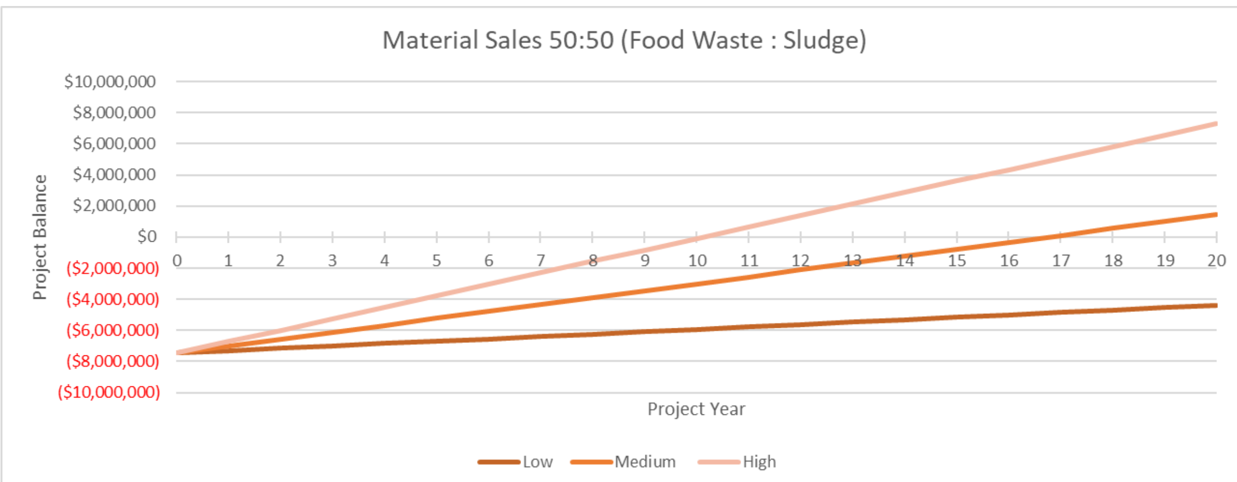


Figure 16 - Projected Economics - Material Sales 100:0 (FW:SS)

The table below captures two key data points from the graphs above, year of return on investment, and total project balance after 20 years, as well as hydrochar production and heating value of the hydrochar for given ratios. Additional graphs for the 25:75 and 75:25 ratios are in the appendix.

Table 17 - Projected Economics Summary - Material Sales

	ROI (Year)	20-Year Balance
	Hydrochar (US Tons) (d.b.)	**Heating Value (MJ/kg)**
0/100	**1474.5**	**18.9**
Low	>20	($2,392,559)
Medium	14	$3,790,051
High	9	$9,972,661
25/75	**1446.3**	**20.4**
Low	>20	($2,984,624)
Medium	15	$3,028,542
High	10	$9,041,709
50/50	**1418.1**	**21.8**
Low	>20	($3,224,690)
Medium	15	$2,619,034
High	10	$8,462,757
75/25	**1389.9**	**23.3**
Low	>20	($3,464,755)
Medium	16	$2,209,525
High	10	$7,883,805
100/0	**1361.7**	**24.8**
Low	>20	($3,704,820)
Medium	17	$1,800,017
High	11	$7,304,854

As shown in the graphs and table the low tip fee and hydrochar sales price scenarios have a payback period greater than 20 years. As the ratio of food waste increases, the payback period for the medium and high scenarios increases. Also, the 20-year project balance decreases. As discussed, this is due to the higher as received %TS and lower solid yield. The lower solid yield is shown in the table with the decreasing tons of hydrochar, but the heating value increases as the ratio of the food waste increases. The quality of the hydrochar increases with increasing food waste percentage of feedstock, and could impact the sales price, while not modeled.

The Massachusetts biosolids study cited $140 as the median tip fee for biosolids in Massachusetts, thus the 'high' scenario is a possible outcome, which shows payback periods between nine and eleven years and a 20-year project balance as returned between $7.3MM and

$9.9MM to Gardner, which could turn the Gardner WWTP into a revenue generating facility for the municipality.

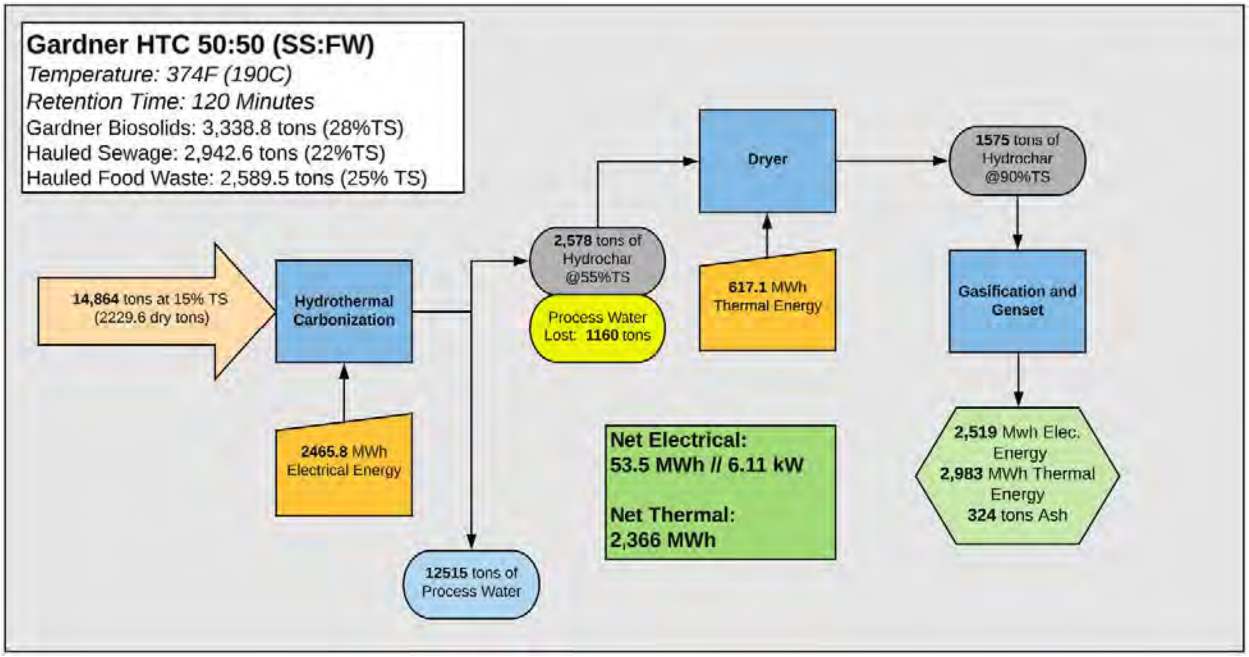
HTC + Gasification for Energy Production

The next scenarios assess hydrothermal carbonization paired with gasification for electricity production, which is Gardner's stated goal. The results of these scenarios illustrate that the higher ratio of food waste for hauled waste, the more energy produced from gasification. As shown in the previous table, a higher ratio of food waste results in less hydrochar produced, but the increase in the energy density of the available hydrochar increases the overall energy available through hydrochar production.

Additional information about Gardner's electric utility (Townsend) was requested and not supplied, therefore the potential benefit was not included in the model. At the Borough of Phoenixville, their utility (PECO) is offering $0.11/kWh up to $2,000,000, or 50% of the project costs, for energy demand removed from their supply. For example, the Borough is paying ~$0.06/kWh, resulting in additional savings beyond just offsetting their electricity cost. For Gardner's model, the electricity available beyond HTC consumption was priced at $0.09507/kWh. If additional information about energy offset programs is supplied, SoMax will integrate that data into an updated model, on a time and material basis.

Below is a mass and energy balance for the same 50:50 ratio of hauled waste at 7 GPM, but with drying and gasification included. In this scenario there is a net production in electricity, by ~50MWh, while all electrical and thermal inputs of the HTC system and dryer are covered. The net energy production increases with an increase in food waste of the feedstock, but substantial energy production is not achieved until the flow rate of the system is increased. The high-end flow rate of the system will be verified with the startup of the Borough of Phoenixville HTC facility, but heat transfer calculations show that 10 GPM is attainable. The impacts of increasing flow rate in the system will be captured in the following section.

Figure 17 - Energy Production - Material and Energy Balance 50:50 Hauled Waste (7 GPM)



Similar to the material sales economic assessment, the following graphs illustrate the project economics for low, medium and high tip fees with varying ratios of food waste and sewage hauled waste, at 7 GPM, or 14,864 wet tons per year. The 25:75 and 75:25 ratio scenarios are shown in the appendix.

Figure 18 - Projected Economics - Energy Production 0:100 (FW:SS)

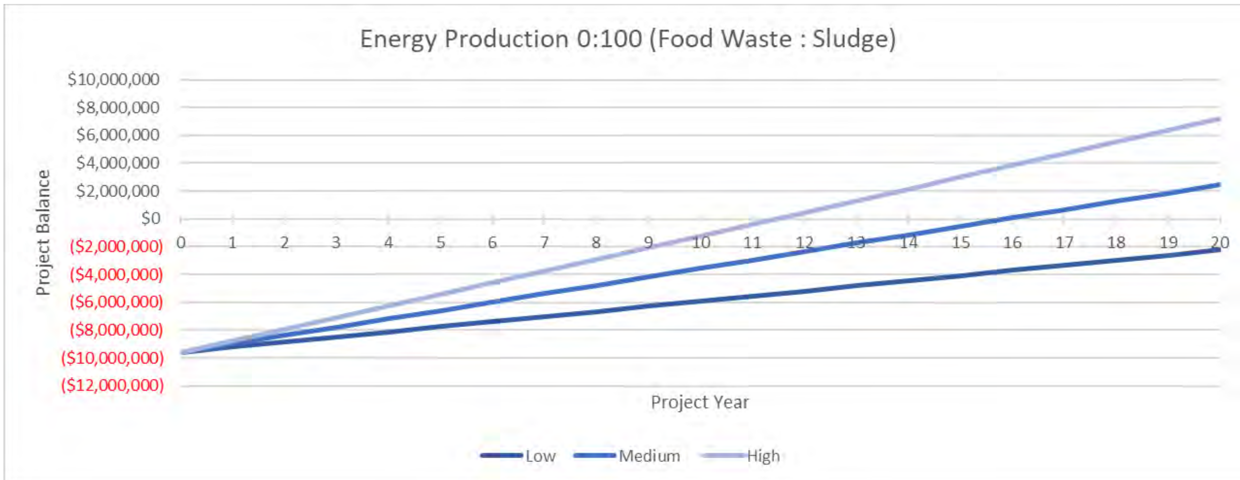


Figure 19 - Projected Economics - Energy Production 50:50 (FW:SS)

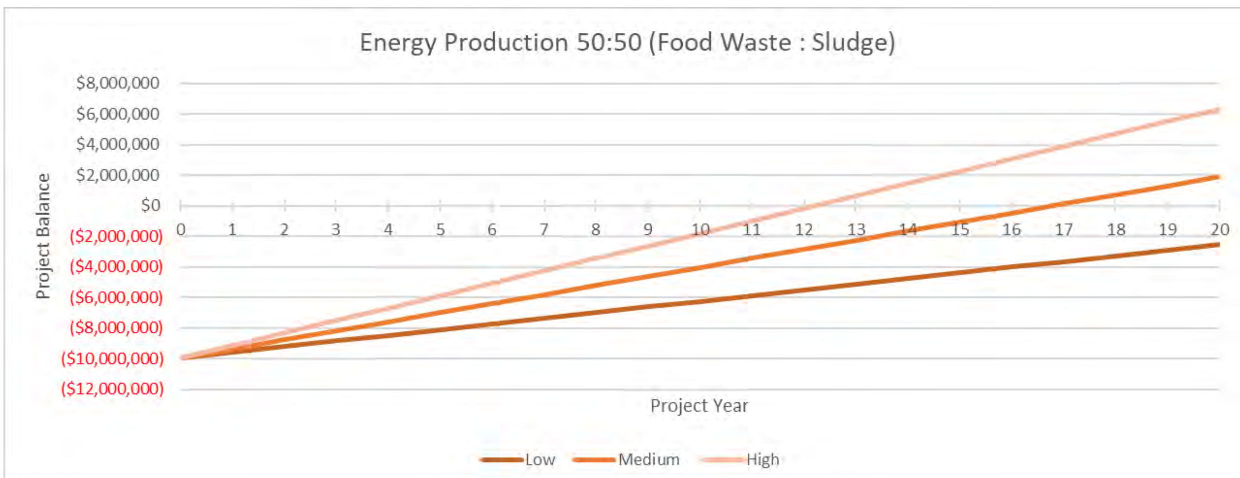


Figure 20 - Projected Economics - Energy Production 100:00 (FW:SS)

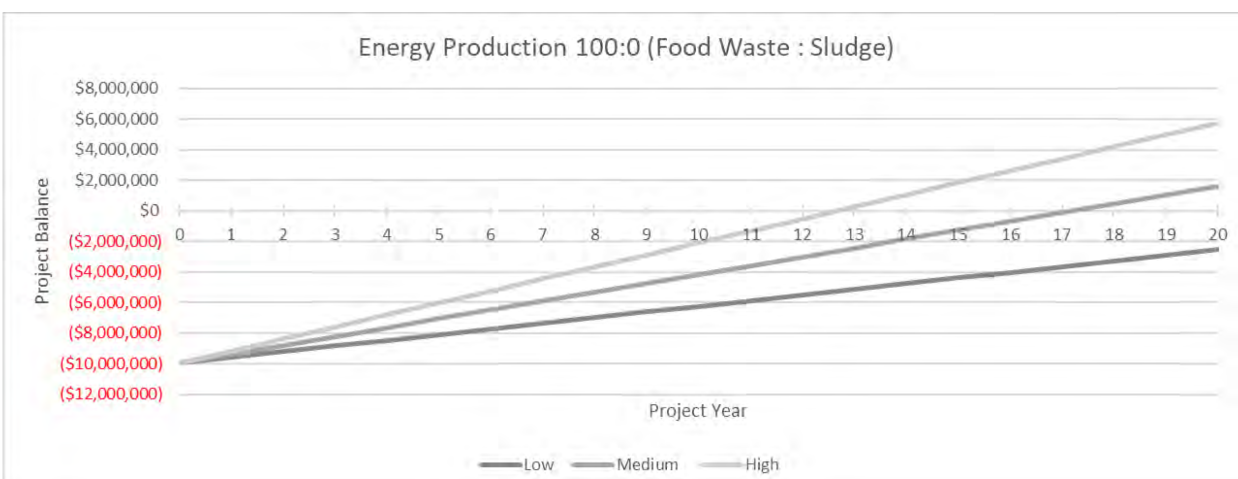


Table 18 - Projected Economics Summary - Energy Production

	ROI (Year)	20-Year Balance		
	Net Electric MWh	**Continuous Power (kW)**	**Hydrochar (US Tons) (d.b.)**	**Heating Value (MJ/kg)**
0/100	**(198.2)**	**(22.6)**	**1,474.5**	**18.9**
Low	>20	($2,235,342)		
Medium	16	$2,472,789		
High	12	$7,180,920		
25/75	**(69.0)**	**(7.9)**	**1,446.3**	**20.37**
Low	>20	($2,553,562)		
Medium	17	$2,013,325		
High	13	$6,580,212		
50/50	**53.5**	**6.1**	**1,418.1**	**21.83**
Low	>20	($2,532,576)		
Medium	17	$1,893,067		
High	13	$6,318,710		
75/25	**169.2**	**19.3**	**1,389.9**	**23.30**
Low	>20	($2,524,385)		
Medium	17	$1,760,014		
High	13	$6,044,413		
100/0	**278.2**	**31.8**	**1,361.7**	**24.80**
Low	>20	($2,528,989)		
Medium	18	$1,614,166		
High	13	$5,757,321		

The resulting data from modeling the energy generation scenarios with an increase in food waste in the feed show an increase in ROI, a decrease in the 20-year project balance, but an increase in energy production as the ratio of food waste increases.

Similar to the material sales models, at the medium and high tip rates the project shows an ROI within 20 years, with as low as 12 and 13 years and a 20 year project balance up to $5.75MM and $7.18MM.

Impact of Energy Production and Economics of Increasing Flow Rate

This section assesses two additional variables, flow rate and IRA tax credits. As previously mentioned, the SoMax HTC has the ability to increase flow rate and overall annual throughput of the system. Our initial functional commissioning experience and heat transfer calculations support this system variability. The follow graphs show the impact of variable flow rates, at 7, 8, 9, and 10 GPM, with the 50:50 ratio of hauled waste, at low, medium, and high tip fee rates. Like previous sections the data is summarized in a table following the graphs.

Additionally, the benefits of the IRA tax credit are summarized in the graphs and table. The economic assessment on looks at the 'Medium' tip fee scenario for various flow rates. The Inflation Reduction Act (IRA) makes tax credits available for bioenergy projects. The tax credits available through the IRA are unique in that they are transferable, so non-tax paying entities, such as municipalities, can benefit from this program and ultimately making municipal projects more cost-effective.

Figure 21 - Projected Economics - 'Low' Tip Fee Scenario - Variable Flow Rates

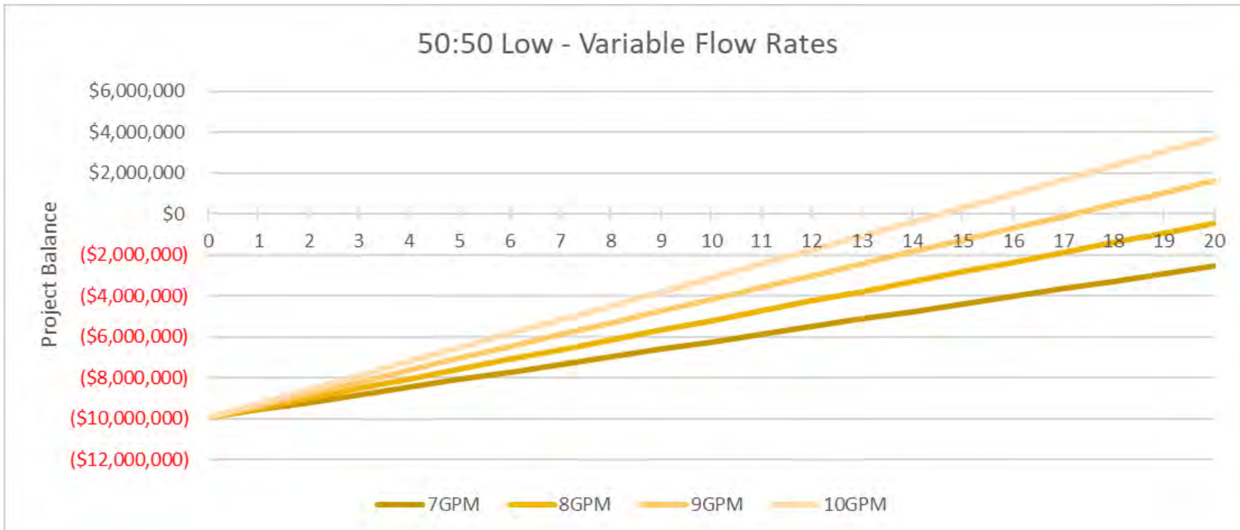


Figure 22 - Projected Economics - 'High' Tip Fee Scenario - Variable Flow Rates

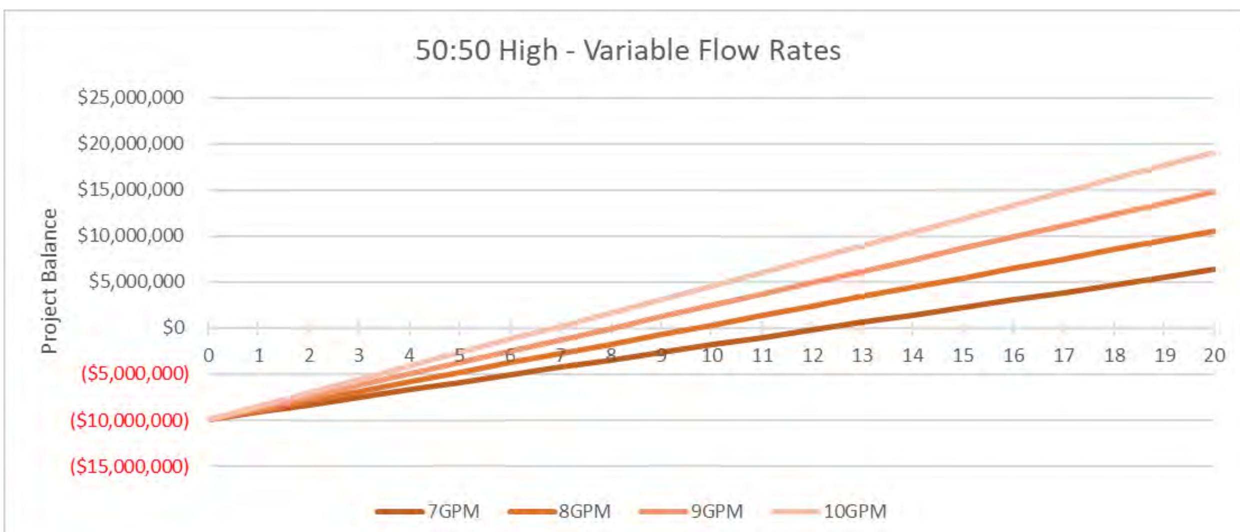


Figure 23 - Projected Economics - IRA Benefits - 'Medium' Tip Fee Scenario - Variable Flow Rates

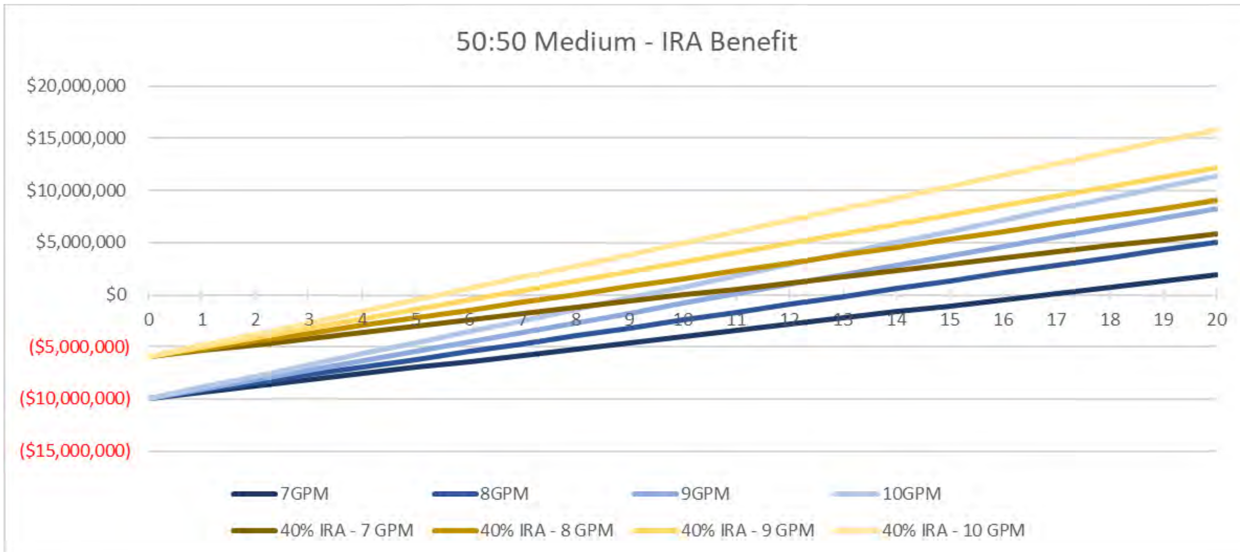


Table 19 - Projected Economics Summary - Energy Production - Variable Flow Rate w/IRA Benefits

			40% IRA Tax Credit	
	ROI (Year)	20-Year Balance	*ROI (Year)*	*20-Year Balance*
	Net Electric (MWh)	**Continuous Power (kW)**	**Hydrochar (US Tons) (d.b.)**	
7GPM	**53.5**	**6.1**	**1,418.1**	
Low	>20	($2,532,576)		
Medium	16	$1,893,067	*11*	*$5,869,931*
High	12	$6,318,710		
8GPM	**290.9**	**33.2**	**1,614.8**	
Low	>20	($448,299)		
Medium	14	$5,065,864	*8*	*$9,042,728*
High	10	$10,580,027		
9GPM	**528.2**	**60.3**	**1,811.53**	
Low	18	$1,635,608		
Medium	11	$8,238,291	*7*	*$12,215,155*
High	9	$14,840,974		
10GPM	**765.5**	**87.4**	**2,008.4**	
Low	15	$3,720,368		
Medium	10	$11,412,084	*6*	*$15,833,160*
High	7	$19,103,799		

The graphs and table show that an increase in flow rate through the HTC system improves the overall economics of the HTC system, as well as the potential for energy generation. The increase in flow rate increases the overall hydrochar production, and the increase in operating costs to heat and handle more material is outpaced by the positive economics of tip fees and energy generated from the product hydrochar.

The financial benefits of a 40% tax credit through the IRA are substantial, resulting in a reduction in ROI by 4-5 years, and in increase in the 20-year project balance by ~$4MM.

Results Summary

Utilizing the primary data generated from the lab scale hydrothermal carbonization tests, models were constructed to analyze the economic and energy generation potential of a full-scale commercial HTC system. A tip fee structure was built on the data of a NEBRA sponsored biosolids report, where the 'high' analysis utilized the median tip fee in Massachusetts, which supports the assumption that the high tip fee scenarios are attainable. The hydrochar sales price mirrored the tip fee structure and was based on feedback to SoMax during market development and product fit discussions across industries.

Primary data, such as sludge production volumes and characteristics and energy prices, from the Gardner wastewater treatment plant were inserted into the financial models to represent a functioning HTC facility at the Gardner WWTP. The modeled HTC process processes all Gardner generated sludge, and the remaining capacity of the HTC system is filled with hauled waste, with a varying ratio of food waste and biosolids.

As the ratio of food waste to biosolids increased, the data showed the following core trends:

- Decrease in hydrochar production
- Increase in energy density of the hydrochar
- Decrease in tip fees
- Increase in energy production
- Decrease in 20-year project balance
- Increase in ROI

Even with the decreasing 20-year project balance with an increase in food waste ratio, the medium and high tip fee scenarios showed an ROI in under 20-years. With Gardner's goal of creating energy, a higher ratio of food waste than biosolids or sewage sludge is required for meaningful levels energy production.

The economics of material sales, which involves grid energy use for the production of hydrochar for sales, modeled with positive economics (<20-year ROI) with medium and high tip fee scenarios. The ROIs with medium and high tip fee and sales price scenarios showed ROIs in 14-17 years and 9-11 years respectively. The 20-year balance for those scenarios ranged from

$1.8MM – $3.8MM and $7.3MM - $9.9MM, respectively. The medium and high tip fee scenarios are highly likely to be supported by the Massachusetts organics disposal market.

The economics for energy production result in higher capital costs, and lower 20-year balances and longer payback periods. For Gardner to meet their goal of energy production, Gardner will need to open their facility to hauled food waste and become a co-processing center and the models support this claim. With a 7 GPM, or nearly 15,000 wet ton annual throughput, at a ratio of 50:50 food waste and biosolids for hauled waste does the HTC and gasification process become net energy positive. This is partially due to the full electrification of the HTC system with no natural gas utilities on site. Converting the thermal energy of combusting syngas to electricity is less efficient overall than heating the HTC system with the syngas.

To increase the overall energy production potential at the HTC facility, the ratio of hauled waste should favor food waste. Also, the flow rate of the HTC system can be increased to accommodate more hauled waste. Increasing flow rate up to 10 GPM could allow for a payback period as low as 7 years (without taking into account the IRA benefits) and increasing net energy production to a steady 85kW at the 50:50 ratio of hauled waste. At 100% food waste for hauled waste, at 10 GPM, the energy production can exceed 125kW, or over 1,100 MWh annually.

If Gardner can capitalize on the 40% IRA tax credits, the resulting payback periods can be reduced to as quick as 4-6 years at 10GPM and 7 GPM respectively at the high tip fee scenarios, and from 6-11 years at the medium tip fee scenarios, while still be net energy positive.

9. Recommendations and Next Steps

Based on the results of the feasibility study SoMax has identified recommendations and next steps in pursuing the implementation of a commercial scale HTC facility. As discussed with Mr. Zadrozny, the overdosing of ferric chloride should continue to be assessed. It is expected the fuel characteristics of the hydrochar generated Gardner biosolids will improve when the concentration of iron in the biosolids is reduced. Additionally, the use of polymer will also be reduced by targeting a reduced %TS sludge from the centrifuge when generating the HTC feedstock. Both reductions will result in cost savings for the municipality, neither of which were captured in the economic models.

To confirm the economic models, the municipality should pursue a market assessment of the locally available hauled waste, including municipal sludge, hauled septage, and food waste. The market assessment will not only show available tonnage, but also the disposal prices that could be obtained by being a waste receiving facility. When discussing waste availability with co-processing facilities, the common mantra has been “If you build it, they will come.” With the Massachusetts organics waste ban, a great opportunity exists to expand into a full organics resource recovery facility.

Additionally, the municipality should begin researching and exploring grant and energy production subsidy opportunities to support the implementation of HTC. The Borough of Phoenixville was able to receive a total of $1,052,000 from county and state grants. They were also granted an ~80% increase subsidy on electricity that offsets their provider’s current demand. Compounding the grants, subsidies, and available IRA tax credits, the economics around implementing HTC and gasification for energy production are very attractive.

Based on the positive economic and energy production results, SoMax recommends moving into a formal engineering and design phase for implementation of HTC. In this phase the HTC system will be designed for construction and placement at the Gardner WWTP, as well as establishing necessary communication with required utilities, and permitting entities.

In summary, the recommendations are as follows:

- Reassess the usage rates of ferric chloride and polymer at the City of Gardner WWTP
- Assess local and regional market potential for hauled waste availability and applicable tip fees
- Explore and evaluate state and county grants and energy production subsidies through public utility
- Move into formal engineering and design phase for implementation of HTC

10. Conclusions

The biosolids generated at the Gardner WWTP were tested for feasibility as a feedstock for Hydrothermal Carbonization. The fuel characteristics of the resulting hydrochar were subpar, but the potential for blending other organic waste streams, such as food waste, present the opportunity to increase hydrochar quality, while increasing revenue through tip fees, and building a net energy producing HTC facility. To meet Gardner's goal of energy production, a mixed organics approach must be pursued.

The current state of biosolids disposal and landfill bans on organic waste streams in the state of Massachusetts present the City of Gardner with an opportunity to profitably accept hauled waste and efficiently convert it to a biogenic based carbon product and subsequent renewable energy via hydrothermal carbonization and gasification. Federal tax credits are available to reduce capital and project costs for bioenergy projects. The tax credits significantly reduce the time it takes to obtain a return on the investment and they increase the 20-year project balance. Based on NEBRA analyzed biosolids tip fees, a return on investment is potentially as low as 4-6 years, while producing 20-year project balance of ~$7,000,000 - $19,000,000. The tip fees in Massachusetts suggest that the projected economics will, at a minimum, land between the 'medium' and 'high' projected scenarios.

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Appendix A – Model Assumptions and Core Inputs

Capital Costs (Sewage Only)	$5,370,160
Capital Costs (Food Waste and Sewage)	$5,722,160
Engineering and Permitting	$640,000
Construction	$1,100,000
Gasification + Ancillary Equipment	$2,480,000

Food waste requires depackaging unit and additional material handling costs - $352,000

Cost of Gardner Sludge Disposal // Savings for not landfilling

- Assumed $25/wet ton for disposal @28% TS

All electric HTC system. No natural gas utility on site.

Using 2021 numbers from Jan. to Dec. = 3,339.8 wet tons produced at Gardner WWTP

Average cost of energy: $0.09507 / kWh – Calculated from Townsend Light Utility Bill

Energy produced will be accounted for at the same price.

Does not include Dist. Demand or Customer Charge in calculation.

Current Billing Charges:						
Delivery Services:		Dist Demand	$	1,854.40		
Customer Charge			$	17.25		
Distribution	.0294x	116600 kwh	$	3,436.20		
Transmission	.0246x	116600 kwh	$	2,869.53		
Renewable Energy Charge	.0005x	116600 kwh	$	58.30		
Total Delivery Service:			$	8,235.68		
Supplier Services:						
Generation	.0404x	116600 kwh	$	4,721.13		
PASNY Credit						
Transition Adj. Charge						
Total Supplier Services			$	4,721.13		
Yard/Other Lights			$	32.96		
Total Current Charges			$	12,989.77	$	12,989.77
Total now due:					$	12,989.77

Hauled Waste:

Sewage sludge assumed 22% TS at delivery (as identified in MA biosolids study)

Table 13. Per-WET-ton cost for transportation and end use or disposal of solids from WRRFs in 2018

Solids end use or disposal option	Mean cost per wet U. S. ton [1]	Range of costs per wet U. S. ton
Incineration (n = 28) [2]	$144	$21 - $432
Landfill disposal (n = 15)	$176	$35 - $608
Class A and Class B land application (n = 3)	$180	$74 - $365
Off-site preparer (n = 5)	$270	$83 - $569

A Low, medium, high tip fee and hydrochar sales price tier approach used for sensitivity.

Tip fees will vary from $60, $100, $140 delivered at 22% TS

Food waste assumed 25% TS at delivery

Hydrochar sales prices: $50, $100, $150

Gas Scrubbing liquid disposal not accounted for.

Energy of depackaging unit and additional material handling not accounted for

Ash disposal is cost neutral

Maintenance Cost for Energy production 50,000

Maintenance Cost for Material Sales 40,000

Appendix B – Additional Graphs and Tables

Figure 24 - Project Economics- Material Sales 25:75 (FW:SS)

Figure 25 - Projected Economics - Material Sales 75:25 (FW:SS)

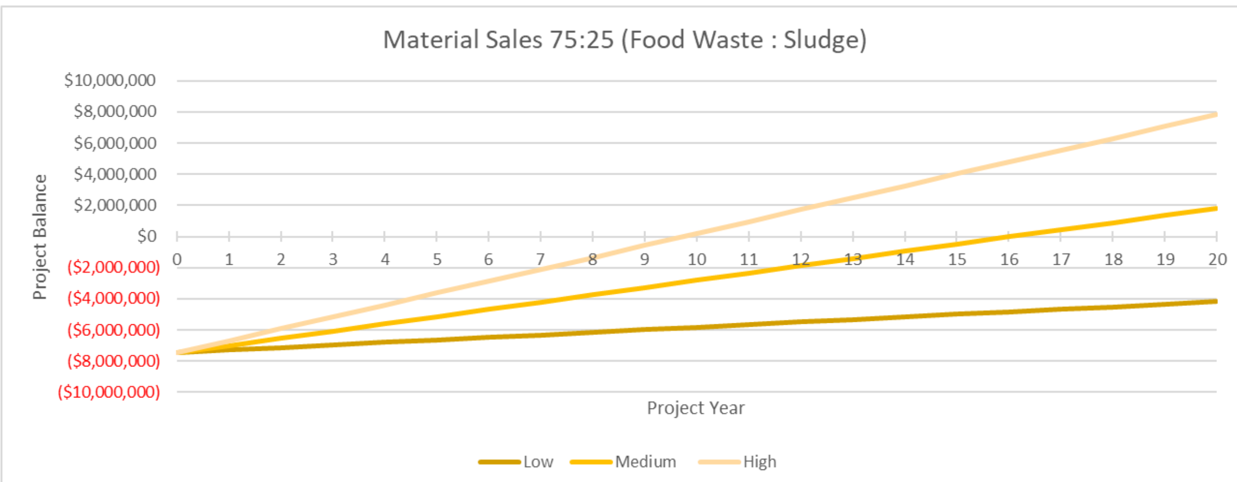


Figure 26 - Projected Economics - Energy Production 25:75 (FW:SS)

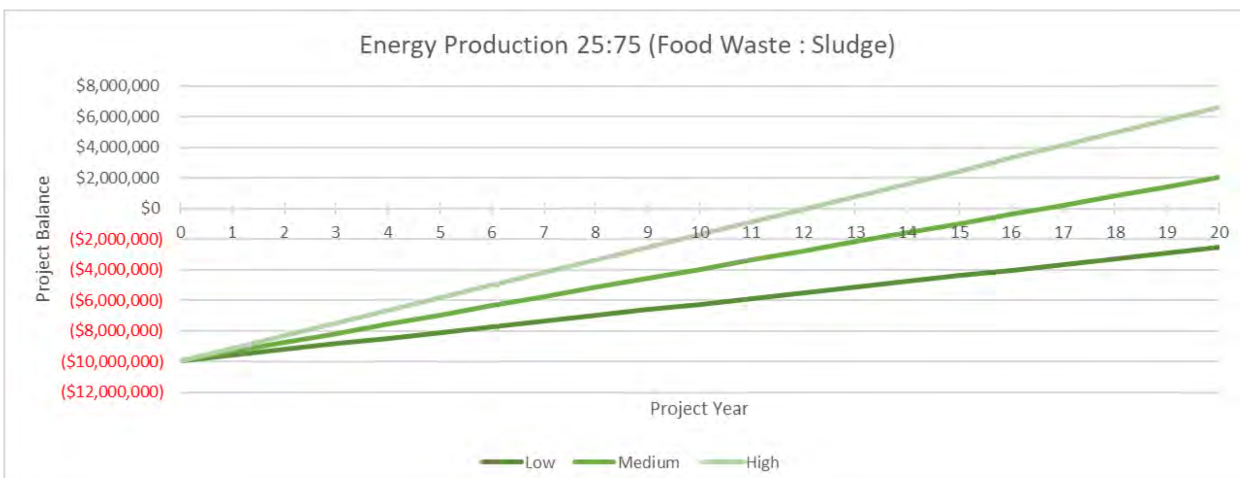


Figure 27 - Projected Economics - Energy Production 75:25 (FW:SS)

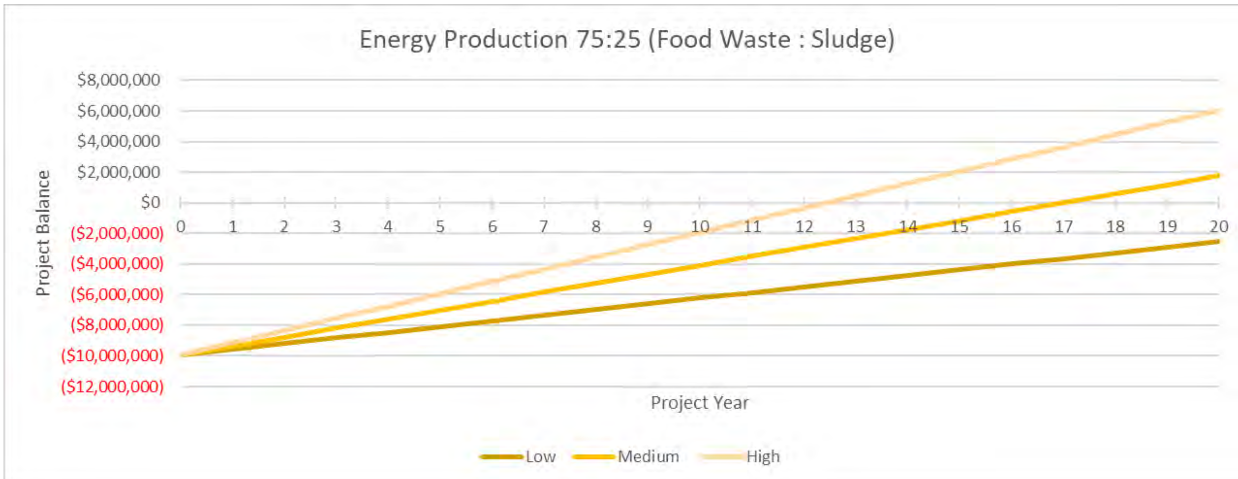
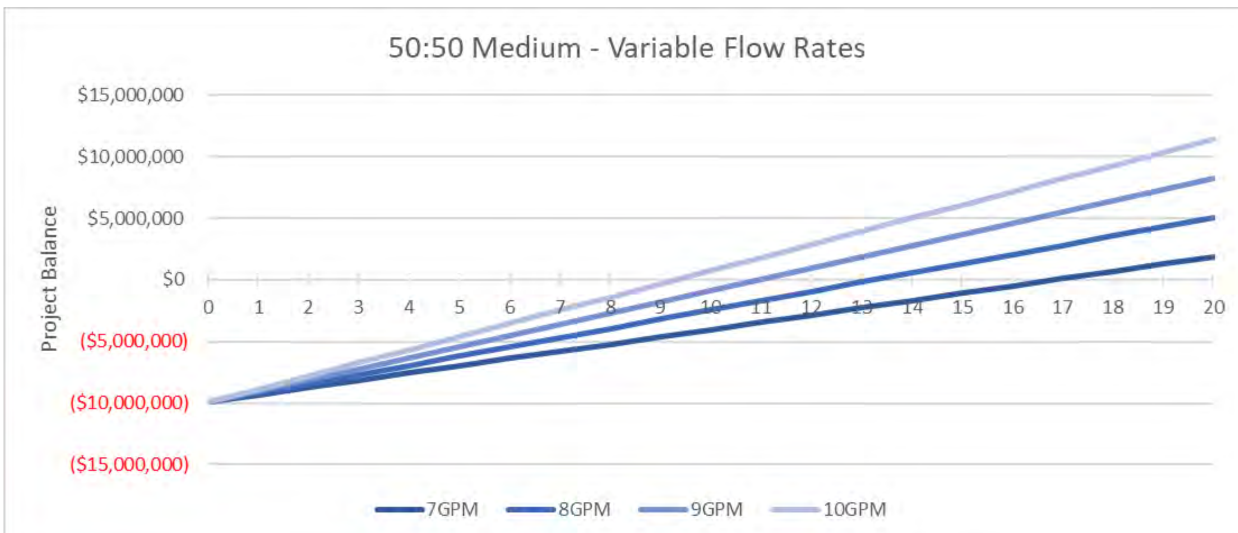


Figure 28 - Projected Economics - 'Medium' Tip Fee Scenario - Variable Flow Rates



ATTACHMENT 4

IEA Bioenergy
Technology Collaboration Programme

Hydorthermal Carbonization (HTC):

Valorisation of organic waste and sludges for hydrochar production and biofertilizers

IEA Bioenergy: Task 36

October 2021

Hydrothermal Carbonization (HTC):

Valorisation of organic waste and sludges for hydrochar production of biofertilizers

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Edited by Mar Edo, Beau Hoffman, Inge Johansson and Daniel Roberts

IEA Bioenergy: Task 36

October 2021

ISBN, 978-1-910154-90-8

Index

PREFACE

This is the second of a case study compilation to explore lessons on material and energy valorisation of waste within the framework of IEA Bioenergy Task 36. The set of case studies will be published during 2021 covering social and public acceptance aspects, barriers in Waste-to-Energy (WtE) implementation, success stories for decentralized solutions, and integration of WtE within material and/or nutrient recovery. The purpose of these case studies is to showcase examples from which countries can get inspiration and support in implementing suitable policies and solutions in the waste/resource management and WtE sector that would facilitate their transition towards circularity.

IEA Bioenergy Task 36, working on the topic 'Material and Energy Valorisation of Waste in a Circular Economy', seeks to raise public awareness of sustainable energy generation from biomass residues and waste fractions including MSW as well as to increase technical information dissemination. As outlined in the 3-year work programme, Task 36 seeks to understand what role energy from waste and material recycling can have in a circular economy and identify technical and non-technical barriers and opportunities needed to achieve this vision.

See http://task36.ieabioenergy.com/ for links to the work performed by IEA Bioenergy Task 36.

SUMMARY

Hydrothemal Carbonization (HTC) technology has demonstrated to successfully convert biowaste and sludge – which are input feedstocks - into high quality hydrochar, sometimes considered to be a more valuable product than biochar materials. Several HTC industrial plants operate in Europe. Ingelia, an HTC technology developer, operates its own industrial HTC plant in Valencia (Spain) since 2010, CPL Industries Ltd operates an HTC Plant in the UK which was commissioned in 2018 and a third plant is under construction in Belgium, expected to start operations in 2021. Ingelia HTC technology has been proven at commercial scale, reaching TRL9.

The HTC process acts as an acceleration of the natural coal formation process, working at moderate pressure and temperature (20 bar and 210 ºC for the Ingelia process), allowing the dehydration of the organic matter and increasing the C-content up to 60 wt.%. By means of HTC, feedstock with high moisture content converts into a coal-like product called hydrochar. The Ingelia HTC technology includes separation equipment for impurities that are present in the waste such as sands, stones, pieces of metals or glass. However, there are some inorganic components in the carbon structure, such as Ca, K, or P, that can be reduced by specific washing and chemical post-treatment steps. As a result of the HTC process, most of the carbon content of different wet organic waste streams is concentrated and retained within the obtained hydrochar.

HTC process represents a solution for the valorisation of biowaste streams, while generating a carbon-based solid fraction, hydrochar, that can be used as an energy source, a soil ameliorant, or as a feedstock to produce bioproducts. The hydrochar is chemically stable and storable, preventing the emission of methane if the feedstock would be landfilled. The moisture present in the feedstock condensates after the HTC process, and solubilises elements like N, P, K, etc. These elements represent a liquid biofertilizer that potentially can be used as a substitution of chemical fertilizers. The HTC process provides a source of renewable carbon whose properties can be adapted to its final application. The hydrochar can undergo specific post-treatment to reduce the content of specific nutrients to the limits accepted in the industry and energy sector, or to modify moisture content and density (by palletisation or briquetting) with the aim of delivering a product that can be sold as a natural resource for fossil coal substitution.

A life cycle assessment was carried out to determine the potential environmental impacts (global warming, freshwater eutrophication, and terrestrial acidification) of a large-scale HTC plant processing 78 000 ton of wet biowaste and sludge per year in Italy. The analysis highlighted three major contributors to overall environmental impacts; electricity and thermal energy used in the process, CO_2 produced in the process, and the organic content in the waste streams impacting the environment when applied to land. The analysis shows that there is potential for improving the environmental performance of the HTC process by optimising energy use and using greener sources of energy.

BACKGROUND

It is estimated that 139 Mton of biowaste and more that 10 Mton of sewage sludge are generated in EU every year [1]. Biowaste includes food and garden waste in mixed municipal solid waste (MSW), and waste from the food and drink industry. The biowaste can be separated at origin or collected in the mixed waste fraction. The waste handling options for the biowaste range from anaerobic digestion and composting, incineration, and landfilling. In the EU, biowaste usually constitutes 35 wt.% of the total mixed waste, but ranges from 18 wt.% up to 60 wt.%, and an important part of it is treated by the less preferable options in the waste hierarchy. On average, 41 % of MSW is landfilled[2] while for some Member States (e.g., Poland and Lithuania) this percentage exceeds 90 %. The amount of sewage sludge landfilled in Europe in 2017 was 282 kton. These figures show that there is still room for further improvement of management of some major waste streams, especially as there is an increasing drive to move towards more 'circular' approaches to waste management.

Coal is steadily leaving the energy market in many developed economies due to a combination of environmental policies and competition with increasingly cost-competitive renewable energies. The International Energy Agency (IEA) recently published the World Energy Outlook 2019[3], drawing up three scenarios for the world coal consumption until 2040. In the Sustainable Development Scenario, industrial coal use decreases, but coal remains as an important fuel, reflecting the difficulty and high costs of finding substitutes for coal in the industrial processes. Coal remains the backbone of the iron and steel industry and cement sub-sectors, and its use in the chemical sub-sector keeps increasing, particularly in China. In the Sustainable Development Scenario, industrial coal consumption is estimated to be 844 Mton. Hydrochar can provide a great opportunity to replace fossil coal as it offers a carbon-designed adapted chemical composition to the customer needs, CO_2 free (carbon neutral) and available in the local market.

Table 1. Hydrochar average chemical composition and properties. daf: dry and ash free; db:dry basis

C (% daf)	H (% daf)	N (% daf)	S (% daf)	Moisture (%)	Ash (% dry)	Volatile (% db)	Fixed C (% db)
60	6	1.5	0.1-0.3	<9	>10	65	25

The table below (Table 2) shows the industrial analysis of pulverized coal comparing the hydrochar with different types of coal[i4].

All the reported hydrochar examples showed beneficial characteristics for usage in blast furnace (BFs), like a low sulphur content, which increases the quality of pig iron and steel, a low ignition point, and a good flammability. Some critical aspects have been identified in the ash content, ranging from 6 % of orange peel hydrochar, to 13% of green waste hydrochar, and grindability, lower than 60 for organic waste hydrochar. Grindability, ash content and ash melting point have been identified to be critical aspects. Orange peel hydrochar have been identified as the highest quality material, capable to increasing the steel quality if mixed with fossil coal. The mixing approach of hydrochar and fossil coal is representing an attractive opportunity for the application of HTC to the steel sector. The process allows to produce bio-coal by using different types of residues at the same time and at different percentages, so that the content of ashes can be controlled whether by mixing the original feedstocks or the hydrochar produced from different feedstocks. A 100 % replacement of pulverized fossil coal

[1] IEA (2019), World Energy Outlook 2019, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2019

[2] Eurostat, Municipal Waste 2008

[3] IEA (2019), World Energy Outlook 2019, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2019

[4] 4 EUBCE 2018 Evaluation of utilising Ingelia hydrochar produced from organic residues for Blast Furnaces Injection

in blast furnaces could be achievable only upgrading the Ingelia bio-coal into a material with higher fixed C content, e.g. by slow pyrolysis.

Table 2. EUBCE 2018 Evaluation of utilising Ingelia hydrochar produced from organic residues for Blast Furnaces Injection

Sample	C (% db)	H (db %)	N (db %)	S (db %)	Moisture (db %)	Volatile (% db)	Ash (% db)	Fixed C (% dry)	O (% db)
Lingyuan anthracite	77.38	3.61	0.86	0.90	0.84	13.21	15.02	70.93	1.35
Shenhua bituminous coal	65.12	4.05	0.92	0.34	5.05	35.88	8.58	49.49	15.94
Hydrochar from green waste	50.94	4.95	1.43	0.38	2.58	57.82	15.97	23.63	23.75
Hydrochar from organic fraction	58.61	6.72	2.24	0.31	2.11	68.76	12.88	16.25	17.13
Hydrochar from orange peel	58.06	5.08	1.56	0.166	3.51	59.66	6.18	30.65	25.45

Energy facilities and industries from different sectors have shown interest in using hydrochar as raw material for substituting coal or as biofuel in the energy sector. However, the average ash and volatile carbon content (Table 1) needs to be reduced in order to increase the quality of the final product. Research and trials carried out by Ingelia showed that it is possible to transform the hydrochar into a high-quality carbon-based material, similar to coking coal (classified as a critical raw material according to the 2020 CRM list of EC[5]), by applying post-treatment to the hydrochar for ash separation and thermal treatment to increase the fixed carbon content.

A by-product of the HTC process is a liquid biofertilizer, containing soluble alkali elements and highly assimilable nutrients. Research carried out in cooperation with IVIA (the public Institute for Agricultural Research in Valencia, Spain) and technology institute AINIA (Valencia, Spain), showed that the HTC liquid phase can be considered as an enriched effluent increasing plant growth, acting as a biofertilizer or for feeding Anaerobic Digestion (AD) plants, generating biogas. Due to the HTC process conditions, this liquid biofertilizer is free from microorganism or bacteria. Heavy metals present in the feedstock are retained in the hydrochar. After some enrichment steps, a suitable concentration of nutrients can be achieved, and the liquid phase represents a potential commercial biofertilizer.

WASTE SOURCE AND LOGISTICS

Heterogeneous waste streams with a high moisture content can be difficult to store and manage without a specific treatment. In addition, decomposition or fermentation generates CO_2 and CH_4 emissions into the atmosphere. HTC provides a solution for converting these waste streams into stable and valuable products. Many kinds of organic waste streams can be used in the HTC process to produce bio-carbon and biofertilizers. As an example, waste streams shown in Figure 1 have been tested at Ingelia industrial plant. HTC can be also a solution for biowaste streams with high content of plastics (up to -15 % on dry base) that cannot undergo composting.

[5] https://ec.europa.eu/docsroom/documents/42849

Figure 1. Waste feedstocks used in the Ingelia HTC process. From left to right: compost out of specification (30% wt. moisture); green waste (50% wt. moisture) and digestate (85% wt. moisture).

The waste stream valorised through the HTC process can vary in moisture content and/or heterogeneity both in particle size and composition (particle size with up to 10 cm is possible to be introduced in the HTC process). Waste streams with up to 88% humidity content have been tested successfully. HTC avoids landfilling of organic waste which often have associated long distance transportation. Results of some trials performed in Ingelia's HTC industrial plant that have been presented in conferences in this topic are presented below:

1. HTC 2017 (Queen Mary University of London)[6]

An industrial trial to recover hydrochar from biowaste was presented in 2017 in London at the HTC international conference. A biowaste with 75 % moisture content was transformed into a 4 % moisture hydrochar. The thermal energy consumption of the process was 2.2 GJ/ton of waste (dry) and the electricity consumption was 148 KWh/ton of waste (dry) (Figure 2).

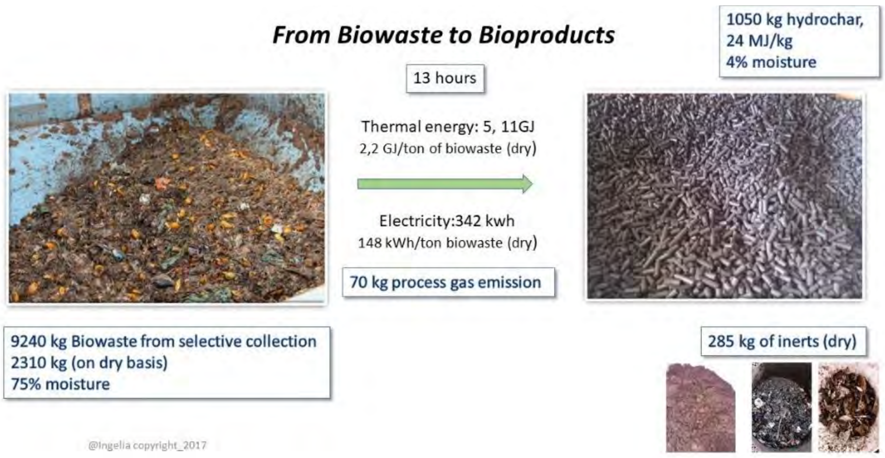

Figure 2. From biowaste to hydrochar - Example of a trial

2. VDI Conference 2017 in Copenhagen[7]

An industrial trial with sewage sludge (80 % moisture content) was presented in 2017 in

[6] https://www.sems.qmul.ac.uk/events/htc2017/programme/
[7] https://www.vdi-wissensforum.de/

Copenhagen at the VDI International Conference. 624 kg of hydrochar were obtained from 9 000kg of sewage sludge with thermal energy consumption of 1.6 GJ/ton of sludge (Figure 3).

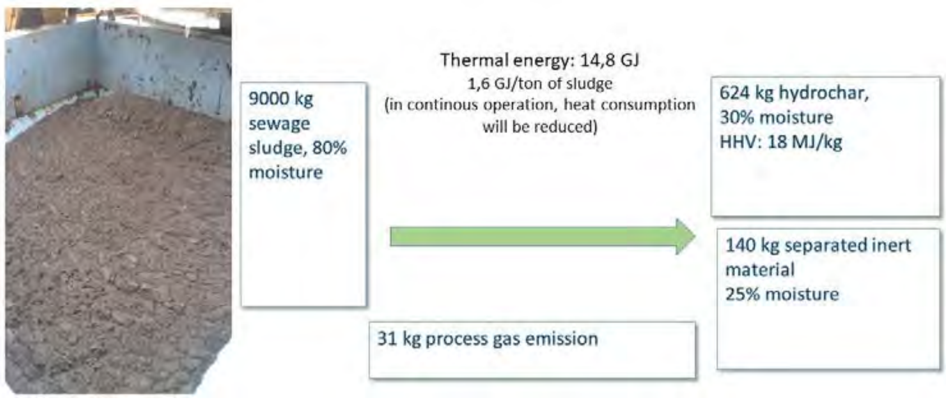

Figure 3. From Sewage sludge to biocharmaterials

3. Jernkontoret 2019 (Stockholm)[8]

A trial using paper sludge as feedstock was performed in Ingelia´s plant in 2019 with the following comparison between hydrochar and paper sludge:

Figure 4. From paper sludge to hydrochar

Table 3. Comparison of the composition of the paper sludge used as feedstock and the char obtained in a trial performed at Ingelia in 2019. Db: dry basis; daf: dry and ash free.

	Moisture (%)	Volatile (% db)	Volatile (% db)	Fixed C (% db)	C (% daf)	S (% daf)
Paper sludge	68.8	64.9	23.1	12	55.3	0.22
Ingelia char	7.5	66.5	16.4	17.1	64.4	0.29

[8] https://www.swerim.se/en/calendar/a-fossil-free-society-what-role-can-the-industrial-symbiosis-play

Due to the speed of the HTC processes and the modularity of Ingelia's process, the plants are upscaled by increasing the number of reactors and they can be installed close to the waste source without odour problems. CO_2 emissions are reduced due to shorter transports of waste, and fossil coal, avoidance of methane emissions and carbon recovery from waste. Following the recommendations of the IPCC (Intergovernmental Panel on Climate Change) for the calculation of CO_2, total $CO_{2\text{-eq}}$ avoided emissions per ton of hydrochar due to activities related to coal mining, waste landfilled, and fossil fuel substitution are estimated to be from 6.5 to 8.4 tons of $CO_{2\text{-eq}}$/ ton of hydrochar.

TECHNICAL ASPECTS

HTC process represents a solution for the valorisation of biowaste streams, while generating a carbon-based solid fraction, hydrochar, that can be used as an energy source, a soil ameliorant, or as a feedstock to produce bioproducts. The hydrochar is produced at low temperatures (200—230 ºC) and moderate pressure (20—30 bar) in subcritical water conditions from a wide range of organic residuals. During the HTC process the carbon content concentrates over 60 % (dry and free of ash) in solid products. The residual is transformed into aqueous phase containing the soluble elements. Since the process temperature is around 200 ºC, no problematic compounds are formed in during the process.

Prior to the HTC treatment, the feedstock needs to be grinded and passed through a trommel to remove materials larger than 8 cm. It is also convenient to install a metal separator to avoid large metal parts reaching the process. Another convenient pre-treatment would be the separation of stones and other hard materials that can cause abrasion and equipment degradation.

Figure 5. Ingelia HTC plant

By means of post-treatment processes, small pieces of glass, stones, metals, and other inert materials that have passed through the process are separated. The separation of inert in the post-treatment is done in liquid phase. The ash content in the final solid product obtained in the tests carried out by Ingelia is > 10 %, and the moisture content < 9 %. According to these results, the hydrochar is suitable for combustion in industrial boilers and for biobased raw materials, substituting coal for the industries. Industrial boilers usually have ash extraction facilities and particle separation cyclones.

Recent combustion tests using hydrochar as biofuel have been carried out in industrial boilers with satisfactory results in terms of emissions, without slag formation and with high performance and combustion stability. The use of hydrochar as biofuel supports the substitution of fossil fuels and the reduction of the impact from the emissions derived from the transport of the HTC feedstocks. However, as circular economy principles become more embedded, the 'linear' pathways of combustion for power generation are being superseded by the desire to use waste streams as manufacturing and other feedstocks. Hydrochar, therefore, in addition to be used as biofuel, is gaining more interest as a feedstock for gasification and manufacture of bioproducts, absorbents, soil amendments.

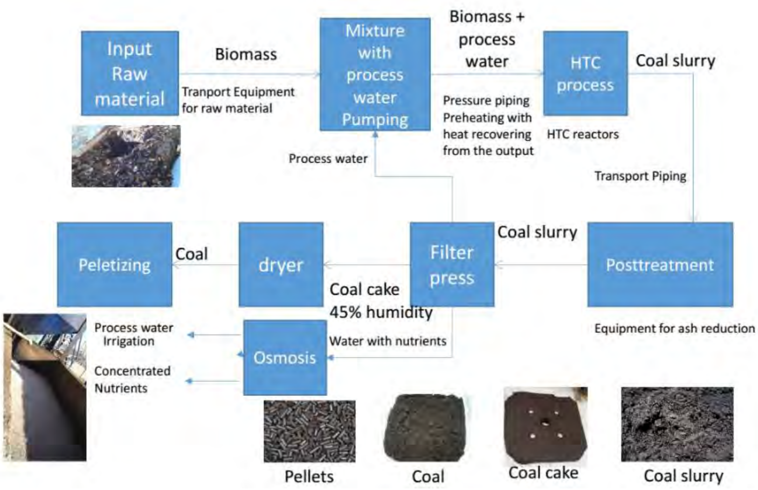

Figure 6. Ingelia HTC Technology flow diagram

In case of heavy metals in the feedstock, they remain mainly in the ash of the hydrochar. That is the case for phosphorus (another critical raw material) that can be extracted by acid leaching techniques, reducing the ash content, and generating an additional raw material for market applications.

The organic content of the excess liquid phase can be easily used as a feed for biogas production by anaerobic digestion, before being discharged. The option of recovering fertilizers from process water, especially potassium and nitrogen, can also be a possible alternative. As the process takes place at low temperature, no nitrogenated aromatics are formed.

Figure 7. Hydrochar obtained in the HTC Ingelia process

An advantage of using HTC process compared to other small scale waste handling processes is the significant decrease in odours and the amount of air that needs to be treated. Once the biomass has entered in the pumping system, the emissions are minimal and easy to manage. Since the HTC process takes place in liquid, only the thermal drying step, included in the post-treatment, implies an air flow that requires a particle removal treatment.

The economic feasibility of the HTC process with organic fraction is obtained by a combination between the biowaste gate fee and the sale of the solid bioproduct obtained.

ECONOMIC ASPECTS

The cost for an HTC plant with treatment capacity of 78 000 tons/year of biowaste (70 % moisture ctent) and production of 15 400 tons/year of hydrochar is shown in the table below. The investment includes a turnkey HTC plant and the post-treatment units. Assuming a market price for the hydrochar of 180 €/ton and tipping fee of 50 €/ton, the project Internal rate of return (IRR) is 18.7%, CAPEX: 351 €/ton of waste; OPEX: 20 €/ton of waste, which is in the range of market drivers.

Since the plant is modular, the treatment capacity can be adapted to the feedstock availability or the needs for local supply of hydrochar, reducing unnecessary transports of waste and products.

The plant can also be installed next to an AD plant or composting facilities providing a solution for the organic residues (digestate or off-spec compost) generated from these processes. In addition, the process water could be reutilized to feed the AD process.

Table 4. Summary of the economic aspects of a Ingela HTC plant

HTC Plant for organic waste 70 % moisture	
Size	10 reactors
Area	5 600 m^2
Investment	27 343 800 €
Wet feedstock processed	78 000 ton/year
Hydrochar produced	15 378 ton/year
Liquid fertilized produced	47 720 m^3/year
Operating costs	
Operating Costs	1 540 505 €/year
O&M	1 269 454 €/year
Technical Service	218 750 €/year
General Expenses	52 300 €/year
Incomes	
Hydrochar sales	6 668 126 €/year
Tipping fee for waste	2 768126 €/year
EBITDA	5 127 622 €/year
Simple Payback	5.3 years

ENVIRONMENTAL ASPECTS

HTC processes take place in a water solution. As the reaction is exothermic, low thermal energy is required and the process is very flexible admitting a wide range of feedstocks regardless of humidity and heterogeneity.

By recovering carbon molecules from organic wastes and sludges, a reduction of methane emissions that, otherwise, would occur during decomposition in landfill is realized. In addition, when the hydrochar replaces fossil coal, the emissions associated with coal use as well as coal mining activities are avoided. Estimations on global emissions of coal mine methane (CMM) were around 40 Mton in 2018, equal to around 1 200 Mton of CO_2-eq. In 2018 the global coal production was 5 566 Mton. Based on these figures, it can be assumed that 0.22 ton CO_2-eq/ton coal were emitted due to liberation of methane contained in coal seams (mining emissions).

Following the World Bank report on waste management, 1.6 billion tons CO_2-eq greenhouse gas emissions were generated from solid waste treatment and disposal in 2016[9]. This is driven primarily by disposing of waste in open dumps and landfills without and without landfill gas collection systems. Food waste accounts for nearly 50% of emissions. Almost 2 billion tons of waste were generated in 2016, of which 44 % was food and green waste. 800 Mtons of CO_2-eq emissions are attributable to landfilling of 887.5 Mtons of waste, which means that approximately the disposal of one ton of waste is responsible for 0,9 tons of CO_2-eq emissions. The conversion ratio from waste to hydrochar, assuming 70 % of humidity in the waste, is 0.18 tons of hydrochar/ton of waste, so that we can calculate that 4.9 ton of CO_2-eq are avoided in non-controlled landfills per ton of hydrochar produced.

Methane emissions from organic waste when deposited in controlled landfills as in most cases in Europe are estimated following the method from the IPCC report[10]. Methane emissions depend on several factors: the waste composition, the management method, and climatic conditions.

The CO_2-eq avoided emissions due to activities related to coal mining, waste landfilled, and fossil fuel substitution are estimated in the table below.

Table 5. CO_2-eq avoided emissions

CO_2-eq avoided emissions	
Average humidity of waste	70 %
Hydorchar produced	0.18 ton/year
CO_2-eq avoided	6.54 – 8.32 CO_2-eq ton/year

The use of the process water for replacement of chemical fertilizers (NP and NPK) will have a positive impact in the CO_2 calculations as well as a reduction of methane consumption for their production. According to the EC report "*Fertilizers in EU*" dated June 2019, producing 1 ton of UREA takes 696 Nm^3 of Methane. However, to make an exact calculation of the impact on the emissions, a life cycle assessment is foreseen with specific assumptions for each project.

[9] World Bank report on waste management
[10] https://www.ipcc-nggip.iges.or.jp/public/gp/bgp/5_1_CH4_Solid_Waste.pdf

POLICY ASPECTS

The following EU policies support the construction of HTC Plants:

- EU Circular Economy Action Plan[11]
- Waste framework directive[12]
- Waste landfilling
- Sewage Sludge directive 86/278/EEC
- EU climate action[13]

Ingelia has worked hard to certify and standardize the hydrochar according to EU legislation. So far, the hydrochar from green waste, agricultural waste and food waste has been included in the Technical Specification of ISO 17225-8[14]. Currently, national standardization bodies are working on it for it to be adopted in different countries. Also the Joint Research Centre, based on the work of the Strubias group, on Sept.2019 made a publication titled "*Technical proposals for selected new fertilising materials under the Fertilising Products Regulation (Regulation (EU) 2019/1009*" *where HTC process and hydrochar have been requested to be added respectively, as permitted core process and new component material category (CMC ZZ (pyrolysis & gasification materials)), also opening the possibility to use sewage sludge as input (new Product Function Categories (*PFCs*) of* EU *fertilising products).*

Additionally, Ingelia has already initiated the REACH procedure with the European Chemical Agency, to ensure a safe product for commercialization. In Italy, Ingelia obtained positive feedback from the Environment Protection Agency, demonstrating that the HTC plant capacity to turn organic wastes and sludges into hydrochar, usable for different scopes, such as energy or soil conditioning. Two plants are in operation with biowaste as feedstock, one in Spain and one in the UK and a third plant is under construction in Belgium with biowaste as feedstock.

SOCIAL ASPECTS

Besides enabling energy and carbon recovery from wastes there are further advantages derived from the HTC process:

- Water is also generated in the HTC process originating from the biowaste humidity. After the micro- and nanofiltration process a liquid fertilizer is generated that potentially could be reused for agriculture.
- Fertilizer companies will reduce their CO_2 emissions by incorporating the biofertilizers produced in the plants, so that an improved ecosystem will be created around each project.
- Job creation for plants operation will be created. Around 8 people are required to operate a plant of 10 reactors.

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[11] https://ec.europa.eu/environment/circular-economy/pdf/new_circular_economy_action_plan.pdf
[12] https://ec.europa.eu/environment/waste/framework/
[13] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015PC0594 and https://ec.europa.eu/clima/policies/eu-climate-action_en

[14] https://www.iso.org/standard/71915.html

- A beneficial impact on the local economy will be created around the plants' location, due to supply of materials, spare parts and maintenance.

LIFE CYCLE ASSESSMENT

Description of the case study

The aim of this task was to carry out a life cycle assessment (LCA) to assess the environmental impacts of a large-scale HTC plant for conversion of biowaste and sludge (i.e., green waste, food waste, organic fraction of MSW, and digestate) to high quality hydrochar in Italy. The processing capacity of this plant was assumed to process 78 000 ton of wet biowaste per year. The LCA results are intended to identify the environmental impacts/benefits of different biowaste based hydrochar pellets at a large-scale plant in Italy. This LCA study was carried out in accordance with ISO Standards[15,16], and has been internally reviewed. The details of the study, results and conclusions are outlined in the following sections.

Goal and Scope

The functional unit (FU) is defined as one ton of dry biowaste treated by the HTC plant. The selection of this FU in line with other published LCA studies on waste management[17,18], and allows comparison with other waste management processes. The potential environmental impacts are expressed according to this unit.

The specification of the geographical boundaries is an important aspect in LCA as location can influence factors such as biowaste composition, technology type (including waste recovery), and the electricity gid mix. This LCA analysis is based on Italy where possible. The scope of the study is limited to the HTC plant and assumed to be located near to the AD or composting facilities to avoid unnecessary transport of feedstock. Moreover, providing a solution for the reutilisation of digestate and water within the process.

Description of the system studied

The study represents a 'gate-to-gate' LCA and as such the system boundary includes processes from raw material pumping to the operation of the HTC to disposal of waste stream. The aspects of the life cycle considered are resource extraction (for all materials and energy inputs) and operation of the HTC plant. The HTC process includes pumping of feedstock into the reactor, drying and pelletizing, and disposal of post treated ash and treated water. It is important to note that the analysis does not consider upstream impacts from the production of feedstock, hence the 'zero burden assumption' is used which suggests that the waste carries none of the upstream burdens into the waste treatment site. This approach is in line with other published studies which assess the

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[15] ISO, *ISO 14040:2006 - Environmental management - life cycle assessment - principles and framework. 2006.*
[16] ISO, *ISO 14044:2006 - Environmental management - Life cycle assessment - requirements and guidelines. 2006.*
[17] Cherubini, F., S. Bargigli, and S. Ulgiati, *Life cycle assessment (LCA) of waste management strategies: landfilling, sorting plant and incineration.* Energy, 2009. 34(12): p. 2116-2123.
[18] Owsianiak, M., Ryberg, M.W., Renz, M., Hitzl, M. and Hauschild, M.Z., 2016, *Environmental performance of hydrothermal carbonization of four wet biomass wase streams at industry-relevant scales.* ACS Sustainable Chemistry & Engineering, 4(12), pp: 6783-6791.

environmental impacts of waste management systems[18,19,20]. The products of the HTC plant are hydrochar pellets, process waste (treated and reused) and ash (landfilled). The system boundary is shown in Figure 8.

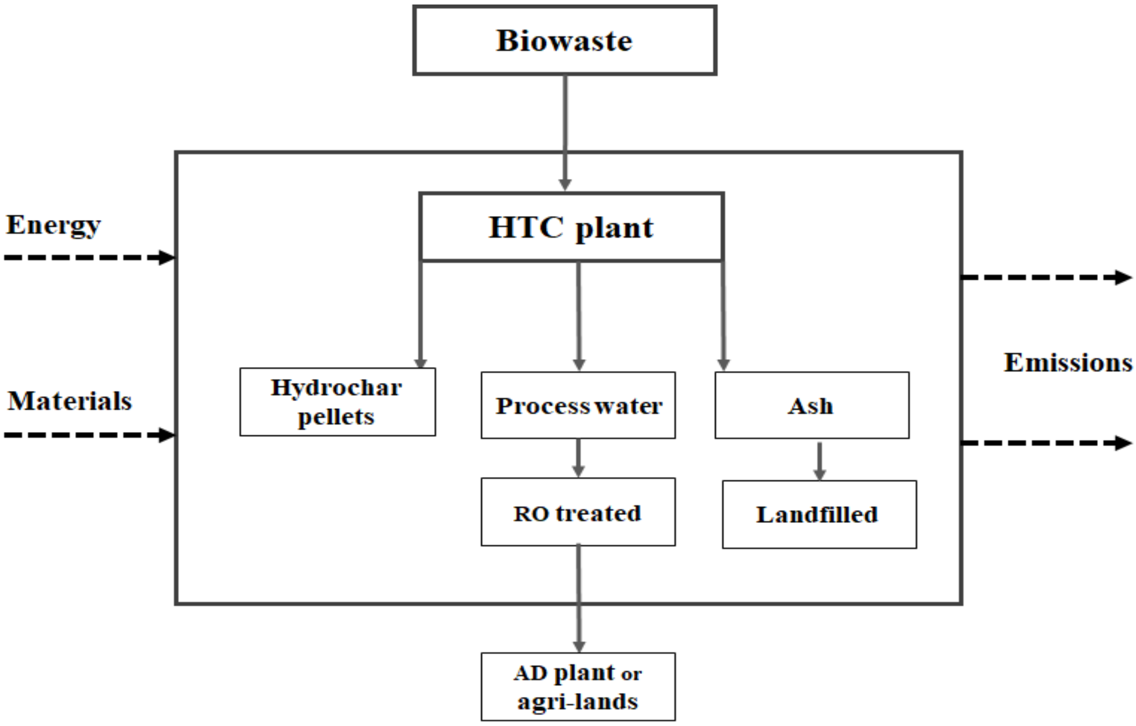

Figure 8. System Diagram

Life Cycle Inventory

The Life Cycle Inventory (LCI) consists of the data collection associated with the different process stages. The data inventory compiled for this LCA study consists mainly of data specific mostly to Italy. When specific data were not available, data were based on average European data. Foreground data for the HTC was adopted from Owsianiak et al[21] and scaled to the industrial level and represented in Table 6. Life Cycle Inventory per functional unit (one ton of biowaste). Electricity production in Italy was obtained from Ecoinvent data which contains data on the electrical grid fuel mix from 2017[22]. The thermal energy production and use in the study was considered at an industrial scale using the

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[19] Eriksson, O., et al., *Municipal solid waste management from a systems perspective.* Journal of Cleaner Productions, 20005. 13(3): p. 241-252.
[20] Fruergaard, T., T. Astrupo, and T. Ekvall, *Energy use and recovery in waste management and implications for accounting of greenhouse gases and global warming contributions.* Waste Management & Research, 2009. 27(8): p. 724-737.
[21] Owsianiak, M., Ryberg, M.W., Renz, M., Hitzl, M. and Hauschild, M.Z., 2016. *Environmental performance of hydrothermal carbonization of four wet biomass waste streams at industry-relevant scales.* ACS Sustainable Chemistry & Engineering, 4(12), pp.6783-6791.
[22] Ecoinvent, T., T. Astrup, and T. Ekvall, *Energy use and recovery in waste management and implications for accounting of greenhouse gasses and global warming contributions*. Waste Management & Research, 2009. 27(8): p. 724-737.

feedstock softwood chips from forest burned in a furnace of 1,000 kW capacity with Europe as geographical location. Reverse osmosis (RO) data set (global) with 8-inches spiral wound modules SW30HR-380 and 35.3 m^2 of active surface per module was used in the analysis for process water treatment and obtained from the Ecoinvent database[20]. The ash landfilling was analysed using dataset "process-specific burdens, residual material landfill" available in the Coinvents database. This process considers inorganic landfill for polluted inorganic wastes with carbon content below 5 %.

Table 6. Life Cycle Inventory per functional unit (one ton of biowaste)[23]

Inputs & Outputs	Units	Green Waste	Food Waste	Organic fraction of MSW	Digestate
Inputs					
Waste	ton dw	1	1	1	1
Moisture content	%	45	84	34	59
Electricity for pumping	kWh	0.003	0.003	0.003	0.003
Thermal Energy	kWh	611.1	611.1	611.1	611.1
Electricity for drying & pelletizing	kWh	40	40	40	40
Electricity for reverse osmosis	kWh	0.540	0.370	0.620	0.560
Outputs					
Raw hydrochar	ton dw	0.590	0.370	0.720	0.560
Cleaned hydrochar pellets	ton dw	0.54	0.37	0.62	0.56
Process waster	ton	0.5597	0.8543	0.4714	0.6678
Ash	ton	0-0703	0.0179	0.1011	0.0597
N in waste stream	ton	0.0011	0.0017	0.0008	0.0013
P in waste stream	ton	0.0001	0.0001	0	0.0001
Inputs & Outputs	Units	Green Waste	Food Waste	Organic fraction of MSW	Digestate
K in waste stream	ton	0.0002	0.0008	0.0005	0.0009
Carbon dioxide (CO_2)	ton	0.0624	0.0434	0.0257	0.0118
Carbon monoxide (CO)	ton	0	0.0006	0.0004	0.0006
Hydrogen (H_2)	ton	0	0.0001	0.0009	0

[23] Owsianiak, M., Ryberg, M.W., Renz, M., Hitzl, M. and Hauschild, M.Z., 2016. *Environmental performance of hydrothermal carbonization of four wet biomass waste streams at industry-relevant scales.* ACS Sustainable Chemistry & Engineering, 4(12), pp.6783-6791.

Life Cycle Impact Assessment

Environmental impacts considered include terrestrial acidification (TA) expressed in kg SO_2-equivalents, freshwater eutrophication (EP) expressed in kg PO4-equivalents, and global warming potential (GWP) expressed in kg CO_2-equivalents. ReCiPe 2016 Midpoint (H) methodology[24] was used in characterising the environmental impacts.

Results

Table 7. Life cycle impacts for processing of 1 ton of biowaste to hydrocar pellets shows the results of the impact assessment for different biowaste conversion to hydrocar at an HTC plant with 78 000 ton per annum capacity. The table shows the impacts per ton of biowaste treated, with major contributing factors (CO2/phosphates, electricity, and thermal energy) highlighted across the study. HTC of 1 ton of biowaste causes total global warming (GW) emissions in the range of 73 to 110 kg CO_2-eq, acidifying emissions of 0.355 to 0.511 kg SO_2-eq, and eutrophying emissions of 0.020 to 0.102 kg P-eq. With highest global warming (GW), freshwater eutrophication (FE) and terrestrial acidification (TA) for treating green waste (110.4 kg CO_2-eq), food waste (0.102 kg P-eq) and digestate (0.511 kg SO_2-eq), respectively. The higher GW, FE and TE values within the study were mainly due to the higher levels of CO2 released in the process and the presence of organic contents in the waste streams. The higher NPK contents in the waste streams of green, food waste and digestate waste makes it nutritionally rich process and leading to higher eutrophication emissions. The electricity usage is the prime contributor to GW in for MSW and digestate feedstocks. The terrestrial acidification (TA) across all the processes was mainly due to emissions involved in the resource extraction and production of electricity and heat.

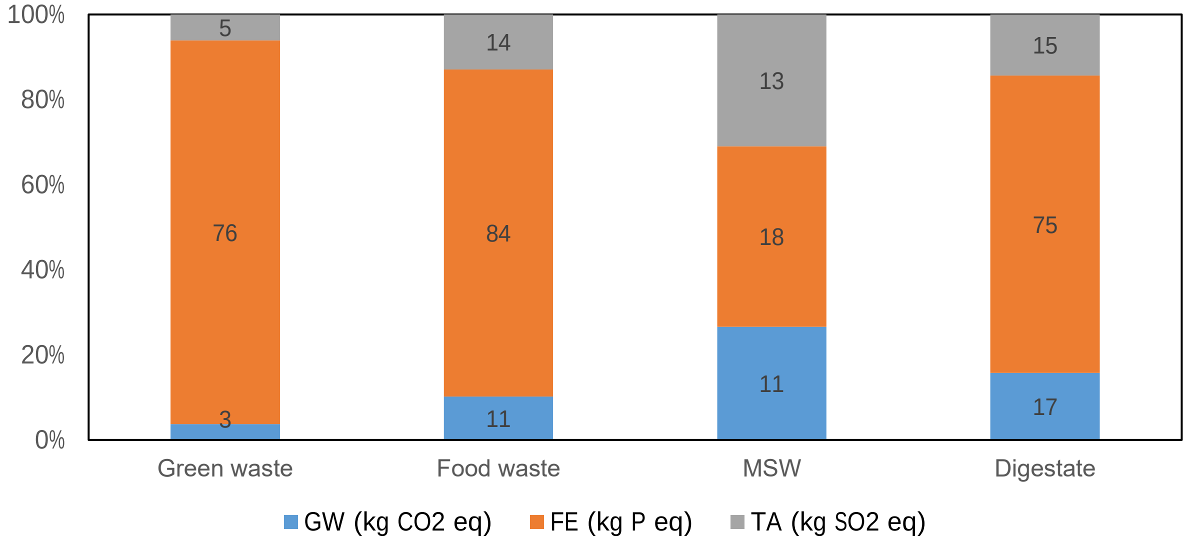

Figure 9. Avoided emissions by reusing the wastewater stream for agri-land

Table 7 shows that freshwater eutrophication (FE) is highly affected in all the waste conversion

[24] Huijbregts, M.A., Steinmann, Z.J., Elshout, P.M., Stam, G., Verones, F., Vieria, M., Zijp, M., Hollander, A. and van Zelm, R., 2017. *ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level.* The International Journal of Life Cycle Assessment, 22(2), pp. 138-147.

processes except MSW, where all three impacts were almost equally avoided. Reusing the process water, and displacement of NPK-based fertilisers in the field would reduce the eutrophication emissions in the current process significantly, ranging from a 17.62 to 76.10% reduction depending on the feedstocks. The higher range of avoided FE emissions can be attributed to the presence of nutritionally rich (NPK contents) in the process water stream (Table 1). Whereas GW and TA impacts are reduced to a lesser extent, however, have a more significant impact in the HTC process with MSW as feedstock.

Table 8 demonstrates the comparative impacts associated with HTC technology utilising different resources across various geographical locations. The aim of this comparative analysis was to ascertain the impacts of HTC technology if it was operating in different parts of the world. It is evident in Table 7 that energy consumption esp. electricity is one of the major contributing elements that can be linked directly to the impacts of the system. Therefore, considering the average electricity grid mix from different countries would provide an estimation of emissions that would facilitate the stakeholders to strategically plan the establishment of HTC plant in future in a particular location or country by keeping environmental sustainability in mind.

The LCA analysis revealed that the GWP and TA were higher for the HTC technology when South Africa (SA) is the place of operation, whereas FE was higher in case of Australia (AU). Higher GWP and TA can be attributed to the source of production of electricity in SA i.e., primarily coal which accounts for 88.8% of the total electricity produced in the country. Whereas FE was dominating in AU electricity grid mix due to its higher phosphate emissions (68 times) involved in electricity production than SA based electricity. However, Norway (NO) was found to be best in terms of impacts as the primary energy for electricity production is 98% renewable leading to lower emissions in comparison to other countries fossil dominating electricity production Moreover the hierarchy of the impacts with respective to the countries analysed i.e., from higher to lower values is also shown in the bottom of the Table 8.

Table 7. Life cycle impacts for processing of 1 ton of biowaste to hydrocar pellets

Biowaste	Green Waste				MSW					
Impacts	CO_2/phosphates	Electricity	Thermal Energy	Total	Impacts	CO_2/phosphates	Electricity	Thermal Energy	Total	
GWP (kg CO_2-eq)	62.436	37.94	9.81	110.44	GWP (kg CO_2-eq)	25.68	37.79	9.82	73.61	
FE (kg P-eq)	0.05461	0.01	0.0038	0.073	FE (kg P-eq)	0.0018	0.0145	0.0038	0.0202	
TA (kg SO_2-eq)	----	0.18	0.17	0.356	TA (kg SO_2-eq)	----	0.18	0.172	0.35	
Biowaste	Food Waste				Digestate					
Impacts	CO_2/phosphates	Electricity	Thermal Energy	Total	Impacts	CO_2/phosphates	Electricity	Thermal Energy	Total	
GWP (kg CO_2-eq)	43.45	40.10	9.82	93.87	GWP (kg CO_2-eq)	11.80	54.68	14.12	80.87	
FE (kg P-eq)	0.083	0.015	0.0038	0.10	FE (kg P-eq)	0.065	0.021	0.0055	0.092	
TA (kg SO_2-eq)	----	0.19	0.172	0.36	TA (kg SO_2-eq)	----	0.26	0.248	0.511	
Impact category	Unit	Incineration	Sodium hydroxide	Quicklime	Chemicals organic	Chemicals inorganic	Light fuel oil	Electricity	Incineration on plant	Residues Disposal	Total
Global warming	kg CO_2-eq	917.46	6.47	15.22	2.63	3.09	3.68	36.48	3.42	1.15	989.59
Acidification	kg SO_2-eq	0.69	0.03	0.01	0.01	0.03	0.01	0.08	0.01	0.01	0.87
Eutrophication	kg PO_4-eq	0.11	0.02	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.16

Table 8. Environmental impacts of HTC system with different source feedstock and across various geographical locations

Impacts	Global warming potential (GWP kg CO_2 eq)				Fresh water eutrophication (FE, kg P eq)				Terrestrial Acidification (TA, kg SO_2 eq)			
Waste	*Green waste*	*Food waste*	*MWS*	*Digestate*	*Green waste*	*Food waste*	*MWS*	*Digestate*	*Green waste*	*Food waste*	*MWS*	*Digestate*
Country												
Italy (IT)	110.444	93.87	73.61	80.87	0.073	0.102	0.020	0.092	0.356	0.36	0.35	0.51
Ireland (IE)	124.039	108.23	87.14	100.47	0.017	0.018	0.017	0.025	0.34	0.36	0.34	0.49
South Africa (SA)	187.623	174.90	150.53	192.07	0.084	0.088	0.083	0.12	1.21	1.27	1.21	1.74
Australia (AU)	170.771	157.09	133.75	167.78	0.15	0.16	0.152	0.22	0.49	0.50	0.49	0.70
Norway (NO)	75.551	56.99	38.85	30.58	0.0061	0.0062	0.0061	0.0088	0.18	0.18	0.18	0.26
Sweden (SE)	77.231	58.77	40.52	33.01	0.0073	0.0075	0.0073	0.011	0.195	0.19	0.19	0.28
United states (US)	146.114	131.02	109.18	132.24	0.0771	0.081	0.077	0.11	0.366	0.37	0.36	0.52
GWP: *SA>AU>US>IE>IT>SE>NO*; FE: *AU>SA>US>IT>IE>SE>NO;* TE: *SA>AU>US>IT>IE>SE>NO*												

LESSONS LEARNED / RECOMMENDATIONS

HTC process offers a unique way to recover materials from organic wastes and sludges which are otherwise difficult and expensive to be valorised. This novel technology has been developed at industrial scale during the last 10 years and represents a very stable and simple process which simulates an accelerated process similar to the natural formation of coal. The products generated within the HTC plants can be adapted to the industry's requirements by applying further post-treatments enabling the industries to substitute fossil coal, reducing the CO_2 emissions and encouraging circular economy.

Environmental authorisations for HTC plants should be as simple as possible in order to shorten the time to market of this new and interesting process to valorise organic waste. A coordinating group of experts could give general advice to public administrations in order to simplify the procedures.

ATTACHMENT 5

New technological applications for wet biomass waste stream products

Reporting

Project Information

NEWAPP

Grant agreement ID: 605178

Closed project

Start date
1 November 2013

End date
30 April 2016

Funded under
FP7-SME

Overall budget
€ 2 580 061,78

EU contribution
€ 1 756 000

Coordinated by
EUROPEAN BIOMASS INDUSTRY ASSOCIATION
Belgium

Final Report Summary - NEWAPP (New technological applications for wet biomass waste stream products)

Executive Summary:
1. Executive summary (1 page)
Approximately 120 to 140 million tonnes of bio-waste are produced every year in the EU [1]. This corresponds to almost 300kg of bio-waste produced per EU citizen per year. From these, a substantial amount is organic waste. These, also called wet biomass waste streams, (i.e. wet agricultural residues, wet municipal waste such as foliage, grass or food waste), are abundantly available in Europe, while their disposal and recycling becomes increasingly difficult as energy efficient, environmentally sound and economically viable processes hardly exist.
NEWAPP aims at developing an alternative cost- and resource-efficient and environmentally sound way of dealing with wet biomass waste through HTC technology.

The existing treatment methods for these streams are mainly incineration or landfilling, 67% of the waste is disposed of in these ways. A small amount is composted, digested anaerobically or used as animal fodder. However, the most used methods are not the best: landfilling not only takes up more and more valuable land space, it also causes air, water and soil pollution, discharging carbon dioxide (CO_2) and methane (CH_4) into the atmosphere and chemicals and pesticides into the earth and groundwater. This, in turn, is harmful to human health, as well as to environment.
In parallel to the growing amount of biowaste there is a fast growing demand for new raw materials worldwide. Applications such as chemical separation, water purification, catalysis, energy conversion and storage, bio imaging, fertilization and soil remediation and fuels are based on high value products and secondary raw materials demanded by our current technological growth and society. These products have several aspects in common: they are scarce, expensive, located in very concrete regions of the world and carbon based. The concept behind NEWAPP is that wet biomass can be a resource more than a waste, and does not need to be disposed of in the costly and inefficient way it is nowadays. The alternative, which NEWAPP introduces, is to create a continuous system which will allow to recover carbon in an energy efficient for tailor made HTC (Hydrothermal carbonization) products way. NEWAPP will focus on green waste, agricultural waste, municipal solid waste, waste from food processing industry and waste from markets for running the HTC process and exploring the possibility to obtain high-value carbon products. NEWAPP will gather international researchers, industrial associations and SME's from different European countries in its thirty months lifecycle to assess the requirements and constraints of SME-AGs in the reuse of wet biomass with HTC, analyse the potentials of the different wet biomass streams for using them for HTC, perform intensive testing with this innovative system technology for heat recovery and efficiency for tailor made HTC products launch a standardization process for the two most promising waste streams to prove their viability for commercial applications.
Project Context and Objectives:
HTC consists in applying high temperatures and pressures to biomass in the presence of water, which results in two main products: a coal-like product (hydrochar) and water-soluble products. This process allows converting different biomass streams, such as waste, into fuels and other substances of industrial interest.
There is a clear need to develop new technological pathways for reuse that are economically attractive and environmentally sound at the same time. Promising technologies such as hydrothermal carbonisation show high potentials but so far only very few commercial units have been present on the market. Up to now there have been some experiments done with municipal solid wastes at lab scale aiming to take and separate carbon in order to get high value products through the HTC process. Different products can be obtained from this process, such as active carbon, electrodes, fertilizers, etc. NEWAPP will focus on green waste, agricultural waste, municipal solid waste, waste from food processing industry and waste from markets for running the HTC process and exploring the possibility to obtain high-value carbon products. In 2011, EU-27 imported these products for a value of 22.666.570.073 €, while it exported for a value of 1.917.542.097 €, 12 times less. At the same time, EU generates yearly 80.000.000 tons of wet biowaste that can be effectively recycled to carbon materials by means of HTC. Based on this it can be concluded that EU industry has a need for carbon products, as fuel and as raw material.
This existing technology requires however, of several improvements in order to be ready to be used at the large scale as a reuse alternative for wet biomass. Pre- and post-treatment, are critical points for HTC, and pose questions not yet answered for a widespread implementation. The adequate mix of different kinds of wet biomass and the fine-tuning of the systems required for reaching high efficiencies are is still a

hindrance for HTC at the industrial scale.
NEWAPP has gathered international researchers, industrial associations and SME's from different European countries in its thirty months lifecycle to (1) assess the requirements and constraints of SME-AGs in the reuse of wet biomass with HTC, (2) analyse the potentials of the different wet biomass streams for using them for HTC, (3) perform intensive testing with this innovative system technology for heat recovery and efficiency for tailor made HTC products (4) launch a standardization process for the two most promising waste streams to prove their viability for commercial applications.
The developments in NEWAPP have targeted the upgrade of turning waste into new resources using HTC process and have paved the way to provide economically attractive and environmentally friendly alternatives to utilisation of wet biomass, allowing European SME-AGs to advise their SME members to use the optimal utilisation technologies for their specific needs. The companies from the biomass and waste sectors usually belong to at least one sector-specific association. It is from these that new technologies are introduced in the sector and standards and codes of practice are set. As NEWAPP aims at making a broad impact in these sectors, the scheme of research for SME Associations has been chosen by the three SME-AGs leading the consortium, two of them Europe-wide associations (EUBIA and ACR+) and one of them working at the national level (BSVE, Germany).
Increasing amounts of urban organic waste and farm organic residues are produced and often landfilled or burnt in Europe. The total annual amount of bio-waste in the EU is estimated at 76.5 - 102 Mt food and garden waste included in mixed municipal solid waste and up to 37 Mt from the food and drink industry. In addition, annually around 700 Mt of agriculture wastes are produced within the EU, which represents a high load for farmers due to the numerous problems they face handling them.
This consortium has aimed to combine the above and increase the amount of bio-waste diverted from landfill and burning into high value products that can be used as fuel, activated carbons for water treatment, soil remediation, carbon sequestration schemes and other applications. This requires the transformation of urban organic waste and farm organic waste from a costly disposal process into an income-generating activity.
In Europe there is a surplus of organic waste of municipal and agricultural origin. The material was, and in many countries still is, discarded in landfills or, for some agricultural wastes, burned in the field. Both practices are no longer acceptable in a modern European context and European targets for reduction have been set (EC, 2008).
Bio-waste is a putrescible, generally wet waste. There are two major streams – green waste from parks, gardens, and kitchen waste. The former includes usually 50-60% water and more wood (lignocelluloses and cellulose); the latter contains no wood but up to 80% water. Currently, the data collected under the Waste Statistics Regulation is not of sufficient detail on a country by country basis to relate to the definition of biowaste launched in COM(2008) 811 final (EC 2008, EC 2002). However, for the European Waste Code (EWC) for animal and vegetal wastes, which also includes manure and the like, European wide data is available.

Waste reduction initiatives have been active for the past decades, but their impact is not large enough to solve the waste disposal problem. In parallel, the demand for energy has increased in the EU-27 countries, as well as the need to use renewable energies. The EU has set a target of 20% of energy from renewable and an increase of 20% in energy efficiency by 2020, which will not be met only through brand new development (i.e. installation of solar fields). Taking existing resources, like waste, and using their potential achieves success faster while promoting innovation in already mature sectors. The impact of this innovation is much higher in terms of revenues and employment, because it strengthens the existing industrial fabric. NEWAPP is composed by national and international SME-AGs that acknowledge the potential of HTC treatment of wet biomass and its reuse for energy, and have the means to spread these innovations to a large number of SMEs at European level.

To achieve this, the consortium has focused on:
Developing a new technical utilisation pathway for turning biowaste into high value products. Hydrothermal carbonisation is a technology that already exists. However, a suitable solution for its up-scaling, energy consumption optimization or technology costs not yet been developed, despite the huge potential it represents. Additionally, the knowledge on what products can be obtained by what exact biowaste is very limited. The starting point of NEWAPP will be to address the existing technological barriers that these heterogeneous waste streams pose for our technologies and to assess the conditions that need to be met for the successful implementation of HTC.
Exploring what different products can be obtained from the selected waste streams after the HTC process. HTC carbon can be further upgraded to high-value materials by physical and/or chemical speratation methods for more sustainable applications than simply burning. By a purely thermal treatment it can be split into two parts – fixed carbon together with the inorganic matter and volatile part. Up to present the volatile part has not been separated and characterized. The fixed carbon together with the inorganic content is the lower value part that can be used for energy valorization or studied as fertilizer for crop plants. As the volatile part is ash-free and has a more homogeneous composition with a very low lignin derived content, its separation will be a possibility to obtain purified HTC material suitable for specialised applications.
Standardization. The results achieved will enable the partners to the first st of standards for HTC products to be distributed to through the participating SME-AGs to their members. The focus will be on achieving a large implementation, ensuring products with properly quantified relevant calorific value. The need to meet quality and safety standards will stimulate the waste management industry to improve the bio-waste treatment process and will thus lead to technological development. No coherent set of product norms dealing with sufficiently detailed end user needs and environmental and human safety standards has been proposed yet.
Techniques for added value. This consortium will develop and introduce several techniques for the application of the products of HTC with increased added value for energy purposes, farmers (as soil amendment) and other industrial uses, such the creation of activated carbons and nanostructured materials.
The above focuses will create a virtuous cycle which will increase mutually beneficial interactions between urban and rural areas. It will create new opportunities for the waste and related industry and it will reduce the negative carbon and nutrient footprint of cities. It will also enhance the environmental sustainability of energy production while simultaneously contributing to climate change mitigation.
Technical objectives
- Turning 20% of the presently disposed biowaste into high-value carbon products
- Finding and testing the 5 most appropriate wet biomass waste streams for obtaining different products – green waste, agricultural waste, municipal solid waste, waste from food processing industry.
- To develop a suitable, practical and scalable HTC carbon separation procedure
- To improve the potential for producing more high-value carbon products by optimized pre- and post treatment of biomass

- Defining the 4 most valuable carbon products that can be obtained with HTC, their production methods, potential applications, and market opportunities
- A full characterization of the effects of different wet biomass streams in the HTC reactor, as well as the products obtained, creating standards for high-value HTC products

Economic objectives:
- To reduce the HTC carbon product costs by 10%
- To develop an upgrading process for wet biomass which is 25% more cost efficient than existing disposal and treatment procedures
- To target a market of 10 000t of biowaste to carbon products (approx. 1.5M €)
- To substitute 20% of the currently imported carbon products with HTC carbon upgraded ones
- To strengthen the waste-to-enegy sector, increasing the amount of waste treated with technologies for the production of energy
- To create a business plan for the implemetation of the technologies developed in the project
- To define a set of quality standards for the use of wet biomass that will enable the producers and the energy industry to build reliable business

Social and environmental objectives:
- Increase SMEs and farmers´ knowledge, acceptance, and practices of new methods for biowaste reuse
Reduce negative environmental impacts (soil contamination) of improper waste disposal and reuse
- Protect/increase employment in the agricultural sector
- Reduce citizen´s health risks associated with improper application of waste disposal and application to agriculture
- Inform about and help meet current legislations/guidelines, present novel and efficient solutions for treatment and reuse of waste to policy makers/legal representative and last but not least help harmonize these efforts on a European scale.

The partners behind NEWAPP are convinced that it is by taking action at the association level that the results obtained by a project like this will reach the highest impact level in all EU Member states. The two international associations in the consortium have the means to disseminate the results, especially the standards and implementation decision tool, to a large number of national associations and SMEs. A similar scheme is ensured by the national association BSVE acting in Germany, which aims at achieving an uptake of these results in at least a 35% of the SMEs it represents.

Project Results:
The work performed in the first period focused on the selection of the biomass waste streams that would be dealt with, their characterization and the assessment of their potential. The partners dealt also with the description of the marketable products to be obtained from HTC, and the definition of the characteristics these have to comply with in order to be competitive in the current markets. Once the waste streams were selected, their HTC processing started in the pilot plant in Náquera, Spain. The purchase, building and commissioning of new equipment required in WPs 2, 3 and 4 resulted in a stop in this phase and a delay in the technical development of the project.

This delay was overcome in the second project period. The partners worked in the improvement of the coal obtained, specifically in the reduction of inorganic and halogen content, with positive results. In WP3 the partners studied the different fractions obtained and their applications. The hydrochar obtained was separated successfully into two parts: a solid one and a viscous liquid. The viscous liquid obtained was

further evaluated for its use as liquid fuel. A direct use as drop-in diesel fuel cannot be recommended but its use as a refinery feedstock would definitely be feasible.
A second application the solid product fraction was the preparation of battery electrodes. However, although the surface area stipulated in the DoW of 350 m2/g was obtained, the whole composition with an elevated inorganic content made the material unsuitable for this application. Therefore, an alternative higher value application for which the ash content could be tolerated was chosen: the use as adsorbent for waste water treatment, as a substitute for active carbons. Furthermore, the potential of hydrochar for soil amelioration if hydrochar can be a suitable substitute for the biochar that is currently used in soil amelioration products was studied. The results were in line with existing literature, and indicate some negative effect in plant growth. The exact reason for that, and possible solutions have been identified (i.e. co-composting), but this would require a longer testing period, beyond the time available in NEWAPP.
Once results were obtained in this respect, the work shifted towards the technology assessment, LCA, and the development of a suitable business plan, as well as the quality standards for the reuse of waste biomass. The connections of the partners in the consortium with standardization bodies that are working on standards for HTC allowed them to share information and harmonise NEWAPP's results with ongoing initiatives, which will render these result much more useful in this nascent industry.
Demonstration workshops were held at the Ingelia plant throughout the second period. In order to achieve a higher demonstration impact, workshops were also held remotely, using audiovisual material and HTC-coal samples to demonstrate the process. As a result of these activities, new HTC plants are planned to be built by Ingelia in the coming years (i.e. in Italy).

Finally, the RTD partners prepared training materials and gave training to the SMEs and associations in the project. As a means of achieving a long-lasting transfer of the project results, the partners prepared a handbook on the main activities and results of the project. In this way, NEWAPP has published the first long and comprehensive publication, and made it available for free at the website.

All partners contributed to the dissemination of the project's objectives, and NEWAPP has been present in six international scientific conferences and has appeared in local, regional and national media of the countries represented in the consortium.

• Result 1: New waste biomass reuse technologies based on HTC developed and tested
The work performed in WPs 1 to 4, especially 2 and 3, will render new ways to valorise waste, focusing on the use of waste streams selected by the SME-AG and SME partners in the project and the technological improvements described in WPs 2 and 3.
This result has been achieved in the successful completion of WPs 2 and 3. The project has developed new knowledge about the characteristics and uses of HTC coal, both indicating feasible uses and identifying others that are not directly achievable in with the substrates used. The impact of this result goes beyond the pure academic success, to devising new ways to deal with specific waste biomass streams.
• Result 2: Quality standards for the reuse of wet biomass waste streams
Defined in D 4.2 they will comprise the range for a variety of parameters that the biomass products must have in order to comply with the conditions from the industry for their use: maximum, minimum and optimum, for example for Cl- content, calorific value, etc. As a variety of uses will have been studied in WPS 1-4 (energy, soil amendments, water quality, etc), D4.2 will include the assessment of the industry requirements and real performance values obtained at the lab or prototype tests.

This result has been fully achieved. Furthermore, the NEWAPP standards have been presented to ISO, to be considered in the the ISO 238 technical committee for the elaboration of standard EN ISO 17225-8. In this sense, NEWAPP has maximized its impact and provided a long-lasting effect in future standards.

• Result 3: Decision tool for the implementation of wet biomass reuse technologies
The completion of WPs 4 and 5 will entail the achievement of result 3: the information gathered along these tasks will allow the RTDs to complete a decision tool for the SME-AGs, their members and the SME partners to choose what waste streams can be treated best with HTC, and what products are the most appropriate for their markets.
The work carried out throughout the project has led to the successful completion of this result. The knowledge generated after treatment of different biomass waste streams, their analysis and further consideration of LCA and business plan will enable municipalities to consider HTC as a viable option for waste treatment. This approach has already born fruits in the most recent agreements at Ingelia for establishing new plants in Italy.
• Result 4: HTC carbon products developed
Result 4 deals with the carbon products developed, and the processes used how to obtain them, as well as their commercial exploitation. This result is directly linked with the work in WPs 1 to 5.
The work performed in WPs 1,2 and 3, which was later demonstrated to relevant stakeholders has led to the achievement of this result. As described in WP3, NEWAPP has generated new knowledge on the products that can be obtained from waste biomass and their market placement.
• Result 5: Cost-benefit analysis
This result will be comprised in Deliverable D 4.1 result of task 4.3 and it will give the end- users potential calculations of inputs required for a theoretical HTC system for the products studied in the project, investments required for the implementation and selling prices.

This result has been achieved, and is a valuable tool for the relevant stakeholders to decide on the installation of an HTC plant. This will enable an easier and broader implementation of HTC.

S&T work that led to the achievement of the project’s results:
Work package 1: Characterization of wet biomass waste streams and definition of end-user requirements
Task 1.1 Screening of suitable wet biomass waste streams
The aim of Task 1.1 was to screen the available wet biomass waste streams on a European level both in qualitative and quantitative terms under consideration of their economic relevance.
It was originally planned to send out questionnaires to relevant stakeholders to obtain the required data. Based on unsatisfactory experiences the consortium had made with questionnaires in previous projects it was decided to use the Statistical Institute of the European Union (EUROSTAT) databank to obtain the data and to crosslink the data with the data on waste generating sectors from NACE-2. The results of the questionnaire were used to fill information gaps afterwards. Moreover the literature study and the chemical analyses conducted in Task 1.2 were taken into account.
Four criteria were established to identify suitable wet biomass waste streams:
1) The waste must be or contain an organic fraction
2) It must be available in sufficient volume
3) It must not have a suitable application as secondary raw material yet

4) It must be suitable for HTC with respect to composition

In the beginning ttz identified 13 waste stream categories containing carbon in the EUROSTAT database (e.g. wood wastes, vegetal wastes, animal faeces, urine and manure, household and similar wastes, different types of sludge, etc.) which were reduced to five categories after the application of the four criteria stated above. In a workshop conducted in the kick-off meeting questionnaires were developed for each of these waste stream categories and sent out to the respective actors, i.e. municipalities, waste managers, water treatment plant operators and digestion plant operators. The Associations participating in the project had an important role in the distribution of the questionnaire: for ACR+, Mr Jean-Jacques Dohogne and Ms Françoise Bonnet gave important input to develop the questionnaire to gather information on which types of wet biomass are of utmost interest for treatment and in which season, in task 1.1. In the same task, Ms Cristina Mestre Martinez and Ms Lisa Labriga conducted comprehensive dissemination activities to spread the questionnaire amongst the members of ACR+ and to motivate them to fill them in. This included mass mailings, articles in the weekly Newsletter of ACR+ plus personal mailings and calls to some members, in the months February – April 2014. EUBIA disseminated the project to its members in order to get information regarding most interesting waste biomass streams to process in HTC. In addition, EUBIA participated to the dissemination of the questionnaire to about 40 contacts of municipalities. Bvse participated in the discussion on the characterization of biomass within NEWAPP on the knowledge of characterization of biowaste from the requirements of national und European legal framework, i.e. European Waste Framework Directive, EU 1774/2002 and EU 1069/2009, and in Germany, i.e. the Bioabfallverordnung, the Klärschlammverordnung, the Düngemittelverordnung, the Düngegesetz and the Düngeverordnung. Bvse provided an overview on the biomass streams in Germany accordingly to waste flows and agriculture origin was given. Hence, first suggestions for the selection of suitable biomass streams for HTC processing on the knowledge of main biomass waste flows in Germany were performed. Dr. Thomas Probst, from bvse: took part in the discussion of various biomass streams in Europe, which could be suitable for HTC processing. He also participated in the evaluation of conventional biomass processing in Europe, as well as in the discussion of the data available from national and European statistics, bvse contributed significantly to the identification on the restrictions of processing various biowaste flows for hygienic reasons and their transport requirements to the processing plant. The SMEs Terra Preata and Ingelia supported the rest of the partners in the discussions that led to D 1.1 the preparation of the questionnaires and their distribution among their network of contacts. Ingelia also provided the boundary conditions for the waste streams to be successfully processed with HTC.

After analysing the data obtained from the questionnaires and considering the data obtained in the literature studies and practical biomass analyses of Task 1.2 five biomass waste streams were selected that were identified to be most suitable as feedstock for the HTC process and will be further considered in NEWAPP:

1) Sewage sludge from domestic wastewater treatment plants
2) Digestate from the biogas production
3) Biomass from garden prunings
4) The organic fraction of municipal solid waste (OFMSW)
5) Vegetable waste from markets and similar waste

DTU contributed to task 1.1 in the identification of companies, municipalities and institutions dealing with one of the identified waste streams (i.e. organic household waste) in Europe, distributed questionnaire to them, and analysed their responses. Additionally, Mr. Morten Ryberg identified and collected literature data to complement results from questionnaire analysis. Both results are included in D1.1. Mr. Mikolaj

Owsianiak gave an important input to D1.1 by describing the methodology used to screen wet biomass waste streams in Europe suitable for HTC.
As a common result of Task 1.1 and Task 1.2 detailed information in terms of the availability and the chemical properties of all five selected biomass waste streams was compiled and first conclusions on how to process them were drawn. All the information obtained in Tasks 1.1 and 1.2 can be found in Deliverable D1.1 “Screening and chemical analysis of suitable wet biomass waste streams” which was submitted to the Commission on June 30th, 2014.
Task 1.2 Chemical analysis of wet biomass
Task 1.2 completed the work performed in task 1.1. First, to obtain relevant and representative Europe wide results a statistical review was conducted using the Statistical Institute of the European Union (EUROSTAT) databank. After a short evaluation, further information was been retrieved by cross linking the data with the data on waste generating sectors from NACE-2. Then, data have been further completed by a questionnaire survey, carrying out analysis and literature research.
Evaluation of the data was done after all steps and decisions were made when possible depending on the available data. Four criteria were established. The first one was a very soft one which was only applied (criterion 1 in Figure 1) to get the widest range of waste stream categories that are or contain organic fraction. Three further additional criteria were established which were applied in each evaluation step: (i) it must be produced in sufficient volume; (ii) it must not have a suitable application as secondary raw material yet, and (iii) it must be suitable for HTC with respect to composition.
CSIC carried out literature surveys for data on chemical properties of food waste, garden prunings, green waste, the organic fraction of municipal solid waste, sewage sludge and digestate from biogas production plants. CSIC carried out all analysis summarized in D1.1. The biomass was obtained from sewage sludge, digestate, green waste/prunings and OFMSW. These analysis involved analysis of humidity, pH (if applicable), elemental analysis (CHNS), ash content, lignocellulosic composition, and lignine and hollocelulose among others. Higher heating value was determined at CSIC in Zaragoza.
The final conclusion was the selection of the following five biomass waste streams for the trial in WP2 and further considering in the project:
• sewage sludge
• digestate residue from biogas production
• green waste/garden prunings
• OFMSW
• food market waste/vegetable waste

Task 1.3 Identification of marketable products, definition of end-user product requirements
The aim of Task 1.3 was the identification and quantification of the most interesting carbon products that can be produced from HTC carbon and to determine the characteristics and quality parameters that the produced HTC carbon must comply with.
During the preparation of the project proposal, a literature study was conducted to identify products and applications where HTC carbon has shown suitability on a laboratory scale. These products and applications comprised solid fuel, coke, battery electrodes, soil remediation products such as peat or charcoal, activated carbon, catalysers, liquid fuel, carbon sequestration, carbon fuel cells and hydrogen storage.A market study was conducted for all products and applications in order to obtain information on specifications and requirements of the raw carbon (physical properties, applicable standards, existing alternatives and current market price), on the European market size and on the main sectors demanding

the products and applications. Based on the results of the market study the following five products with the best market potential have been identified and will be further considered in the NEWAPP project: Solid fuel, liquid fuel, peat, charcoal (and coke).

The SMEs and Associations contributed with relevant data: bvse coordinated the writing and contributed with information about the European markets, and Ingelia and Terra Preta contributed with their existing knowledge of the market for HTC products. CSIC participated in the preparation of deliverable D1.2. CSIC composed the chapters on coke, catalyser and liquid fuel. Mr. Morten Ryberg from DTU identified marketable products for carbon sequestration, carbon fuel cells and hydrogen storage and defined their end-user requirements and requirements to the char. This is included in Deliverable 1.2.

All the information obtained in Task 1.3 can be found in Deliverable D1.2 "Report on marketable products and requirements of the desired end products" which was submitted to the Commission on February 24th, 2014.

Work package 2: Obtaining HTC carbon from seleted waste streams and post-treatments developed for improved products

Task 2.1 Processing of the five selected biomass streams at industrial scale

The need to install a new boiler at the Ingelia plant in order to perform the work foreseen in WP3 and 4 with the best results entailed a delay in this work package already in the first period. The work in the second period focused in completing the processing of the biomass streams and collecting the data necessary for fulfilling the objectives set or this and subsequent tasks. This task started during the first reporting period and continued during the second. The major part of the pilot plant trials was carried out during second reporting period, including a second trial on the organic fraction of municipal solid waste (BO+), sewage sludge (BS), bell pepper residues (BF+) and orange peel waste (BF) as food wastes, a second trial on green waste (BG+) and a second trial on digestate (BD). CSIC-ITQ contributed to this task by analyzing the raw material employed in the trial in the same way as during the first reporting period. The analyses include humidity content, ash content, volatile content, fixed carbon content, elemental analysis (CHNS), ash composition by ICP-OES (Na, K, Mg, Ca, Si, Al, Ti, Mn, Fe and P), holocellulose content and lignin content). For the feedstocks BO+, BD and BS also heavy metals (As, Cd, Cr, Co, Cu, Pb, Mo, Ni, Se, Zn and B) were determined in the ashes by ICP-OES. Higher heating values were measured at the Carbonchemistry Institute of the CSIC in Zaragoza. According to the wet biomasses defined in the previous work package, Ingelia, with the support of ttz, EUBIA, bvse and ACR+ designed the tests to be performed in their HTC plant located in Náquera, as well as designed the improvements and modifications to be done in the HTC plant in order to adapt the pre-treatment of biomass (initially designed for vegetable residues).

CSIC-ITQ was in charge of collecting the results of this task and compiling them in Deliverable 2.1 "Analysis of HTC carbon samples", which was sent to the EC on 15th January 2016. The long delay in this submission was due to the delay in the restart of the plant operation as described in the first periodic report.

Task 2.2 Analysis of HTC carbon samples

CSIC-ITQ analyzed the solid products obtained from the trials carried out in task 2.1. These analyses were coordinated with TTZ in order to obtain the required data for subsequent work packages. CSIC-ITQ analyzed all samples provided by Ingelia. The analyses included humidity content, ash content, volatile content, fixed carbon content, elemental analysis (CHNS), ash composition by ICP-OES (Na, K, Mg, Ca, Si, Al, Ti, Mn, Fe and P). During this reporting period for almost all trials and conditions heavy metal contents (As, Cd, Cr, Co, Cu, Pb, Mo, Ni, Se, Zn and B) were determined in the ashes by ICP-OES. Higher heating value and chloride and fluoride content were measured at the Carbonchemistry Institute of the CSIC in Zaragoza.The determination of the heavy metal content was estimated, in coordination with TTZ and the other NEWAPP partners, to be strongly required although this work was not specified in the DoW. Therefore, budget shifts within the RTD activities from travel costs to personnel and consumables were necessary. All information acquired with task 2.2 was summarized in deliverable D2.1.

Task 2.3 Improvement of HTC solid fuel by reduction of inorganic content

During the second period, CSIC-ITQ, Ingelia and ttz completed the work in this task, and Ingelia prepared Deliverable 2.2.

Decreasing of the ash content of hydrochar has been the focus of this work. The experiments preformed on the AT1 hydrochar sample were adapted from the Ultra Clean Coal (UCC) process. The selected consisted in a caustic digestion at 225 ºC followed by an acid treatment. There are numerous combinations for setting up the alkali-acid treatment as well as numerous different coal types all having specific ash contents. It is not feasible to do experimental work on all combinations and ash contents. To save experimental work, the developed model allows for comparison of different scenarios with different alkali-acid leaching setups. The model can be readily used to optimize alkali-acid cleaning of hydrochar, as it predicts that final ash content of a hydrochar should be < 5 wt%, which is within range of measured values.

In the experiments it was confirmed that this process can be adapted and applied to hydrochar and the required limit of a maximum ash content of 5 wt% as demanded by milestone MS2 was met. The temperature for the first, alkaline treatment was above the process temperature of the HTC process and this high temperature was responsible for advanced carbonization. However, the high temperature would involve higher energy costs of the process which is undesired. Therefore, lower temperatures for the first step were also studied. In this case silicon was not extracted efficiently. This was in accordance with the prediction from the model elaborated from literature data. Therefore, it was concluded that the two-step ash treatment is a valuable procedure for producing low-ash hydrochar for high-value applications. However, for the use as solid fuel, the procedure had to be simplified. Therefore, a single step treatment was designed and evaluated.

As summary it can be stated that the UCC process applied to hydrochar is an efficient method for reducing the ash content to below 5% as demanded by milestone MS2. Interestingly, the carbon content (on a dry and ash-free basis) was further increased.

Figure 1. Diagram of the general procedure 1 for the ash reduction adapted from the Clean Coal Process.

Single step ash treatment

A single step ash treatment (GP-2) was developed consisting in a treatment with sulphuric acid, subsequent filtration for hydrochar recovery and washing. It was found that with a reaction temperature of 100 ºC and a reaction time of 2 h the ash content was lowered to below 2 wt%. With this result milestone MS2 was reached which demanded an ash content of below 5 wt% of the treatment. The treatment was especially efficient for the removal of calcium and phosphorous. It was further found that an efficient ash reduction involves a penalty on the mass balance. This means that approximately one third of the hydrochar was lost when the low ash content was achieved. This has clearly a negative impact on the process economics in the case that the low ash has at least a 50% higher value than the initial high-ash hydrochar. Sulphuric acid might be substituted by hydrochloric acid which showed also an interesting potential. However, for this acid reaction conditions have to be still optimized further. A further critical point is that washing procedure after the treatment. A relatively high amount was needed for efficient ash reduction. This might be recovered by means of the inverse osmosis unit incorporated into the pilot plant during the NEWAPP project. As a limitation of the present procedure it has to be stated that it can only be applied to low silicon (and low aluminium) hydrochars since both elements are not removed during the treatment with an acid.

The existing ash reduction unit at the prototype was used and optimized during the NEWAPP trials. Additionally two different chemical processes were studied on laboratory scale (see first reporting period). With both processes MS2 was reached, i.e. ash content was reduced to below 5%. CSIC-ITQ compiled the results in deliverable D2.2.

Task 2.4 Improvement of HTC solid fuel by reduction of halogen content

The work in this task continued in the second period from the preliminary literature review performed by CSIC and DTU to the development of procedures for the reduction of the halogen content.

CSIC-ITQ, with support from INGELIA and ttz, designed two different procedures and evaluated them at lab scale. The first one was the treatment with an alkaline solution with the aim to substitute halide anions by hydroxide anions described in the DoW. The second procedure was derived from a control experiment when the hydrochar was treated only with washing water and from a literature survey. Hence, with the alkaline solution and the neutral water the chloride content was decreased. Then a second study was carried out to confirm the possibility to use only water for the treatment. During this study all produced samples met the requirement of milestone MS3. With these satisfying results CSIC-ITQ designed the implantation at the pilot plant together with Ingelia. The most straightforward incorporation was the washing step in the filter press after removal of the process water. The corresponding trials were carried out at Ingelia's pilot plant and supervised and analyzed by CSIC-ITQ. However, a final proof for the efficiency of the procedure could not be obtained. The hydrochar produced when the experiment was run had already a low chlorine content, already fulfilling the established values, so that it could not be further decreased.

Work package 3: Post-processing of HTC carbon for high-technological applications: bio-diesel and electrodes

Task 3.1 Separation of HTC carbon into two or more fractions

Based on preliminary tests, CSIC-ITQ and ttz selected the following separation method for hydrochar: in a down-flow reactor with a porous plate in the heating zone hydrochar was treated at different temperatures passing a nitrogen flow down flow producing three products: thermally treated hydrochar, a condensed liquid and a gaseous effluent. All three products were collected and analyzed. The amount of each product was quantified in function of the temperature of the treatment and the time of the treatment. In this study CSIC-ITQ could show that this treatment was suitable to eliminate the volatile content from the hydrochar and to enrich the fixed carbon and ash content. On the other hand not all the volatiles were lost and part could be recovered as a viscous liquid. The gas consisted mainly of carbon dioxide and had no value for further uses. Perhaps, it might be used for energetic valorization in a potential industrial application for generating the heat for the thermal treatment.

For the production of solid and liquid on a larger scale (kg scale) CSIC-ITQ designed a different apparatus since a straightforward up-scaling of the down flow method was not possible. With this apparatus several kg of solid were obtained whereas the yield of liquid was lower. With respect of the solid the quantity produced was sufficient for other Tasks of the project. Contrarily, for the liquid several down-flow reactions had to be carried out to accumulate the amount required for the hydrogenation reactions of Task 3.2. CSIC-ITQ analyzed the surface area of the solid and showed that after the treatment it was much higher (approx. 300 m2/g). CSIC-ITQ showed that the higher heating value is increased by approx. 20% for the treated solid.

The thermal treatment was not carried out for the ten samples as specified in the DoW. Table 24 of deliverable D2.1 showed that all the regular hydrochar samples (with exception of the ones which were separated in the post-process treatment due to a high ash content) had a very similar volatile content (55 to 68%) and, therefore, it was concluded that results of the thermal treatment should be very similar. It was preferred instead to focus on the characterization of the products and on up-scaling. Hence, thermal treatments were mainly carried out with hydrochar samples derived from green waste and from orange peel waste.

As a summary it can be stated that hydrochar was separated successfully into two parts: a solid one and a viscous liquid. CSIC-ITQ compiled all the results obtained with the thermal treatment in a chapter which was included in deliverable D3.1.

Task 3.2 Upgrading of HTC carbon fractions to products of commercial interest

In the DoW it was proposed to develop two marketable products from the fractions obtained in Task 3.1. Since the results of the separation were not completely predictable some deviation from the initial working plan occurred.

bvse performed an overview of products generated by the various techniques, e.g. composting, biogas plants, substitute fuel, bio-diesel, applied for biomass conversion. In addition technologies and techniques applied therefore were screened and shown to the NEWAPP partners. Also the qualities of the conversion products were presented. Hence, an insight on the costs of biomass collection, transport and processing were given. At least, the actual prices of secondaries generated from bio-waste conversion were given. This knowledge is the basis to enhance commercial interest.

EUBIA screened the average composition required for the commercialization of the char as feedstock to be applied for a wide range of end use. Among the most relevant markets, EUBIA studied the char application potentials as fuel, soil conditioner and activated carbon source. Additionally, EUBIA studied the present market potentials and the main barriers of char application as soil conditioner, fuel, activated carbon and c source in metal industry

The viscous liquid obtained was further evaluated for its use as liquid fuel. For doing so, CSIC-ITQ hydrogenated the liquid in an autoclave after removal of the water contained. In this first experiment it was observed that the catalytic activity ceased very rapidly. It was assumed that this was due to coke deposition, the latter evidenced by thermogravimetric analysis of the catalyst. In two further trial CSIC-ITQ distilled the viscous liquid prior to the hydrogenation. This measure improved the hydrogenation result and two highly deoxygenated liquids were obtained. Oxygen content and lower heating value were determined at the Carbonchemistry Institute of the CSIC in Zaragoza. As a result of the hydrogenations it can be stated that the chemical process improved considerably the flow properties of the liquid. A direct use as drop-in diesel fuel cannot be recommended but its use as a refinery feedstock. A high nitrogen content, which has its origin in the plant raw material employed for the HTC process, makes it less suitable for the direct use but it should be possible to reduce this nitrogen content in an oil refinery. Hence, using the liquid as feed in the refinery it is separated into different refinery flows according to their physical properties. CSIC-ITQ determined a yield of 5 wt% for the hydrogenated liquid with respect to dry hydrochar after water elimination, distillation and hydrogenation.

A second application for a product fraction of Task 3.1 in this case for the solid product, was proposed in

the DoW, i.e. the preparation of battery electrodes. However, although the surface area stipulated in the DoW of 350 m2/g was obtained, the whole composition with an elevated inorganic content made the material unsuitable for this application. Therefore, an alternative higher value application was chosen for which the ash content could be tolerated and this was the application as adsorbent for waste water treatment, as a substitute for active carbons. CSIC-ITQ selected methylene blue as a model compound of a colorant contaminant. In laboratory experiments, CSIC-ITQ showed that this was a potential application the thermally treated hydrochar. However, a control experiment showed that pristine hydrochar had an even higher affinity to the colorant. This was unexpected since pristine hydrochar has a very low surface area. Therefore, it can be concluded from this study, apart from the fact that hydrochar has an interesting potential as adsorbent, hydrochar possesses particular properties due to its polar surface involving many oxygen functionalities. This has not been foreseen in the DoW and opens up a wide area for the application as alternative adsorbent to active carbons.
In Task 3.2 it has been demonstrated that thermally treated hydrochar may be used as adsorbent for waste water purification. This has been shown with methylene blue as a model compound for colorant contaminants. In Task 3.1 one of the samples employed in the adsorption study was prepared on kg scale. Therewith it can be concluded that MS6 has been achieved.

CSIC-ITQ compiled all the results obtained with the hydrogenation and the adsorption experiment in a chapter on Task 3.2 which was included in deliverable D3.1 prepared by ttz.
Task 3.3 Hydrochar soil application and process water quality
3.3.1 Hydrochar soil application
This task was planned in order to assess the potentials of hydrochar for soil amelioration, i.e. to answer the question if hydrochar can be a suitable substitute for the biochar that is currently used in soil amelioration products. The work performed under this task was divided into two main parts: a large series of tests conducted in 2015 and a smaller series of tests conducted in 2016. All the work was performed by TTZ, with contributions from TP.
The work began with a comprehensive literature study, e.g. on the scientific basics of soil amelioration with char and on the state of the art in research on soil amelioration with hydrochar in particular. On this basis, the research needs were identified and a research plan was developed, which was confirmed by TP.
EUBIA has a strong interest in biofertilizers sector and dedicated strong attention to the hydrochar potential application as soil conditioner. EUBIA staff contributed to assess the potentials of the hydrochar for soil amelioration and also to define the potential post processing activities which will be needed to upgrade the product into a higher value biochar.
The tests conducted comprised germination and plant growth rates, nutrient and water storage capacities, the compliance with widely accepted biochar standards, and others. In order to confirm the test results, some of the tests were repeated by TP in a smaller series. In the end, the results of all tests were collected and compared to the available literature and conclusions were drawn. All results of this first series of tests can be found in Deliverable D3.1.The first series of tests conducted in 2015 for the analysis of the effects of hydrochar on the growth of plants delivered negative results: plants of all 3 tested species grew best in substrates containing no hydrochar at all, while increasing concentrations of hydrochar increasingly inhibited plant growth. These observations were confirmed by various further studies. However, some of these studies stated that the negative effects of hydrochar on plant growth could be removed by thoroughly washing the char, incubating it with compost of exposing it to weather for some time (e.g. Busch et al. 2013). Since one of the hydrochar samples was available both untreated and exposed to the weather for a

year, it was decided to conduct a second series of tests to compare the effects of the two char varieties on plant growth.

The germination and plant growth tests were conducted in exactly the same way as the first series of tests was conducted in 2015 (compare D3.1) with the only differences in the tested char samples. In the first series of tests, 5 different hydrochar samples (made from different feedstock) and 1 biochar sample were used, while in the second series 2 varieties of the same hydrochar sample were used, 1 left standing outside exposed to the weather for a year, while the other one was kept inside protected from all potential influences. All seeds were planted on March 30th, 2016. The germination tests were finished 2 weeks later; the plant growth tests were finished 4 weeks later.

Germination rate

Lactuca sativa reached the highest germination rates of all 3 species. Between 45 (90 %) and 48 (96 %) of all planted seeds germinated. There were no significant differences between the germination rates in the different hydrochar varieties and concentrations (Table 1, Figure 1).

Avena sativa reached the lowest germination rates of all 3 species. Between 21 (42 %) and 30 (60 %) of all planted seeds germinated. Germination rates were, on average, slightly higher in the "treated" hydrochar samples, while the char concentrations did not have an effect on the germination rate (Table 1, Figure 2).

Raphanus sativus reached intermediate germination rates. Between 36 (72 %) and 45 (90 %) of all planted seeds germinated. There were no significant differences between the germination rates in the different hydrochar varieties and concentrations (Table 1, Figure 3).

In summary, it can be stated, that the germination rate of all 3 seed species was neither influenced by the hydrochar variety nor by the char concentration., except for small effects of the hydrochar variety observed for Avena sativa.

The observations made clearly indicate that hydrochar does not have significant effects on the germination rates of seeds. Germination rates were very similar for all char concentrations and for both hydrochar varieties. However, germination rates of Avena sativa seeds were slightly lower in substrates containing untreated char. An explanation could be that there are substances in the hydrochar that can influence the germination rates, but the concentrations of these substances were too low to have stronger effects on the germination rates.

Growth rate

Concerning Lactuca sativa, there were significant differences in the biomass production between the 2 char varieties and the 6 char concentrations. The by far highest biomass production was reached in substrates containing no char at all (9.6 g per 10 plants), while already very low char concentrations of only 1.25 % substantially reduced the biomass production (2.2 and 2.6 g per 10 plants). Biomass production at low char concentrations (1.25 % and 2.5 %) was higher for the untreated (not exposed to weather) hydrochar variety, while at higher char concentrations (5-20 %) the biomass production was higher for the treated (exposed to weather) variety. Higher concentrations (5 % or more) of untreated char almost completely inhibited growth.

Concerning Avena sativa, there were significant differences in the biomass production between the 2 char varieties and the 6 char concentrations. The by far highest biomass production was reached in substrates containing no char at all (4.9 g per 10 plants), while already very low char concentrations of only 1.25 % substantially reduced the biomass production (1.6 and 2.1 g per 10 plants). Biomass production at low char concentrations (1.25 % and 2.5 %) was higher for the untreated hydrochar variety, while at higher char concentrations (5-20 %) the biomass production was higher for the treated variety. Higher concentrations (5 % or more) of untreated char significantly inhibited growth.

Concerning Raphanus sativus, there were significant differences in the biomass production between the 2 char varieties and the 6 char concentrations. The highest biomass production was reached in substrates containing no char at all (4.6 g per 10 plants), while already very low char concentrations of only 1.25 % substantially reduced the biomass production (2.3 and 2.5 g per 10 plants). Biomass production at low char concentrations (1.25 % and 2.5 %) was higher for the untreated hydrochar variety, while at higher char concentrations (5-20 %) the biomass production was higher for the treated variety. Higher concentrations (5 % or more) of untreated char significantly inhibited growth

In summary, it can be stated, that the biomass production of all 3 plant species was by far highest for substrates containing no char at all, while already low char concentrations substantially reduced the biomass production. Effects of growth inhibition were observed for all 3 species for substrates containing 5 % or more of untreated char, while for treated char this effect was not observed. The negative effects of the char on the biomass production were highest for Lactuca sativa and lowest for Raphanus sativus.

The fact that the biomass production of all 3 species was highest in substrates containing no char at all clearly indicates that hydrochar does have strong negative effects on the plant growth, even at very low concentrations of only 1.25 %.

The observed differences in the biomass production between the treated and the untreated hydrochar at char concentrations of 5 % or more confirm that the exposure of the char to weather does reduce negative effects on the plant growth.

These results confirm the observations made in similar studies (e.g. Busch et al. 2013). Hydrochar seems to contain substances that negatively affect the growth of plants. These substances still need to be identified, since the most common substances with a toxic potential (heavy metals, dioxins, furans, PAHs and PCBs) were not responsible (compare D3.1). It was moreover confirmed that the exposure of hydrochar to weather for a certain time reduces the negative effects on plant growth, probably caused by the degradation of the toxic substances.

CSIC-ITQ supported TTZ and TP in this task by analyzing samples and facilitating information on the hydrochar contributing in this way to the interpretation of the obtained results by these NEWAPP partners.

The results of this sub-ask were compiled by ttz in Deliverable 3.1 “Post processing of HTC carbon for high-technological applications”, submitted on March 30th 2016. The reason for this delayed submission is the overall delay in obtaining the carbon samples and the climatic conditions to carry out the germination and growth tests.

3.3.2 HTC process water quality

The main goal of this sub-task was to evaluate the process water quality and its potential re-use and valorization options. The HTC process itself, i.e. the conversion of wet biomass streams into a HTC carbon, does not consume water; in contrast, it produces water by chemical dehydration.

Other steps in the process do however involve the consumption of water, as the production of steam for the heating of the reactor or the halogen reduction post-process. Therefore, water is consumed by the operation of the HTC plant and excess process water is produced, which needs to be handled, re-used and or disposed. While the DoW considered the possibility of identifying organic compounds such as acetic acid, aromatics, aldehydes and furanic and phenolic compounds that could be extracted and valorised, the experience acquired since the proposal preparation from Ingelia and ITQ-CSIC show that the concentration of such components, if found, would be too low for a viable and profitable recovery.

Hence the excess process water is submitted to an aerobic treatment in order to decompose unstable process intermediates and achieve a pH above 6. Remaining organic compounds are mainly humic compounds, which could be considered beneficial for agricultural soils. Process water has also been analysed for presence of potential pollutants in the frame of this task.
ttz was in charge of the analysis of the water, and the appraisal of the data received against current legislation and scientific literature for finding out the most adequate use. Due to incompliance with the current regulation, direct application of process water in agricultural fields is not possible. The application of diluted process water would allow to compile with the regulations. The balance of nutrients provided does not fulfill the needs of the studied crops, meaning additional fertilizers would be needed for some compounds, mainly N and P. Hence, the attractiveness of the agricultural use of HTC process water seem to be more on the reclaimed use of the water in water-scarce regions, than in its nutrient composition.

Since the first application to explore for the process water is fertigation in agricultural fields, persistent organic pollutants (POP) were selected, since they will have the highest environmental and health hazard.Literature on POPs in the potential feedstocks was screened, as to identify pollutants that could come into the system with the feedstock. This literature search included El-Sahawi et al (2010), K.T. Semple et at (2001), Rogers (1996), Paxéus (1995), Düring and Gäth (2002), Palmu (2011), Wang et al (2010), ADEME (1995) as well as the Stockhold Convention (2001). The following families of POCs were selected:

-Clorophenols and chlorobenzenes
-PAHs and Clorinated PAHs
-PCBs.
-Clorinated PAHs
-Dioxines
-Pesticides

From the 677 POCs that were analysed, only 8 were detected in the process water sample, mainly chlorophenols. This is consistent with the literature, which had already identified phenols formation in HTC. Although the chemistry of the reaction is not totally known, chlorophenols formation could be linked to the relatively high Cl content in green waste. The obtained results have been crossed checked with the pollutants analysed in the hydrochar in the frame of Chapter 3, finding no correlation. Further research is needed to confirm is these identified pollutants generally occur in HTC, if they come in with the biomass feedstock of if they are formed in the HTC process. Other authors suggest that organic pollutants are degraded through HTC (Weiner et all 2013).

The results of this sub-ask were compiled by ttz in Deliverable 3.1 “Post processing of HTC carbon for high-technological applications”, submitted on March 30th 2016. The reason for this delayed submission is the overall delay in obtaining the carbon samples and the climatic conditions to carry out the germination and growth tests.
Work package 4: Technology assessment and business plan development
Task 4.1 Life Cycle Assessment and cost-benefit analysis
Task leader: DTU
Mr. Mikolaj Owsianiak, from DTU expanded the LCA model, in agreement with Ingelia and ACR+, by: (i)

assessing environmental performance of HTC at full commercial scale with 2 and 4 reactors (in addition to pilot scale operation with 1 reactor that was promised in the DoW); (ii) adding LCA-based comparison of HTC with alternative waste treatment options, including anaerobic digestion, incineration and ladfilling (in addition to compositing that was promised in the DoW). In addition, Mr. Mikolaj Owsianiak contributed to cost-benefit analysis of hydrochar used as soil conditioner. Mr. Morten Ryberg from DTU contributed to the comparison of HTC with alternative waste treament options by interpreting resuts and identifying environemntal hot-spots in respective treatment technologies. The resources to cover the aforementioned tasks are those assigned originally to WP3, and it was agreed between TTZ and DTU that tasks originally assigned to DTU in WP3 will be covered by TTZ.
Mr. Mikolaj Owsianiak finalized the LCA model of hydrochar used as soil conditioner for carbon sequestration. (Note that most of the work in WP4 was carried out in RP1).
CSIC-ITQ collaborated actively in the life cycle assessment and the cost benefit analysis. CSIC-ITQ provided all required data on the NEWAPP trial related to chemical analysis. In particular CSIC-ITQ carried out detailed analysis on the gaseous effluents and confirmed the presence of furan in this effluent. LCA had attributed a negative impact in one of the impact categories. As a consequence, the HTC process was improved by conducting the effluents to the boiler combusting the furan and eliminating this emission.
Bvse collaborated win the discussion of various suggestions made from the participants of NEWAPP due to the Life Cycle Assessment, LCA, of HTC-hydrochar were performed. A special of NEWAPP was the processing of bio-sludges, rich in water contents. LCAs of various biomasses were reviewedFrom ACR+, Mr Dohogne, Ms Bonnet, Ms Labriga, and Ms Spasova gave significant input to this task by discussing the results obtained with DTU and by suggesting to also comparing HTC to other Waste Management options.
EUBIA monitored the LCA and cost benefits analysis results, providing a review of the achieved goals and comparing them with the present technologies currently used for organic waste treatment in Europe.
Task 4.2 Definition of quality standards for innovative technologies for the reuse of waste biomass
ttz, with the support from the rest of the partners, compiled and prepared the quality standards. From the several potential products studied in NEWAPP project, the most promising has been found to be solid fuel. To support the use of HTC carbon as a solid fuel, they focus on a proposal for a new product standard in Europe. Other working groups are working in standards applicable for to HTC solid fuels, and hence synergies have been sought for to maximize the outreach and relevance of the results and work developed in NEWAPP in this task.

As background, the International Organisation for Standardisation (ISO) Technical committee 238 (ISO/TC 238) has started to draft an international product standard for torrefied pellets and briquettes made from woody and non-woody (herbaceous, fruit and aquatic biomass) in February 2013. The European and International Standard will be developed in parallel, hence the standard will be published in Europe as EN ISO 17225-8 “Graded thermally treated and densified biomass fuels”. Thermal treatment includes processes such as torrefaction, steam treatment (explosion pulping), hydrothermal carbonization and charring, all of which represent different exposure to heat, oxygen, steam and water. Hence, this standard will be the reference for solid fuel HTC products. In order to ensure that all findings from NEWAPP project reflect in the standard, D 4.2 includes the definitions and quality tables that reflect the project’s research and results, required for a successful marketability of the obtained high quality NEWAPP products. Data and results from NEWAPP have been provided to the German standardization body contact point, Daniela Thrän from DBFZ, and the ISO 238 working group contact point Eija

Alakangas from VVT (Finland), and the Spanish contact point at AENOR. INGELIA participating in AENOR's ISO standardization committee TC238 in Work Group 2, this document has been presented in the last committee meeting in April 2016 in Kuala Lumpur.

CSIC-ITQ collaborated actively to the completion of this task. CSIC-ITQ also contributed by providing regular analyses data. CSIC-ITQ searched for laboratories specialized in the analysis of contaminants and sent samples for analysis. CSIC-ITQ carried out analysis on hydrochar and process water (e.g. heavy metals) to acquire necessary information for the quality standards. The corresponding analyses were not foreseen in the DoW and, therefore, a budget shift from the prototype to consumables within RTD activities of CSIC-ITQ was required.

ACR+ and bvse participated actively in the discussion of suggestions concerning the definition of quality standards for innovative bio-technologies. In addition, the evaluation of chemical parameters, which limit the use of biomass in biosphere was discussed. Since a special of NEWAPP was the processing of bio-sludges rich in water contents, it was found, that the main parameters of concern were the halogen contents, i.e. bromine and chlorine, as well as the heavy metal contents. Legal standards are settled in the European Waste Framework Directive, EU 1774/2002 and EU 1069/2009. In Germany, legal framework is settled in the Bioabfallverordnung, the Klärschlammverordnung, the Düngemittelverordnung, the Düngegesetz and the Düngeverordnung. Furthermore, the evaluation of HTC-hydrochar – short-term, medium-term and long-term was discussed. Here, positive results for water retention capacity and water storage by biaohar and hydrochar were obtained. Moreover, first results HTC-char application show no negative influence on N2O-emissions. Furthermore, positive effects were expected from biochar and hydrochar, which include CO2 minimizing energy production, soil amendment and C-sequestration. Up to now, some studies on the soil amendment properties of HTC-char showed negative effects of plant growing.

EUBIA contributed to this task by identifying the most interesting quality standards for the integration of char as fuel in the EU market. In particular, EUBIA also investigated the present potentials of new standardisation programmes for the application of biochar and hydrochar as soil conditioner in different EU countries. The standardization bodies included in EUBIA study are ASTM, CEN, ISO.

Task 4.3 Business plan and patent research for the implementation of reuse options for wet waste biomass

ttz carried out a preliminary analysis of different business models related to waste treatment with HTC. After the initial considerations and after presenting and discussing them with the rest of the partners, it was agreed with all SMEs and associations to focus on the case of a municipality with a population of 60,000 using HTC as the mean to treat their waste. This decision was made after discussing with Ingelia their experience in the field and recent business developments. Additional information was provided by ACR+ and bvse. A municipality in Europe with this population produces annually, in average, 225 kg of wet biomass per capita. There are some technologies currently treating these wastes, mainly incineration and composting which have some problems: high costs, waste of energy (incineration), low profit, and huge amount of areas needed (compost). HTC represents a better and more efficient way to treat these residues, which follows the circular and green economy, as well as the European energy and environmental policies.

The business plan includes the simulation of the performance of a 4-reactor HTC plant with a capacity of 21,840 tons of wet bio-waste per year. The plant is estimated will have a lifetime expectancy of 20 years. During this 20 years of operation, it will treat not only the whole wastes from the municipality but also, for some periods of time, the residues from the neighbouring small municipalities. Treating a total of approximately 450,000 tons of wet biomass including parks and gardens, markets wastes, kitchen residues, digestate, and the organic fraction of municipal solid waste.

The payback year of the 4-reactor HTC plant is achieved in the 5.5 year. After that each year has an EBITDA of 856,945 euros per year. Having a total profit, during the 20 years, of almost 5 million euros.

The business plan compares HTC treatment with other six technologies for the treatment of these wastes: incineration, composting and anaerobic digestion, among others, as these are the most widespread technologies and therefore, HTC's direct competitors. It also shows the comparison between different fuels for domestic heat stoves. EUBIA reviewed the business plan and contributed to its implementation by providing information and data on the present market situation and competing technologies currently in place in Europe. Business plan results have been used by EUBIA to assess the potential market development of the Industrial HTC technology investigated by NEWAPP project.

CSIC-ITQ collaborated actively in the discussion of the business plan and provided required information on the technical data.

Johannes Schräder and Dr. Thomas Probst, from bvse was in charge of carrying out the patent search in various databases. These were the German Patent Office (DEPATISnet), the European Patent Office (EPO), the US Patent and Trademark Office (USPTO) as well as the Google Patent Search. The patent search, here search terms were „hydrothermal carbonisation", „hydrothermal carbonization", „hydrochar" and „vapothermal carbonization", revealed a total amount of 150 patents concerning hydrothermal carbonization. Vapothermal carbonization, an HTC-similar process, revealed only one strike. The patents were classified in the six different categories, listed in the NEWAPP proposal. Furthermore, various charts to show the results of the patent search were created and discussed. However, it has to be pointed out, that there are various definitions of the terms „hydrochar" and „biochar". Hence, a further search query with the term "biochar" revealed a total amount of over 700 patents. These biochar patents were not included in the patent search. Ingelia, Terra Preta and EUBIA revised the deliverable draft and contributed with their knowledge of the sectors to cover all relevant results. The results were compiled and analysed and collected in deliverable 4.3 "Update on the patent situation".

Work package 5: Demonstration of project results

Task 5.1: Long term demonstration and adaptation

Task leader: ACR+, EUBIA

Ingelia carried out the long-term demonstration of HTC in the operation of the pilot plant, and maintains its Náquera pilot plant in operation as a showcase for municipal green waste. Ingelia's plant is receiving visits from different stakeholders and organization to show and demonstrate the application of HTC process.Ingelia is arranging Ingelia contunes at the date of writing, to operate the pilot plant and offer the opportunity of arranging visits to interested stakeholders as continuing demonstration efforts beyond the project energy sector for combustion and gasification, in collaboration with WPS, a brokerage consultancy with expertise in this sector.

EUBIA supported the demonstration activity by fostering members and stakeholders from different EU regions to visit the plant during its continuous operational activity in order to show the reliability of the technology for large amount of wet biomass processing. At ACR+, Ms Bonnet, Ms Labriga, and Ms Spasova supported the RTD partners for the long term analysis of the potential of HTC biomass treatment and HTC carbon sequestration. Ms Labriga and Ms Spasova furthermore helped Ingelia and ITQ in organising visits of interested stakeholders to the test site, such as the site visit that was combined with the second workshop, held on 6 March 2015 in Valencia. bvse supported the task advertising the events

among their members.
DTU contributed to the demonstration workshops providing additional information on the work performd in previous WPs: Mr. Mikolaj Owsianiak contributed to the assessment of long-term performance of the HTC technology by providing sets of recommendations for the technology developers on how to optimize the technology further in the context of environmental performance when the technology is scaled up to the full commercial scale in the long-term and (ii) recommendations on how optimize environmental performance of HTC carbon when used as either solid fuel or soil conditioner with carbon sequestration value. In addition, Mr. Owsianiak identified environmental improvement potentials of the technology by highlighting the need for avoiding of potentially toxic emissions from the HTC reactor, minimizing the use of energy as one of the most important parameters determine the overall sustainability performance of the technology.
ttz followed the same strategy, providing information of the performance of HTC coal as a soil amendment and, later in the project, about the business model developed for municipalities using HTC as a means to treat their waste. CSIC-ITQ supported Ingelia at the on-site demonstration events and in meetings with interested stakeholders.
Task 5.2: Demonstration workshops
Ingelia hosted the demonstration workshops at the pilot plant, scheduling the plant operation and providing the attendees with all necessary explanations.
CSIC-ITQ participated actively in five demonstration workshops. Four of them were open to the general public: two in Valencia, one in Lucca, Italy and one in Vienna (EUBCE). CSIC-ITQ co-organized the two workshops in Valencia together with Ingelia. The venues were the campus of the Polytechnic University of Valencia (UPV) near to the CSIC-ITQ building, for initial explanations and discussions, and the Ingelia pilot plant in Náquera. Furthermore, CSIC-ITQ organized a special course for Master students of the UPV including a plant visit.
EUBIA co-organized and participated in three demonstration workshops, presenting the project and contributing to train stakeholders regarding the current framework of organic material valorisation in Europe. Additionally, EUBIA contributed to the dissemination and organization of the workshops by contacting more than 2000 persons including researchers, SMEs representatives and authorities.From ACR+, Ms Labriga and Ms Voltz, co-organised several of the demonstration workshops in the course of the project. The workshops held were:
- Workshop 1: Valencia/Náquera (ES), 13 November 2014
- Workshop 2: Valencia/Náquera (ES), 6 March 2015
- Workshop 3: Lucca (IT), 26 March 2015
- Workshop 4: Vienna (AT), 4 June 2015
- Workshop 5: Valencia/Náquera (ES), 9 March 2016
- Workshop 6: Brussels (BE), 12 April 2016
- Workshop 7: Berlin (DE), 14 April 2016
- Workshop 8: Copertino (IT), 29 April 2016

All details on these demonstration workshops can be found in D5.1 Assessment of overall long-term performance and demonstration workshops, prepared by ACR+ and submitted on 29.04.2016.

Potential Impact:
The project NEWAPP has had as a focal point strengthening the competitiveness of the participating SME-AGs active in the bio-waste treatment sector in Europe. The introduction of novel and cost-effective

technology in this sector will capture the attention of European SMEs who have a leading role in the bio-waste treatment market. The European bio-waste handling market is nowadays experiencing a great challenge due to the numerous EC directives restricting the ways bio-waste is disposed. The demand for innovative and cost-effective ways for reuse rises every year. However, waste and managers lack adequate and innovative technologies for efficient bio-waste reuses allowing for the production of high-value products with steady quality.
HTC as a bio-waste management and recycling technology will have a positive impact on bio-waste producers and handlers as they will clearly benefit from:
• higher cost efficiency due to the HTC system and the savings in which it results
• securing the efficient wet bio-waste stream disposal through HTC and producing high-value products after HTC carbon sequestration process
• meeting present and future regulatory requirements set by the EC waste disposal and handling directives
Another SME group that was anticipated would benefit from HTC are the producers of relevant high-value products (Li/Na batteries, electrodes, etc.). These SMEs will be able to make commercial use of the generated know-how. However, as it has been seen through the work in the project, these aspects of HTC need to be further researched and optimized before reaching their full market potential. All SME IAGs have high interest in the development of the HTC bio-waste treatment technology as well as on the HTC carbon sequestration process and the possibility of having high-value carbon products and their immediate market implementation. HTC has proven to be a valuable tool also for municipalities and agriculture: the main producers of wet biomass waste streams can benefit from the technology that will turn these wastes into a product that can be directly used at the same premises as energy carrier.
Economic Impact for SME-AG beneficiaries and their members:
After 30 months of work, the SME-AGs EUBIA, bvse and ACR+ are the owners of the property rights for the developed high-value carbon products, the optimization of HTC and the standards generated in the project. The efforts spent in training have resulted in a group of professionals trained in the insights of a novel technology that has a huge potential in the coming years. All consortium partners will profit from the knowledge gained about possible risks or optimisation/decision paths to the developed in the work plan technology. Those will guide future technology optimizations and implementations, plus direct market applications of existing technologies in their most suitable fields. Additionally, NEWAPP results will support and contribute for expanding international guidelines on safe and efficient wet bio-waste streams reuse in the European waste sector.
As the work plan of NEWAPP is focusing only on the 5 most promising waste streams for running the HTC process and obtaining high-value carbon products afterwards, further demonstration will be essential to verify the economics of the technology and to expand even further the consumer's acceptance. It is already anticipated that after the completion of the project the participating associations will keep the exploitation of project results demonstration to their members via different programs. In addition, the partners have cooperated in establishing permanent links to continue the training beyond the project's lifetime, as in the booklet, which is available to the general public for free. As a measure of the interest generated by this result, it has been downloaded 181 times in the 17 days it has been available, since its upload to the preparation of the present report. The partners anticipate it will have a great impact in the waste management sector, including academia.

The European sectors and markets addressed by NEWAPP
HTC has the potential to impact a large number of sectors. From producers of these wastes to managers

and end-users, the benefits would affect a large number of European SMEs while providing a solution to a pressing environmental problem shared by all Member States.
Results obtained in the proyect are ready to be implemented under real-life conditions. Indeed, the work carried out in the project, together with the large efforts carried out by Ingelia, have resulted in new compromises and contracts to build new HTC plants in Italy, a first step that illustrates hpw suitable this technology is, and how relevan was NEWAPP from themoment of its conception.
HTC has the advantage that its products will not require a reorientation of existing businesses, as the developed blueprints for waste streams provided by NEWAPP are scalable. Furthermore, NEWAPP addresses several steps in the waste value chain as it takes in consideration producers and managers, keeping the perspective of delivering an innovative product that is competitive in the current market.

One of the results obtained has been the development of a set of quality standards for innovative technologies for the reuse of waste biomass. The biomass sector is nowadays hindered by the heterogeneity of the raw materials and technologies. This yields a great range of qualities in the final products obtained, and an insecure market. The quality standards will allow the end users to have a competitive advantage for the beneficiaries and their members against other competitors.
Furthermore, based on its innovative features, it is expected that the NEWAPP technology has an enormous potential for the European waste sector addressed. Implementing the results provided will allow European farmers to improve the way bio-waste is handled which will ultimately lead to a substantial reduction in waste disposal costs, producing of new high-value carbon products, and thus higher revenues for them. NEWAPP has in this area also reached results beyond the foreseen at the proposal preparation, and has collaborated actively with the ISO task in charge for a standard on HTC and torrefaction products. The impact of this is huge, as it means that the recommendations developed during the project are currently being considered tob e included in the next ISO standard.

Impact of in its NEWAPP SME-AG and SME participants
EUBIA, as the main European association of biomass producers, has as a duty to its members to provide frequent updates on the State-of-the-Art of biomass transformation, and HTC is, as it has been demonstrated in NEWAPP, a technology with a great potential in this area. EUBIA has been able to enlarge its existing work on biochar, build its capacities and establish themselves firmly in the HTC scene. This has resulted in an increase in members, attracted by the work in the project and therefore, an increase in revenues.
The impact of NEWAPP in ACR+ has been building the capacity of its staff in HTC as a waste treatment, which will be transmitted to their members: mayors and municipalities commited to achieving higher sustainability in european cities. In this sense, ACR+ has been actively pursuing the training of this group of stakeholders already during the project, which have led to several of their members considering HTC as an option for their waste disposal. The business plan prepared in the project will be further used for this purpose, due to the fact that the SME AGs own also the files and calculators used by the RTDs for the preparation of this result.
For bvse, participating in the project will have the impact of staying at the forefront of technological developments. This is especially important, as Germany hosts already a vibrant HTC sector, and their knowledge has already attracted new members. Having participated in the projcet gives bvse an advantage also for their members, similar to that achieved by EUBIA. It is anticipated that bvse will continue training its members in the results of NEWAPP after its completion.

For Terra Preta, NEWAPP has provided important insight on a potential ally and competitor: HTC coal is regarded as a potential substitute for biochar. The knowledge gained by Terra Preta in the project will enable them better decision-making with regard to theis product catalogue and ingredients used in their products and their marketing strategy. Although the project has demonstrated that „raw“ HTC coal could have adverse effects on planth growth, with an adequate post-treatment it would be a suitable and cheaper substitute of biochar.
Finally, Ingelia has been the host of the project’s pilot plant and has received first-hand training by the RTDs on the different parts of the HTC process as they have been dealt with in the project. During the project, and as a result of its engagement, Ingelia has expanded its operations Europe-wide greatly, with new plants planned in Italy, and promising developments in other EU countries and beyond. In this sense, NEWAPP has exceeded the expectations of knowledge transfer and increase in revenues. Specifically, the results obtained in those WPs dealing with the process and the plant have opened new business pathways (re-use of the water, pelletizing) for Ingelia that were not reachable before the project started.
Main dissemination activities:
NEWAPP has implemented a powerful dissemination strategy in which the obtained knowledge is transferred directly from RTDs to SME-AGs and from SME-AGs to SMEs and end-users. The SME-AGs within NEWAPP have an overall potential dissemination range of more than 10 000 end-users. BVSE alone is one of the biggest German associations on waste management and recycling. ACR+ and EUBIA belong to the most important professional international organizations which additionally extends the project range Europe-wide. The work plan prepared for NEWAPP comprises a dissemination strategy under WP7, which ensures effective transfer and exploitation of progress, results and knowledge gained within the project, beyond the training workshops for SME-AGs and their members (part of WP6).
The success of NEWAPP, being a project for SME associations is strongly dependent on well-coordinated dissemination and exploitation activities. The individual dissemination activities aim at achieving the best possible spreading of the project results and to establish cooperation among local municipalities, researchers and technical SMEs.
The project’s dissemination activities have focused on fostering the implementation of the new NEWAPP system among companies in the waste sector – both within existing facilities aiming to optimise their processes and new systems with the latest state-of-the-art.

Activities and target groups:
In order to assure appropriate dissemination during and after its duration, raise awareness and assure the continuity of the achievements beyond, the dissemination strategy considers the following target groups:

・Companies working in the solid waste sector, which could improve the efficiency of their processes by the implementation of the new NEWAPP technology
・Municipalities, the end user and clients of these companies
・General public: Given the role played by public opinion concerning waste, it is important to consider the general public as a target group of the NEWAPP plan, raising awareness of advantages of the NEWAPP technology in relation to
・Researchers, aiming at the exchange of knowledge and results to achieve a faster development of the technology
・Standardization agencies and initiatives, working already in including HTC coal in their norms. The efforts have been focused in this case in aligning the NEWAPP standards with future standards

The dissemination activities undertaken during the project aim at ensuring that the results are disseminated as swiftly as possible, with EUBIA being responsible for assuring that they are compatible with the protection of intellectual property rights, confidentiality obligations and the legitimate interests of the SMEs and SME associations.
The general dissemination instruments for the presentation of the project activities and expected results include:

• a web page, http://NEWAPP-project.eu

• a project handout

• Press releases published in generalist media
• Appearances in radio or television outlets

The specific dissemination activities consist of the following activities:

• Including the project in the websites and/or newsletters of the partners

• Advertisement of the project at the SMEs and via institutions supporting the activities of this sector such as chambers of commerce, the relevant ministry of enterprise, as well as any industrial association they might belong to
• Promotion on specialised trade fairs
• Publications in specialised magazines, according to the SME's business, market and target groups.
• Scientific publications: The RTD performers will submit any scientific paper prepared on the work performed in the project to the SMEs, and will request their consent to publication before its submission for review.

The following sentence has been added to all publications developed under NEWAPP, as well as the project's website: "The research leading to these results has received funding from the European Union's Seventh Framework Programme managed by RES – Research Executive Agency (FP7/2007-2013 under grant agreement n° 605178"

Dissemination policy

The partners in the consortium have identified dissemination activities as necessary for the successful completion of the project, and have sought not only participating in events such as conferences and fairs, but also to present the project to their business partners. These contacts are not reflected in the tables for dissemination events due to their informal nature.

Even though dissemination of the project objectives and results is an objective for the partners, each beneficiary is aware of the restrictions in terms of disclosing confidential foreground.

Dissemination activities including but not restricted to publications and presentations shall be governed by

Article II.30 of the Grant Agreement. In the case of a party objecting a publication has to show that its legitimate interests will suffer disproportionately great harm and shall include a request for necessary modifications.

In order to avoid conflict, a party may not publish foreground or background of another party, even if such foreground or background is amalgamated with the party's foreground, without the other party's prior approval. Any data which is to remain secret should be cleared labelled as confidential. Parties agree to abide by the default notice period foreseen in the grant agreement to communicate their planned dissemination activities with a notice at least 45 days prior along with sufficient information about the intended dissemination.
In the final meeting the partners have agreed on continuing the dissemination activities once the project is over, both attending to events (fairs, conferences) where the results of the project can be showcased, and meetings at the Ingelia plant, where the prototype can be used in demonstration workshops and meetings. The booklet, available online, will be promoted as a high-quality and long-lasting training and dissemination tool after the project ends.
• Scientific publications:
• ENVIRONMENTAL PERFORMANCE OF HYDROTHERMAL CARBONIZATION OF FOUR WET BIOMASS WASTE STREAMS AT PILOT- AND FULL-COMMERCIAL SCALE
Mikolaj Owsianiak, Morten Ryberg, Michael Renz, Martin Hitzl, Michael Hauschild
• LIFE-CYCLE BASED EVALUATION OF HYDROCHAR APPLICATION TO SOIL AS A POTENTIAL CARBON SEQUESTRATION AND STORAGE TECHNOLOGY
Mikolaj Owsianiak, Jennifer Brooks, Alexis Laurent
• LIFE-CYCLE BASED COMPARISON OF HYDROTHERMAL CARBONIZATION OF FOUR WET BIOMASS WASTE STREAMS WITH ALTERNATIVE TREATMENT OPTIONS
Mikolaj Owsianiak, Morten Ryberg
• Fuel and chemicals from wet lignocelulosic biomass waste streams by hydrothermal carbonization
Pedro Burguete et. Al. Green Chemistry, 2016, 8. P.1051-1060
• Hydrothermal carbonization (HTC) for valorizaiton of food waste. M. Renz et al, presentation at the 3rd International Symposium on Green Chemistry, May 3-7 2015 La Rochelle, France
• Production of a solid fuel from garden prunings, food waste, OFMSW, digestate and sewage sludge on pilot plat scale, M. Renz et. Al, oral presentation at the 23rd European Biomass Conference and Exhibition
• Poster presentation at the Green and Sustainable Chemistry Conference, Berlin, Germany, 03/06/2016–06/06/2016
• NEWAPP, estudio de la valorización de residuos alimentarios a través de carbonización hidrotermal (HTC), Retema: Revista técnica de medio ambiente, ISSN 1130-9881, Año nº 27, Nº 179, 2014, págs. 6-7

Expected exploitation:
The partners started discussing the need for patenting the results obtained from the end of the test season until the end of the project. In the discussion about IPR issues in the final meeting, all SMEs agreed on the following points, as collected in the final meeting's minutes:
The partners in the consortium have identified dissemination activities as necessary for the successful completion of the project, and have sought not only participating in events such as conferences and fairs, but also to present the project to their business partners. These contacts are not reflected in the tables for

dissemination events due to their informal nature.

Even though dissemination of the project objectives and results is an objective for the partners, each beneficiary is aware of the restrictions in terms of disclosing confidential foreground.

The partners will not pursue any joint protection action (patent).

Dissemination activities including but not restricted to publications and presentations shall be governed by Article II.30 of the Grant Agreement. In the case of a party objecting a publication has to show that its legitimate interests will suffer disproportionately great harm and shall include a request for necessary modifications. In order to avoid conflict, a party may not publish foreground or background of another party, even if such foreground or background is amalgamated with the party's foreground, without the other party's prior approval. Any data which is to remain secret should be cleared labelled as confidential. Parties agree to abide by the default notice period foreseen in the grant agreement to communicate their planned dissemination activities with a notice at least 45 days prior along with sufficient information about the intended dissemination.

In the final meeting the partners have agreed on continuing the dissemination activities once the project is over, both attending to events (fairs, conferences) where the results of the project can be showcased, and meetings at Lempe, where the prototype can be used in demonstration workshops and meetings.
A session of the final meeting was dedicated to future dissemination events, and the partners have prepared a list of events where the objectives and results of the project can be explained to potential clients. A preliminary list of actions and comprises the references below:

- Integration of the booklet in existing training programs at the SME-AGs
- Presentation of the booklet at the EUBCE conference in Amsterdam in June 2016
- 5. Mitteleuropäische Biomassekonferenz, Graz, Austria, January 2017
- 2nd World Bioenergy Congress and Expo, Madrid, Spain , June 2017
- Conference on Energy efficiency and Renewable Energy, April 2016 ,Sofia, Bulgaria
- 2nd Euro Global Summit and Expo on Biomass, Brussels, Belgium, August 2017
- Presentations at fairs (IFAT, TERRATEC, etc)

The RTDs have also expressed their compromise to further dissemination using the basic materials prepared during the project (leaflets, PowerPoint presentation)

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www.newapp-project.eu

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Last update: 7 October 2016

ATTACHMENT 6

Carbon2H

Paving the Path to Carbon Neutrality

The Renewable Route to Carbon Storage

Berlin, Germany

Table of Contents

We are using state-of-the-art technology to remove carbon from the atmosphere by converting biomass into renewable energy and capturing CO_2.


CO2

A simple switch for a brighter future.

Making a simple switch in our energy consumption and production habits can lead to a significant reduction in carbon dioxide (CO_2) emissions, paving the way for a brighter, more sustainable future.

CO_2 is the primary greenhouse gas contributing to climate change, released largely through the burning of fossil fuels for electricity, heating, and transportation. By transitioning to renewable energy sources like solar, wind, and biomass gasification, we can drastically cut CO_2 emissions and mitigate the adverse impacts of global warming.

Moreover, reducing reliance on fossil fuels enhances energy security and decreases vulnerability to volatile fuel prices and geopolitical tensions. Encouraging this switch not only helps stabilize the climate but also improves air quality and public health by reducing pollutants.

Power your world with biomass

Biomass energy offers a compelling solution for powering our world with sustainable and renewable resources. Derived from organic materials like agricultural residues, forest byproducts, and dedicated energy crops, biomass is a versatile energy source that can be converted into electricity, heat, and biofuels. Unlike fossil fuels, biomass is part of the natural carbon cycle, meaning the carbon dioxide released during its combustion is offset by the carbon dioxide absorbed by the plants during their growth. This makes biomass a carbon-neutral energy option that significantly reduces greenhouse gas emissions. By utilizing local biomass resources, communities can not only reduce their dependence on imported fuels but also create jobs and stimulate rural economies, fostering a more resilient and sustainable energy infrastructure.

By powering your world with biomass, you contribute to a more sustainable future, where energy is generated responsibly, ecosystems are protected, and communities thrive on renewable resources.

Turning today's waste into tomorrow's fuel.

Turning today's waste into tomorrow's fuel represents a revolutionary approach to energy production that tackles two major challenges: waste management and sustainable energy generation.

Every year, millions of tons of organic waste, including food scraps, agricultural residues, and municipal solid waste, are discarded in landfills, contributing to greenhouse gas emissions and environmental degradation. However, through advanced technologies such as gasification and pyrolysis, this waste can be transformed into valuable biofuels like biogas, bioethanol, and biodiesel.

These biofuels can power vehicles, generate electricity, and provide heating, creating a circular economy where waste is minimized, and resources are efficiently utilized. By converting waste into fuel, we reduce our reliance on fossil fuels, lower carbon emissions, and address waste management challenges in a sustainable manner.

Turning Organic Power into Carbon Solutions

Together, we are building a greener, cleaner world where energy is renewable, resources are regenerated, and the air we breathe is pure.

Harnessing Nature's Cycle for a Carbon-Free Future

By enhancing and optimizing natural processes, such as photosynthesis, where plants absorb CO_2, and combining them with cutting-edge technologies for the efficient capture, utilization, and storage of carbon, this strategy offers a sustainable path to reduce atmospheric CO_2 levels.

Our Approach

01

Biomass Preparation

Organic materials, such as wood chips, agricultural residues, and other biomass are gathered. These materials are then prepared for the gasification process, ensuring they have the correct moisture content and are the appropriate size for optimal conversion.

02

Gasification Process

The prepared biomass is subjected to high temperatures in a controlled environment with limited oxygen. This process converts the biomass into syngas—a versatile, clean-burning gas—while producing biochar as a byproduct.

03

Decarbonization

During gasification, CO_2 is captured and stored in the biochar. This biochar, which sequesters carbon for more than 1,000 years, can be used in various applications, such as soil improvement, construction materials, and more.

04

Renewable Energy Production

The syngas generated from gasification is used to produce renewable energy, which can power operations, generate electricity, or be further processed into biofuels. This contributes to a sustainable energy supply while reducing reliance on fossil fuels.

05

Continuous Monitoring and Optimization

Our team continuously monitors the system to ensure maximum efficiency and effectiveness. We provide ongoing support to adapt to changing needs and improve the carbon capture process.

Our Solution

Carbon Capturing

Modularization

Customization

Carbon Capturing

Biomass gasifiers efficiently convert organic materials into syngas and biochar. This process captures and stores carbon in biochar for over 1,000 years, providing a stable method of carbon sequestration. The dual output of valuable energy and enhanced carbon management makes biomass gasification a key player in sustainable energy and climate mitigation.

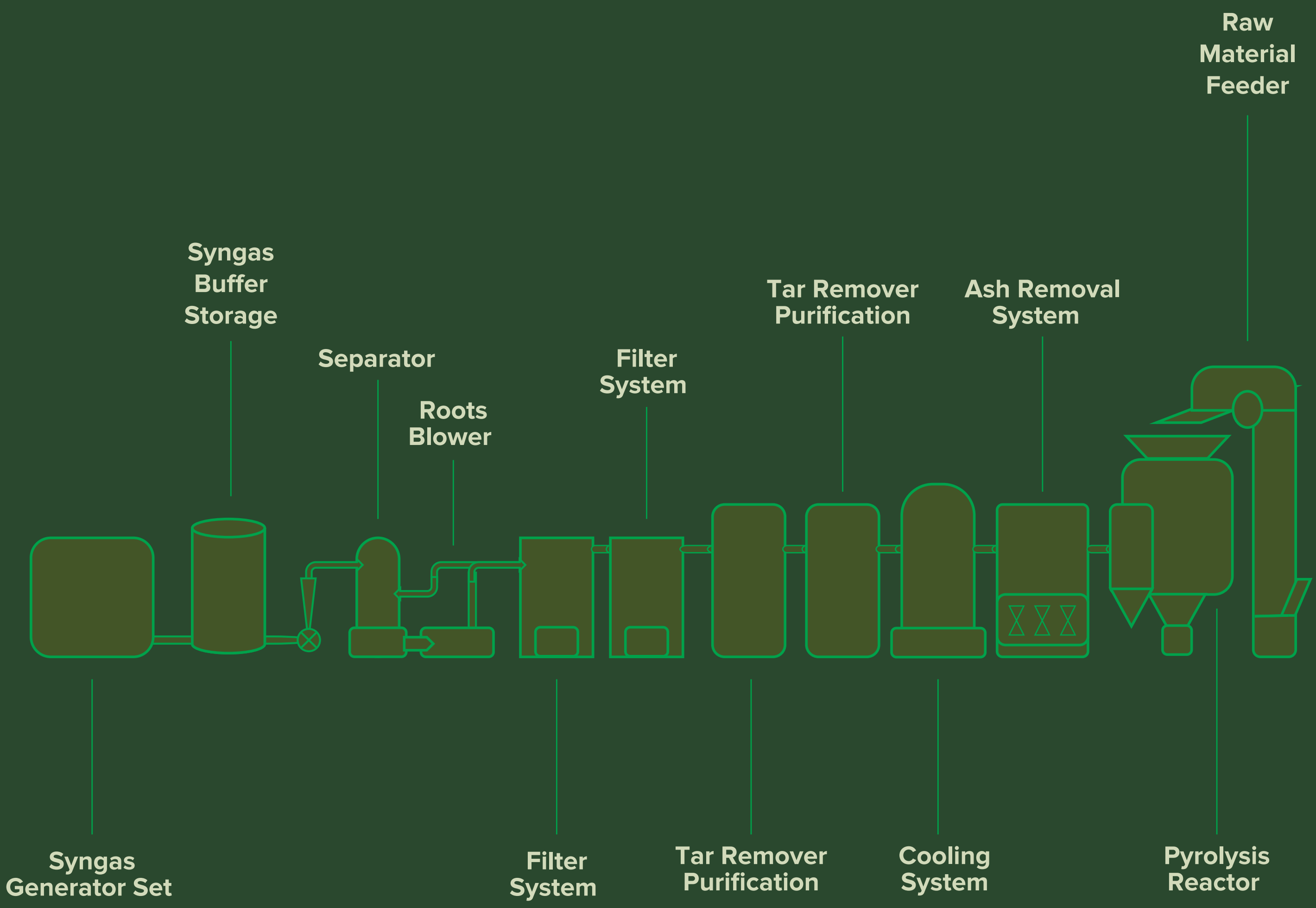
Modularization

Housing biomass gasifiers in shipping containers makes renewable energy solutions more accessible, scalable, and versatile. This design allows for easy transport and rapid deployment across various locations, from remote rural areas to industrial sites. It reduces logistical challenges and costs while offering the flexibility to scale operations based on demand.

Customization

Our biomass gasification systems provide unmatched flexibility and efficiency, converting diverse biomass types into syngas. Tailored to specific needs, they ensure optimal output, making them versatile solutions for various industries and locations.

Gasification System Overview


Raw Material Feeder
Syngas Buffer Storage
Tar Remover Purification
Ash Removal System
Separator
Filter System
Roots Blower
Syngas Generator Set
Filter System
Tar Remover Purification
Cooling System
Pyrolysis Reactor


“Portable power. Sustainable biomass in containers unleashes the energy of tomorrow.”

Carbon2H

Energy
Our 30 kW system fits into a shipping container for mobility. For larger needs, we offer systems up to 500 kW, which are stationary.

Output
Depending on your needs, you can choose to output syngas, hydrogen or, in combination with a generator, create your own electricity.

Mobility
Shipping containers enhance our biomass gasification systems’ mobility, enabling easy transport, rapid deployment, and scalable energy solutions.

Certification

Our CE-certified gasifiers meet the highest standards of safety, health, and environmental protection, ensuring compliance with European regulations and guaranteeing quality and reliability.

Feeding Material

Raw materials like straw, rice husks, cotton stalks, and wood chips and branches can be used with a moisture content of less than 20% and a size of less than 30mm.

Customization

Customization options include more powerful systems, electric energy production instead of syngas, and services like fleet management.

System

The biomass gasification system includes a pyrolysis furnace, dust removal, cooling, tar purification, tar separation, Roots blower, and electrical control. These components efficiently convert biomass into syngas and biochar for clean energy production.

Warranty

We believe in our products and therefore grant a warranty of 1 year. You can book additional maintenance depending on your needs.

Pricing

All prices are net, payment is in advance, ex-works (EXW). Additional services and customization costs are extra.

Diverse Revenue

Renewable Energy Production

Syngas Production: Selling byproducts like hydrogen, carbon monoxide, and methane for use in various industrial applications.

Electricity Sales: Selling electricity generated from syngas to the grid or directly to consumers.

Heat Sales: Providing renewable heat for industrial processes or district heating systems.

Carbon Credits

Carbon Offset Markets: Generating and selling carbon credits from captured CO_2 for businesses looking to offset their emissions.

Government Incentives: Earning incentives and subsidies for reducing greenhouse gas emissions.

Biochar Sales

Agriculture: Selling biochar as a soil conditioner to enhance soil fertility and carbon sequestration.

Construction: Utilizing biochar in building materials, creating long-term carbon sinks and improving material properties.

Product Specification

Model		30 Mobile	100	200	500
Power	Gross (kW) NET (kW)	30 24	100 80	200 160	500 400
Input	Wood Chips (kg/h)	50	150	300	750
Output	Gas Production (m3/h) Biochar (kg/h)	100 13	300 38	600 75	1500 188
Production	Lead Time (days) Setup Shipping Size	90 Mobile 40 ft container	70 Stationary 40 ft container + 20 ft container	90 Stationary 2x40 ft container	120 Stationary 3x40 ft container

CONTACT US.

Thank you for your interest in our innovations and your commitment to a carbon-neutral future. We're excited to connect with you! Whether you have questions, need more information, or want to explore collaboration opportunities, please fill out the form. You can also reach us via email at

sales@carbon2h.com.

Let's work together towards a sustainable and greener tomorrow.

Carbon2H

Berlin, Germany

ATTACHMENT 7

CHAR technologies

High Temperature Pyrolysis (HTP) Technology
July 2023

YES LISTED ON TMX TSX Venture Exchange

Decarbonizing for a Circular Economy

FORWARD-LOOKING STATEMENTS

Statements in this presentation, to the extent not based on historical events, constitute forward-looking statements. Forward-looking statements include, without limitation, statements evaluating market and general economic conditions, and statements regarding future-oriented costs and expenditures. Investors are cautioned not to place undue reliance on these forward-looking statements, which reflect management's analysis only as of the date thereof. These forward-looking statements are subject to certain risks and uncertainties that could cause actual results to differ materially. Such risks and uncertainties with respect to the company include the effects of general economic conditions, actions by government authorities, uncertainties associated with legal proceedings and negotiations, competitive pricing pressures and mis-judgements in the course of preparing forward-looking statements.

WHO WE ARE

CHAR Technologies Ltd. operates as three groups:

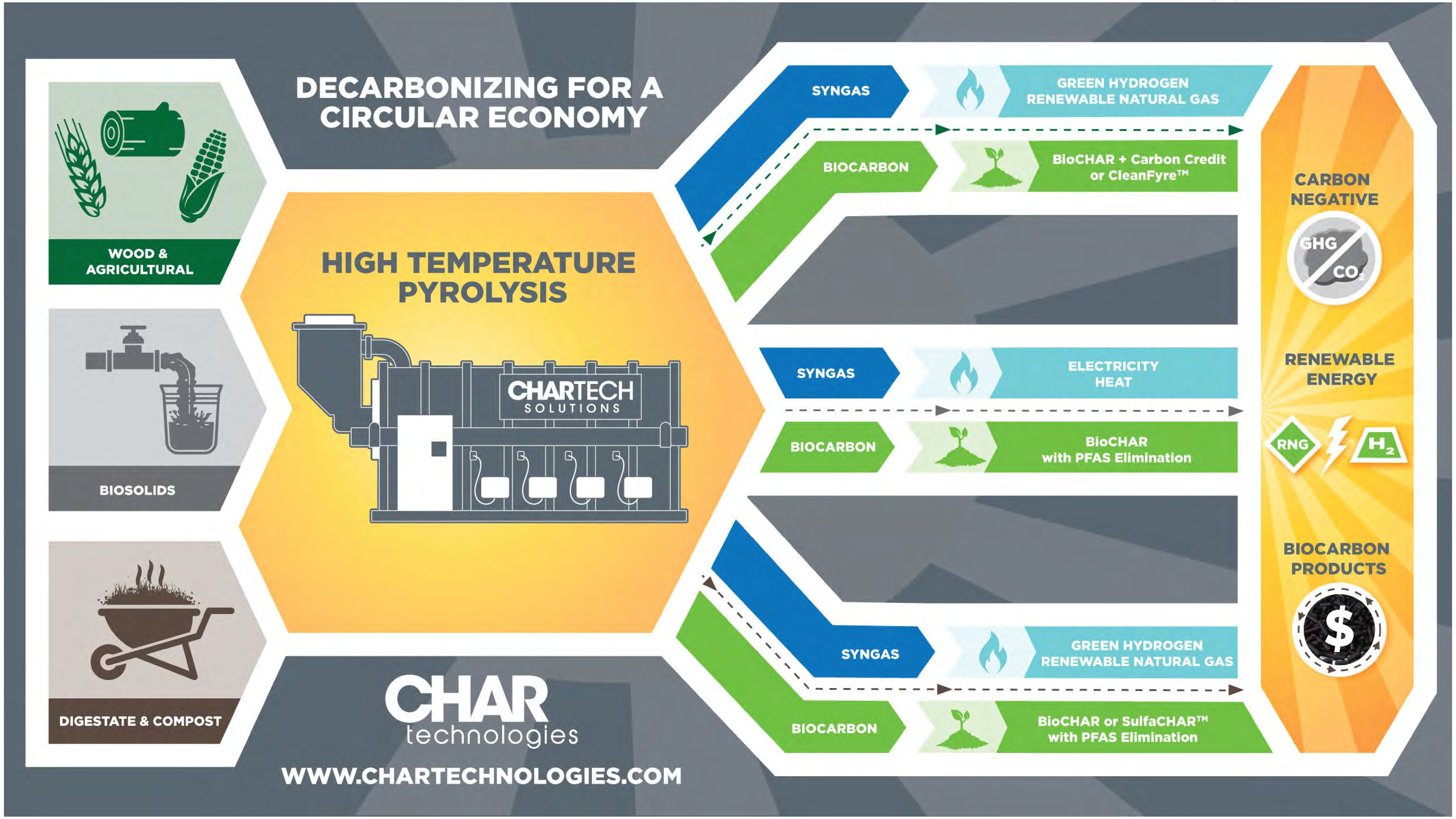
Altech Environmental Consulting Ltd. provides environmental compliance and engineering services

CHARTECH Solutions delivers advanced industrial clean technologies for clean water, waste reduction and renewable energy

CHAR Biocarbon provides pyrolysis plant operations, biocarbon and green energy gas production as well as pyrolysis products market development, offtake and R&D

HIGH TEMPERATURE PYROLYSIS (HTP)

CHARTECH SOLUTIONS



ACTIVE PROJECTS

CHARTECH SOLUTIONS

Thorold, Ontario

- Adjacent to sawmill operations in Archer Drive industrial park
- Process 72,000 tonnes per year woody waste
- Produce biochar (soil amendment & carbon credits) & biocoal
- Produce RNG
- In Construction (biocarbon pilot currently operating)

https://finance.yahoo.com/news/char-produces-biocoal-canada-largest-123000023.html

Saint-Felicien, Quebec

- Add-on to existing Greenfield Power Facility
- Process 36,000 tonnes per year of wood waste
- Produce biochar (soil amendment & carbon credits)
- Produce Syngas
- In Development

https://chartechnologies.com/char-technologies-project-in-saint-felicien-receives-2-8-million-in-government-funding/

Synagro

- Add-on to existing Synagro Facilities
- Mobile Demonstration system to process 9 TPD dried biosolids
- Produce biochar (soil amendment & carbon credits)
- Eliminate PFAS
- In Development

https://financialpost.com/globe-newswire/chartech-solutions-and-synagro-announce-partnership-for-high-temperature-pyrolysis-demonstration-project-to-eliminate-pfas-from-biosolids-and-generate-biochar

CHAR HTP VS. GASIFICATION

CHARTECH SOLUTIONS

High Temperature Pyrolysis (HTP)

- ✓ Oxygen-free, thermochemical conversion
- ✓ High-calorific value gas = no steam cycle addition
- ✓ High fixed carbon, low ash = high value biochar
- ✓ Operationally reliable in harsh conditions
- ✓ Compact footprint & lower CAPEX/OPEX

Gasification

- ✗ Oxygen, incomplete combustion
- ✗ Low-calorific value gas = steam cycle addition
- ✗ Low fixed carbon, high ash = low value biochar
- ✗ Reliability & operational challenges
- ✗ Large footprint & higher CAPEX/OPEX

HIGH TEMPERATURE PYROLYSIS (HTP) VALUE

CHARTECH SOLUTIONS

System Tour/Video

Carbon Negative –
Reduces net greenhouse gas (GHG) emissions.

Reduce Mass –
Reduces organics waste mass by up to 90%.

Energy Generation –
Pyrolysis gas fuels the system, and generates energy.

Value-Added Outputs –
Low-value organic waste streams converted into high value biocarbon products.

CHAR HAS BIOCARBON & PROCESS PATENTS FOR VALUE-ADD PRODUCTS FROM ORGANIC WASTES:

SulfaCHAR™ CATALYTIC DESULFURIZATION

CLEANFYRE

BIOCARBON APPLICATION – BIOCOAL

CHAR BIOCARBON

CLEANFYRE

- Produced from high temperature pyrolysis of wood waste between 600 – 800 °C
- Replaces fossil fuel coal in applications such as steel, cement and smelting processes
- CHAR recently received a 1,000-tonne order from one Canada's largest steel producers

CleanFyre v.s. Anthracite Coal:

Fuel	Energy Value	GHG Emissions
CleanFyre	32 MJ/kg (13 000 BTU/lb)	0.27 tonnes of CO_2/tonne
Anthracite coal[1]	29 MJ/kg (12 000 BTU/lb)	2.9 tonnes of CO_2/tonne

- 1 tonne of CleanFyre replaces 1.1 tonnes of Anthracite, reducing net GHG emissions by 2.90 tonnes of CO_2 per tonne of fuel

BIOCARBON APPLICATION – ADSORBENT

CHAR BIOCARBON

- SulfaCHAR as an adsorbent supplement can be valued at **$1000 CAD/t biocarbon**
- SulfaCHAR can also generate additional value as a sulfur-rich fertilizer, at **$500/t biocarbon**

SulfaCHAR™
CATALYTIC DESULFURIZATION

Feedstock

Low value digestate or compost.

Production

High Temperature Pyrolysis (in the absence of oxygen). The secret sauce (IP protected).

Use

Add SulfaCHAR into a vessel for gas to flow through for supplemental H_2S & odour treatment.

End-of-Life

Sulfur-rich biochar fertilizer. University of Guelph validated enhanced corn growth using SulfaCHAR.

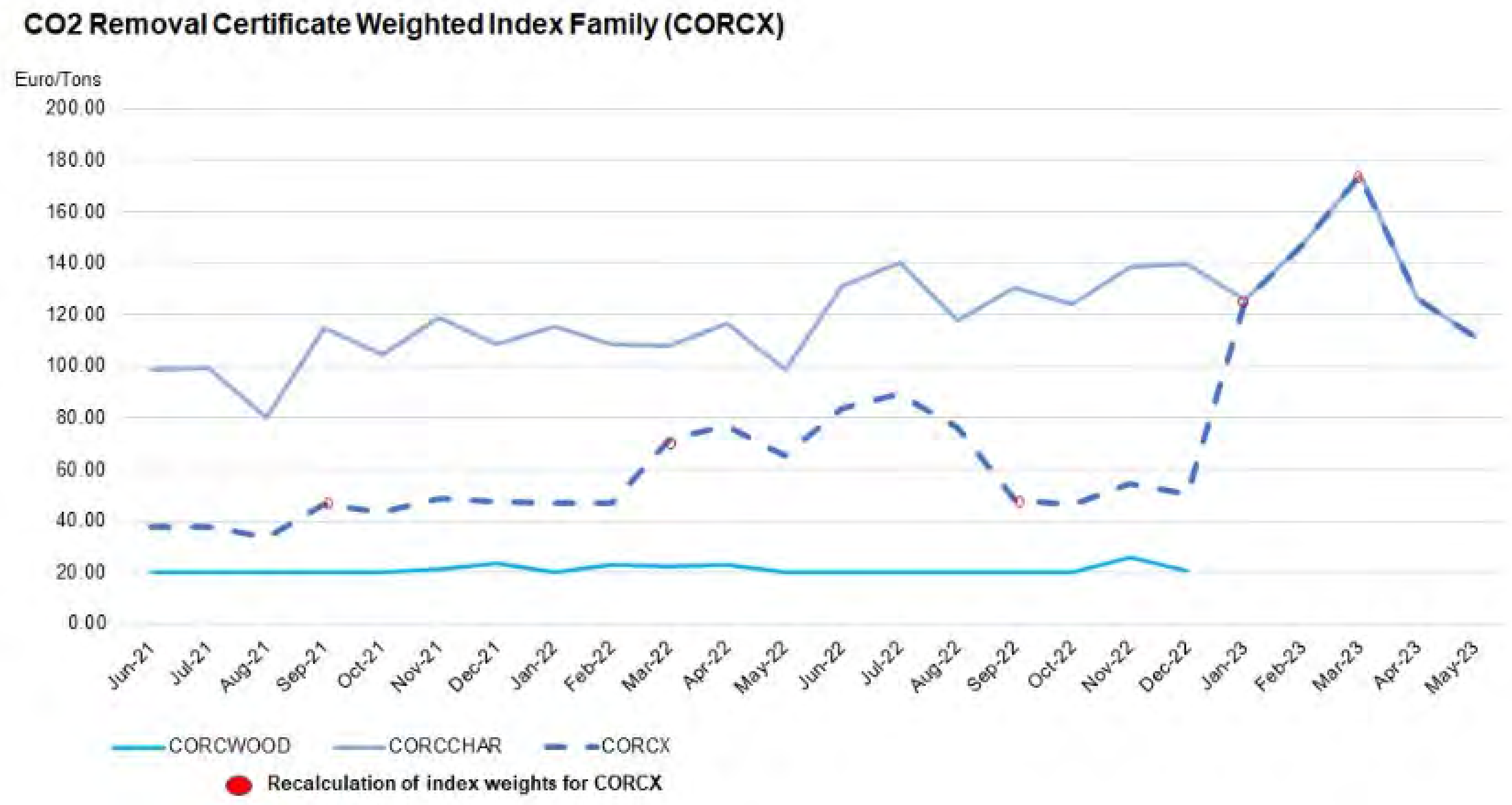
BIOCARBON APPLICATION – BIOCHAR & CARBON CREDITS

CHAR BIOCARBON

- Biochar is produced from organic feedstocks through pyrolysis to create a high-value biochar/fertilizer
- Biochar benefits:
  1. Retains water in dry soils
  2. Improves soil structure
  3. Sequesters carbon in the ground
  4. Holds nutrients in the soil
  5. Reduces odour
- **Biochar can be valued at $100-200 CAD/tonne**

Biochar Carbon Credits – Voluntary Market

- In 2022, Puro.Earth opened all biochar sources to carbon credit application, and the ability to pre-sell biochar carbon credits (Pre-CORCs) to finance projects!
- Microsoft and Shopify spent $10 million+ on CORCs in 2022, and Nasdaq recently acquired Puro.Earth
- **The CO2 Removal Certificate Weighted Index Family (CORCX) value has ranged from €80-200 EUR, the current price as of May 2023 is €110 EUR/$118 USD:**



ENERGY APPLICATION – RNG

Renewable Natural Gas (RNG)

RNG from Pyrolysis

- Pyrolysis is a second-generation technology that can convert woody material into RNG
- In Canada, utilities are offering $20-30/GJ for RNG
- In the USA, 157 operational projects in 2020 produced over 59 million MMBtu, the equivalent of over 459 million gallons of diesel

Jurisdiction	RNG Target	Utility
California	20% by 2030	SoCalGas
Vermont	20% by 2030	Vermont Gas
British Columbia	15% by 2030	FortisBC
Québec	10% by 2025	Énergir

ENERGY APPLICATION - GREEN HYDROGEN

CHAR BIOCARBON

Across North America, **CHAR is well positioned for the growing demand for hydrogen energy** and is a leader in distributed green hydrogen generated from biomass including anaerobic digestate and biosolids.

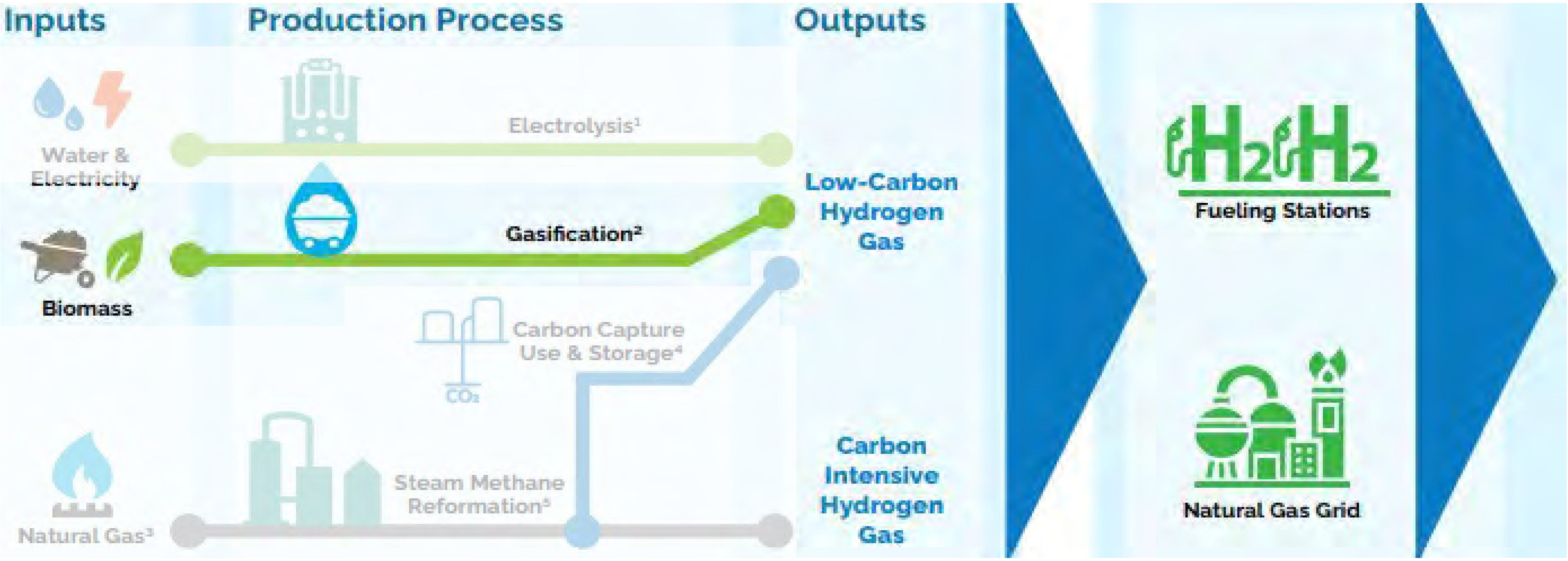
✓ Canada has a $1.5B Low-carbon and Zero-Emissions Fuels Fund to increase hydrogen production.

✓ Demand for hydrogen in the US could reach 41 million mt/year by 2050. (National Renewable Energy Laboratory report)

Our first facility in California will generate 50 kg/hr of green hydrogen.

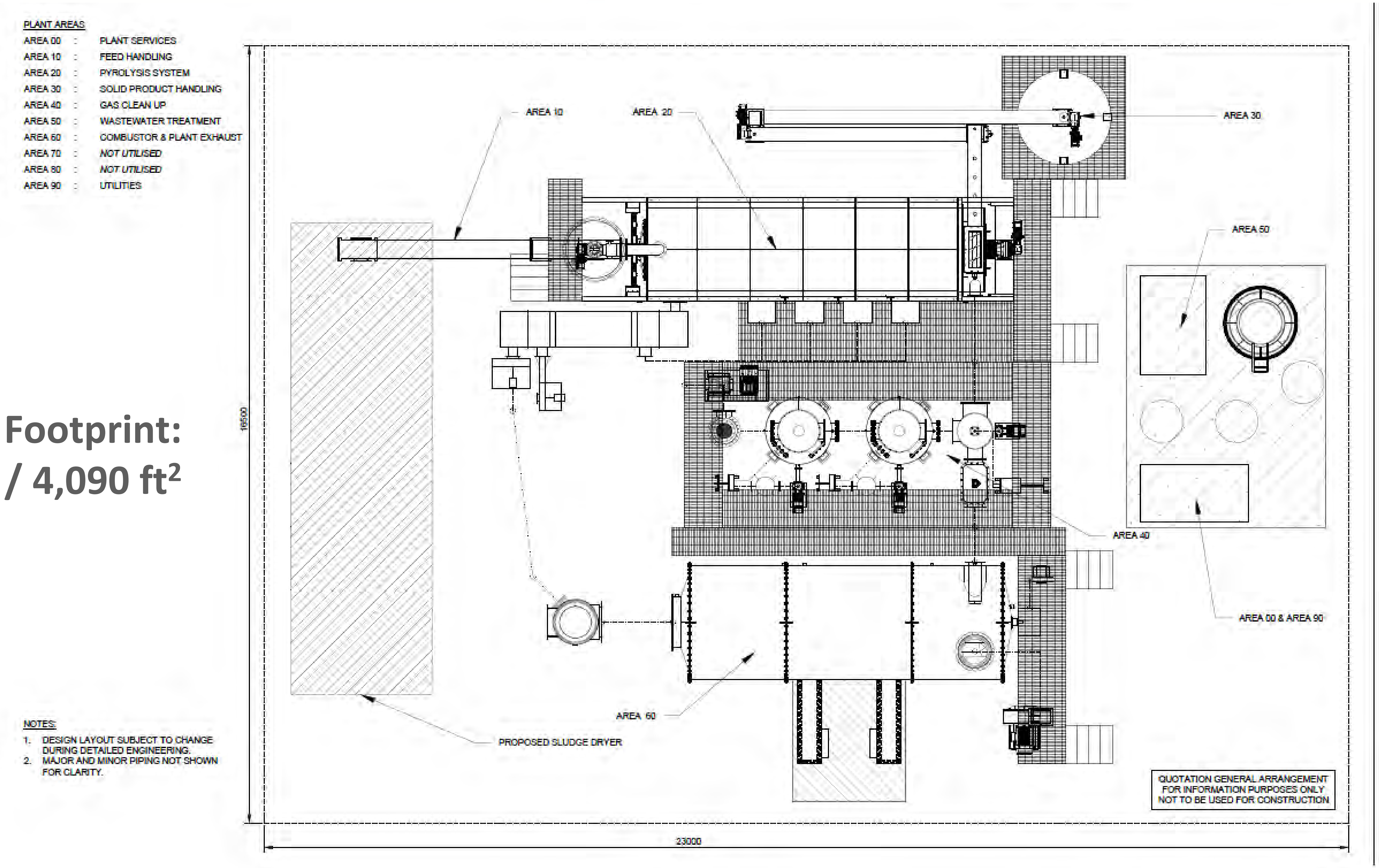
H_2 Opportunity

	2030	2050
% of Delivered Energy	6%	30%
Hydrogen Demand	4 Mt-H_2	20 Mt-H_2
GHG Emissions Abated	up to 45 Mt-CO_2e	up to 190 Mt-CO_2e



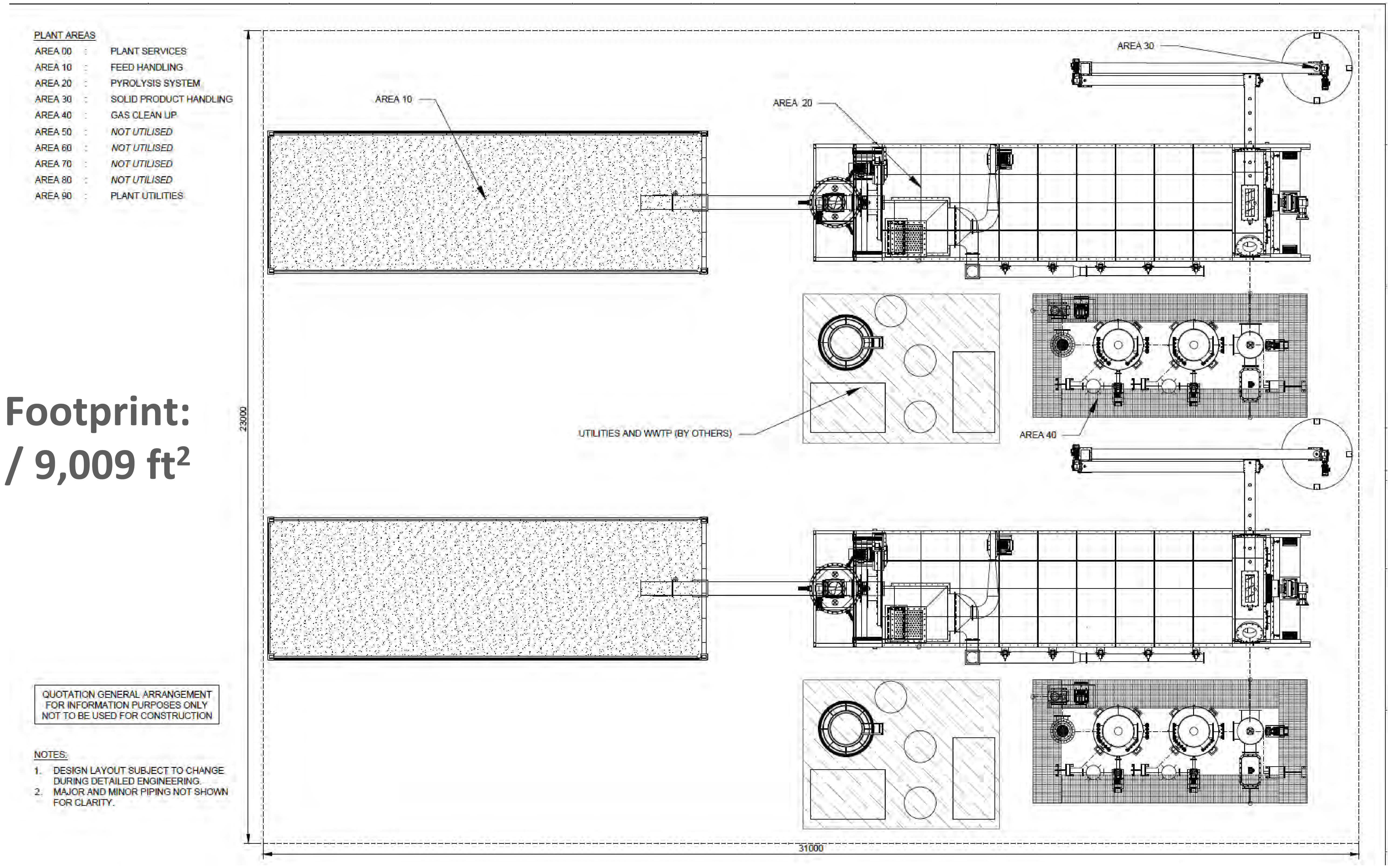
SYSTEM TOP VIEW: 20,000 TPY OF SLUDGE, 35% TS

Total Footprint:
380 m^2 / 4,090 ft^2



SYSTEM TOP VIEW: 60,000 TPY OF WOOD, 90-100% TS

Total Footprint:
837 m^2 / 9,009 ft^2

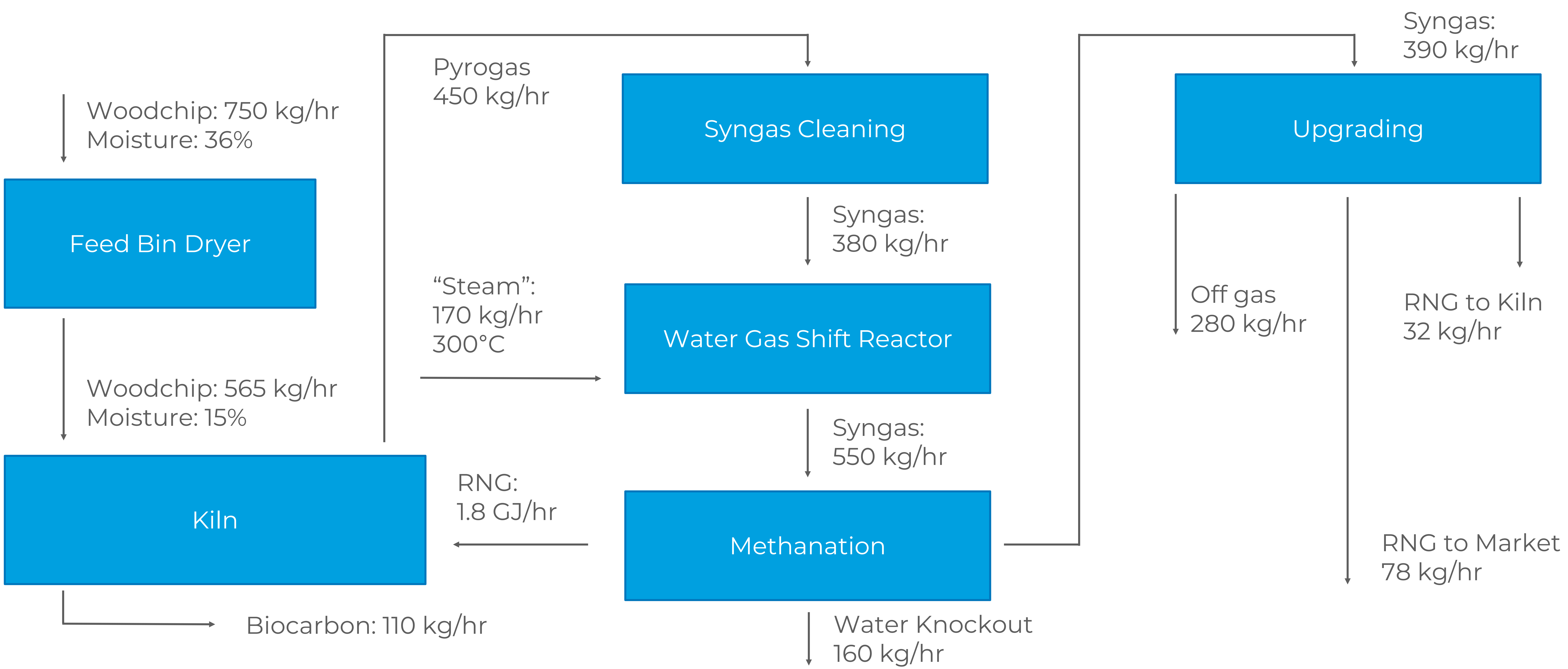


CHAR technologies

YES LISTED ON TMX TSX Venture Exchange

WOOD WASTE TO RNG HTP PROCESS FLOW

CHAR BIOCARBON



WOOD WASTE: HTP MASS BALANCE & GAS QUALITY

CHAR BIOCARBON

	Input Wood waste	Output 1: RNG	Output 2: Biocarbon
Flow (kg/hr)	750	78 (4.3 GJ/hr)	110

%v/v	Pyrogas	Syngas post Scrub.	Syngas post WGS	Syngas post Meth.	Off gas to Stack	RNG Stream
Flow (kg/hr)	450	380	550	550	280	110
CH_4	-	8%	4%	30%	-	98%
H_2	30%	35%	58%	1%	3%	-
CO	27%	32%	9%	<1%	-	-
CO_2	13%	16%	27%	28%	95%	-
H_2O	15%	2%	2%	40%	2%	-
Other HC	15%	7%	<1%	<1%	-	2%

WOOD WASTE HTP – MASS BALANCE

Parameter	HP870	HP1300	HP2100
Quantity (TPY)	4,000	14,500	30,000
Moisture Content	15%	15%	15%
Biocarbon Production (TPY)	625	2,267	4,690
Quantity Reduction	84%	84%	84%
Carbon Credits Available (CORC/Yr)	1,786	6,473	13,392
Net Available Syngas (GJ/Yr)	35,540	109,306	228,705
Electricity Available (MWh/Yr)	12,181	44,156	91,357
Hydrogen Available (Kg/Yr)	68,414	210,412	440,250
Net RNG Available with Catalytic Conversion (GJ/Yr)	18,462	56,782	118,807

WOOD WASTE HTP – SYNGAS BUSINESS CASE

CHARTECH SOLUTIONS

Parameter	4K TPY	14.5 TPY	30K TPY
Yearly Syngas Value	$177,700	$546,532	$1,143,524
Yearly Biocarbon Sale	$125,056	$453,328	$937,920
Yearly Carbon Credit Sale	$214,273	$776,739	$1,607,046
Feedstock Cost	-$120,000	-$435,000	-$900,000
Estimated Non-Labour OPEX	-$200,000	-$300,000	-$400,000
Gross Revenue	**$197,029**	**$1,041,599**	**$2,388,489**
Estimated CAPEX (CAD)	**$4,000,000**	**$7,000,000**	**$10,000,000**

Assumptions:

1. *Syngas Value: $5/GJ*
2. *Biocarbon Sale: $200/tonne*
3. *Carbon Credit Value: $120/CORC*
4. *Feedstock Cost: $30/tonne*

WOOD WASTE HTP – RNG BUSINESS CASE

CHARTECH SOLUTIONS

Parameter	4K TPY	14.5 TPY	30K TPY
Yearly Syngas Value	$612,435	$1,883,597	$3,941,099
Yearly Biocarbon Sale	$125,056	$453,328	$937,920
Yearly Carbon Credit Sale	$214,273	$776,739	$1,607,046
Feedstock Cost	-$120,000	-$435,000	-$900,000
Estimated Non-Labour OPEX	-$400,000	-$500,000	-$600,000
Gross Revenue	**$431,764**	**$2,178,664**	**$4,986,065**
Estimated CAPEX (CAD)	**$10,000,000**	**$15,000,000**	**$25,000,000**

Assumptions:

1. *RNG Value: $35/GJ*
2. *Biocarbon Sale: $200/tonne*
3. *Carbon Credit Value: $120/CORC*
4. *Feedstock Cost: $30/tonne*

WOOD WASTE HTP TO RNG – GHG & CI SCORE

CHARTECH SOLUTIONS

Case	Anticipated CI* (gCO_{2e}/MJ)	Anticipated GHG Reductions** (Total tonneCO_{2e}/year)	Equivalent GHG production from cars
1: Waste Wood to RNG and CleanFyre	-58	-40 000	7800 cars[1] per year
2: Waste Wood to RNG and Biochar	4	-20 000	3800 cars per year

***Production* of renewable natural gas (RNG) only, not use thereof.*
The boundary conditions are set surrounding the pyrolysis kiln only.
**Includes the use of RNG to displace fossil natural gas
[1]https://afdc.energy.gov/vehicles/electric_emissions.html

DAIRY DIGESTATE – LCFS/CARBON INTENSITY

CHARTECH SOLUTIONS

Dairy Digestate

- EcoEngineers completed a study which evaluated the carbon intensity (CI) impact of CharTech Solutions High Temperature Pyrolysis (HTP) technology when used to treat the digestate effluent from anaerobic digesters producing Renewable Natural Gas (RNG).

- The study concluded that HTP shows a significant enhancement of the CI score, with a range from 19 to 35 grams of CO2, eq per Megajoule for the reference case of a dairy.
- "At an LCFS Credit Price of $200/MT CO2, this represents an additional LCFS credit revenue of $4 -$7.50 per MMBTU of RNG"
  - Dr. Zhichao Wang, Senior Engineer and Carbon Analyst for Eco Engineers.

- A 12,000 head dairy producing RNG and using CHAR's HTP System to convert digestate into valuable outputs could:
  - Generate over $50M in additional revenue
  - Realize a short 2-year payback period on Capex for the HTP system

**The actual CI Score impact of CHAR's HTP System will be determined on a per project basis.*

SSO DIGESTATE HTP – MASS BALANCE

Based on recently conducted pilot-scale pyrolysis tests:

Parameter	HP870	HP1300	HP2100
Quantity (TPY)	7,165	22,046	44,092
Moisture Content	40%	40%	40%
Biocarbon Production (TPY)	2,198	6,764	13,529
Quantity Reduction	69%	69%	69%
Carbon Credits Available (CORC/Yr)	731	2,249	4,497
Net Available Syngas (MMBtu/Yr)	-25,653	-10,242	15,719

SSO DIGESTATE HTP –SYNGAS BUSINESS CASE

Parameter	7K TPY	22K TPY	44K TPY
Nat Gas Offset Savings ($)	-$135,222	-$53,987	$82,860
Biocarbon Sale	$199,210	$612,953	$1,225,907
Carbon Credit Value	$73,077	$224,852	$449,704
Transportation/Management Fee Avoidance	$104,035	$320,107	$640,214
Estimated Non-Labour OPEX	-$200,000	-$300,000	-$400,000
Net Revenue	**$41,100**	**$803,926**	**$1,998,686**
Estimated CAPEX (USD)	**$6,000,000**	**$8,000,000**	**$11,000,000**

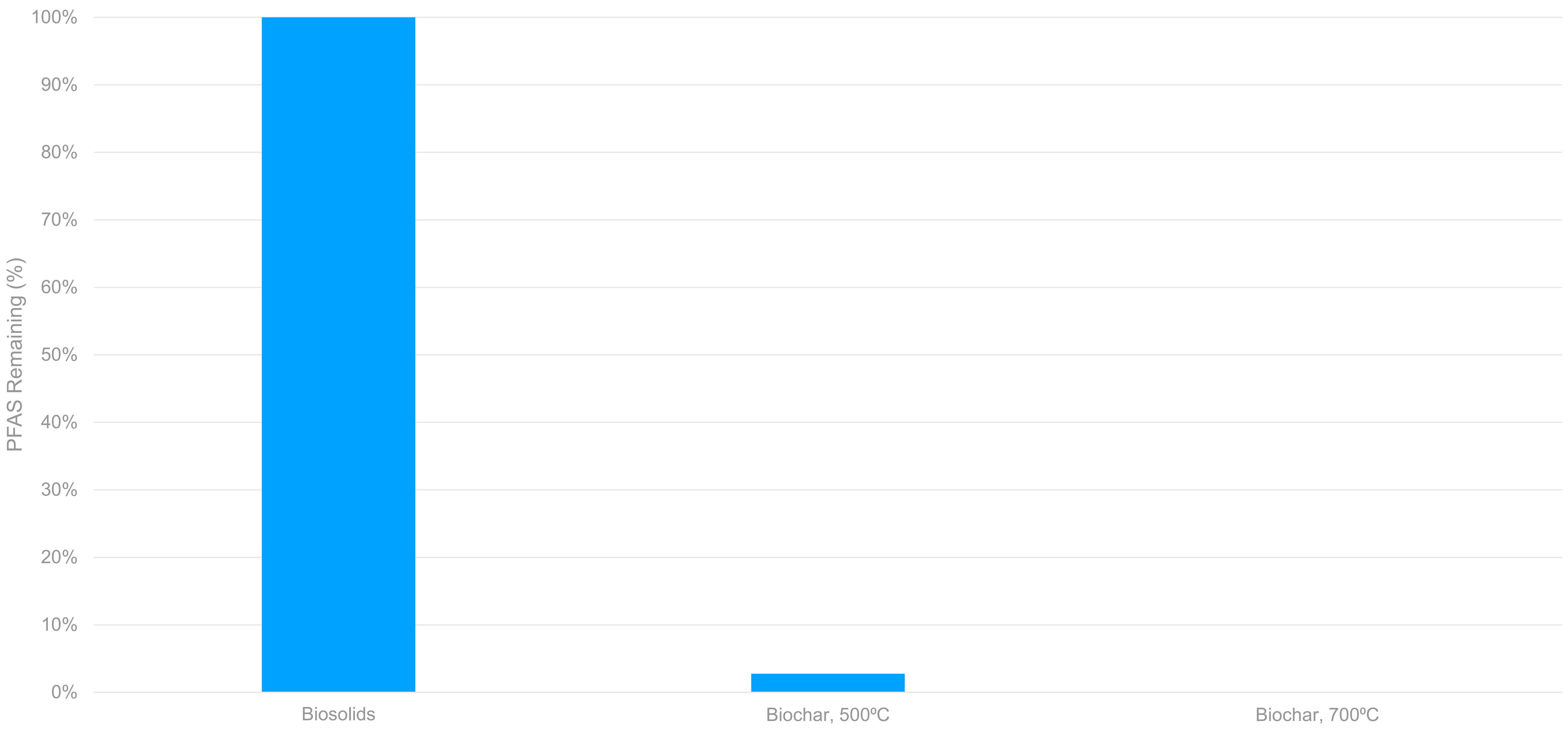
Assumptions:

1. *Natural Gas Price: $5/MMBTU*
2. *Biocarbon Sale: $100/ton*
3. *Carbon Credit Value: $100/CORC*
4. *Transportation/Management Fee: $20/ton*

BIOSOLIDS – HTP PFAS REMOVAL

CHAR BIOCARBON

Presented in Aggregate of 28 Recognized PFAS Contaminants:



At 500°C, what's still present?
- PFHxA (concentration decrease)
- PFOA (concentration **increase**)
- PFHxS (concentration **increase**)

*remember mass yields

At 700°C, all 28 recognized PFAS contaminants are eliminated from the solid fraction.

BIOSOLIDS HTP – MASS BALANCE

CHARTECH SOLUTIONS

Based on recently conducted pilot-scale pyrolysis tests:

Parameter	HP870	HP1300	HP2100
Quantity (TPY)	4,409	15,432	30,865
Moisture Content	10%	10%	10%
Biocarbon Production (TPY)	1,617	5,659	11,319
Quantity Reduction	63%	63%	63%
Carbon Credits Available (CORC/Yr)	892	3,122	6,243
Net Available Syngas (MMBtu/Yr)	23,967	85,583	173,429

BIOSOLIDS HTP – SYNGAS BUSINESS CASE

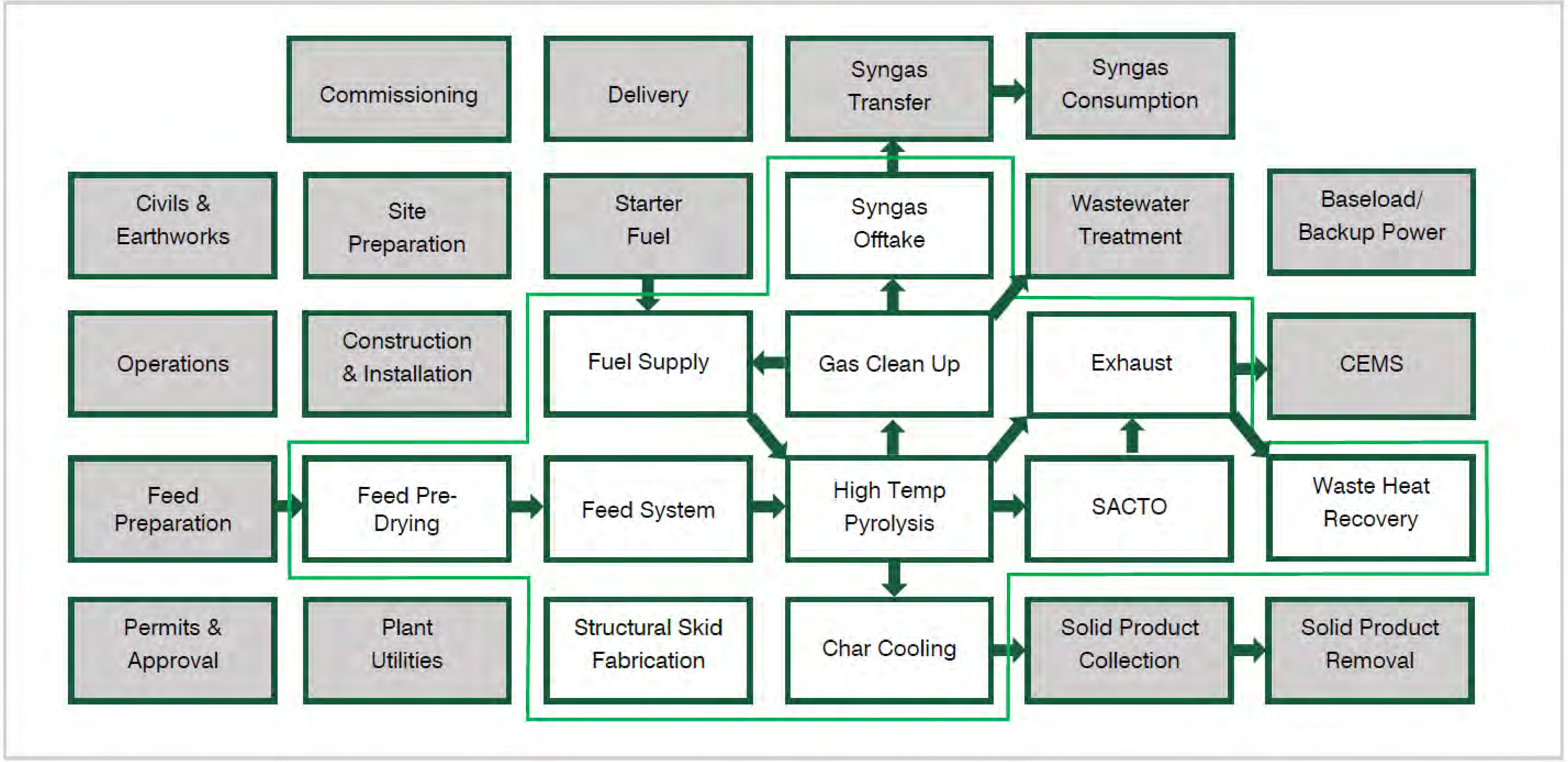
Parameter	4.4K TPY	15.4K TPY	30.8K TPY
Nat Gas Offset Savings ($)	$126,336	$451,127	$914,188
Biocarbon Sale	$109,944	$384,804	$769,608
Carbon Credit Value	$89,189	$312,161	$624,321
Transportation/Management Fee Avoidance	$119,967	$419,884	$839,768
Estimated Non-Labour OPEX	-$200,000	-$300,000	-$400,000
Net Revenue	**$245,436**	**$1,267,975**	**$2,747,885**
Estimated CAPEX (USD)	**$4,000,000**	**$6,000,000**	**$8,000,000**

Assumptions:

1. *Natural Gas Price: $5/MMBTU*
2. *Biocarbon Sale: $75/ton*
3. *Carbon Credit Value: $100/CORC*
4. *Transportation/Management Fee: $30/ton*

CHARTECH HTP - SYSTEM SCOPE

CHARTECH SOLUTIONS



CHAR HTP PROJECT BENEFITS

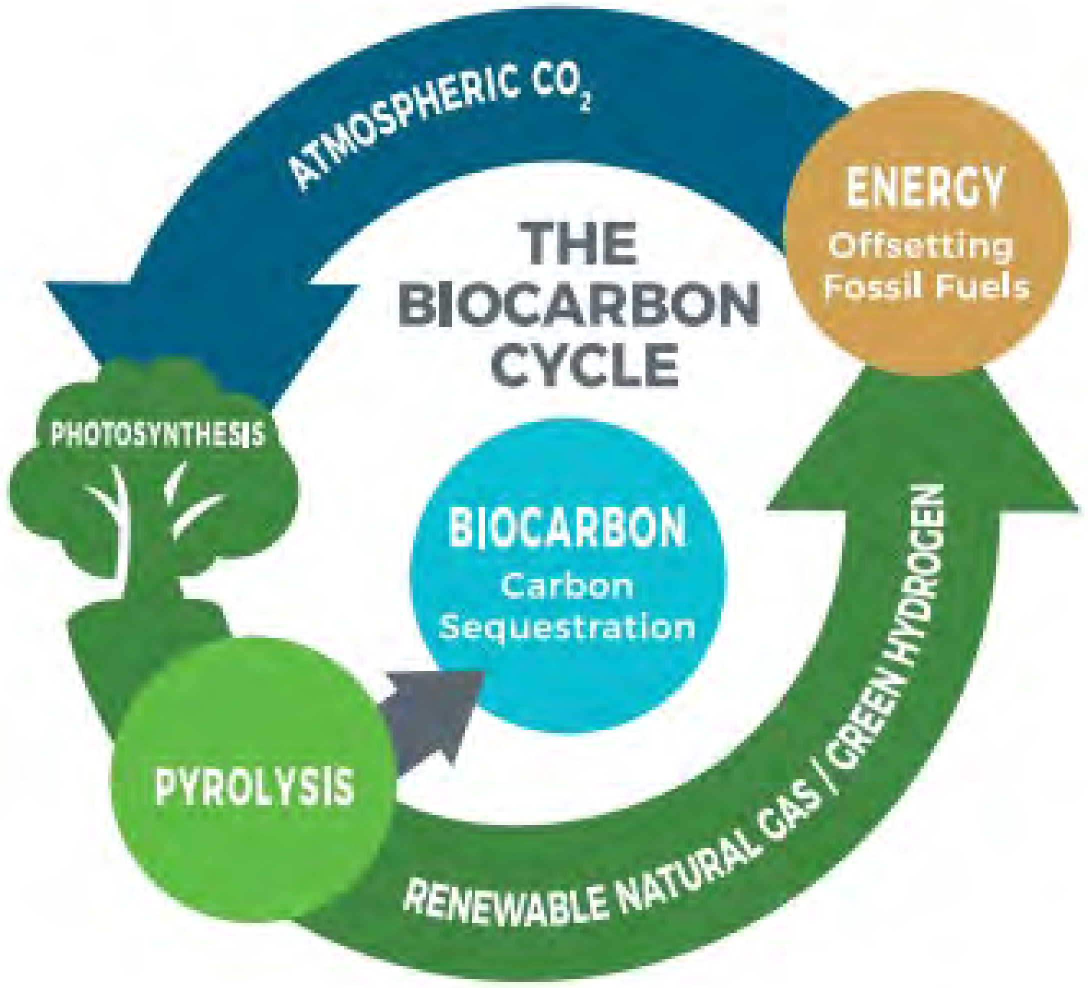
1. **Greenhouse Gas (GHG) Emission Reduction:** 10 year average impact = 607,770 t-$CO_{2,eq}$

2. **Job Creation:**
   - Permanent: Two (2) management + Six (6) Operations staff = 8 new jobs
   - Ongoing Indirect: Contracts for local skilled trades (maintenance & support)

3. **Recreational:** Odours are eliminated at high temperature, quiet operation

4. **Socioeconomic:** Compact, scalable system allows for minimal impacts on surroundings

5. **Compliance:** Environmental Compliance Approval (ECA) issued by the Ontario Ministry of the Environment



CHAR HTP BUSINESS MODEL OPTIONS

Capital Purchase: The HTP System is purchased outright by the client.

Lease/Lease-to-Own: The HTP System capex value is distributed as a monthly/quarterly lease to the client, with the ability to add a buyout option after 5-10 years.

JV/SPV: CHAR & the client establish a joint venture (JV) / special purpose vehicle (SPV), where both parties provide equal investment in the project. Typically, the partner provides a site, feedstock, while CHAR provides the HTP system and biocarbon offtake. Revenues from the project outputs (both biocarbon and gas) are shared over an established time period.

BOOT - Build-Own-Operate-Transfer: CHAR moves the project forward as the initial project owner by financing the cost of the HTP system, with the client providing system operations and the site/infrastructure. While CHAR owns the assets, CHAR receives revenues directly for the project outputs (energy and biocarbon). Upon executing the transfer, at their option, the partner purchases the equipment. Ongoing project output revenues are dispersed based on a predefined agreement.

Long-Term Offtake: Applying only for woody biomass feedstocks, CHAR can provide a long-term offtake agreement for wood residuals at a set value to generate biocarbons and renewable natural gas.

INNOVATIVE SOLUTIONS THAT CONTRIBUTE TO THE CIRCULAR ECONOMY

CharTech Solutions develops and delivers innovative environmental technology solutions to eliminate air and water pollution and convert challenging waste streams into renewable and valuable outputs, helping our clients contribute to the circular economy.

WHY WORK WITH CHAR?

CHAR is a cleantech company that provides innovative environmental solutions to eliminate liquid and solid organics pollution - contributing to the circular economy.

- ✓ **Innovative HTP Technology** converts organic feedstocks into renewable gases, heat, and biocarbons (biochar)
- ✓ **Patented Biocarbon Outputs**, in addition to traditional biochar fertilizer, CHAR developed a zero-waste adsorption media supplement SulfaCHAR™ and breakthrough biocoal CleanFyre™
- ✓ **Reduce Carbon and Waste** – Reduce waste mass by up to 90%, eliminate transportation, and generate carbon offsetting biocarbon / renewable energy to decarbonize operations

Andrew Friedenthal
Business Development Manager

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ATTACHMENT 8

Hydrothermal Liquefaction to Convert Organic Wet Wastes to Transportation Fuels
DE-FOA-0002636
Topic Area 4: Community Scale Resource and Energy Recovery from Organic Wastes
GLWA 2636-1644

Team Member Organizations
Great Lakes Water Authority: Dr. Xavier Fonoll Almansa, Dr. John Norton
Genifuel: James Oyler
PNNL: Dr. Michael Thorson, Dr. Lesley Snowden Swan, Dr. Uriah Kilgore
Wayne State University: Dr. Carol J. Miller

A collaboration between The Great Lakes Water Authority (GLWA), PNNL, Genifuel, and Wayne State University seeks to turn wet wastes into opportunities for energy recovery through use of hydrothermal liquefaction (HTL). Wastewater solids from water resource recovery facilities (WRRF), if left untreated, present ecological and human health liabilities. As a result, they must be continually and carefully managed. The HTL process has advantages compared to alternative wet waste disposal methods including complete treatment of pollutants, reduction of wastewater operational costs, resource recovery from wastes, and reduced ecological impacts. This collaboration is taking a community centered approach to evaluate the potential of HTL and to measure the social, ecological, and economic impacts of implementing the technology in the Detroit region. At the conclusion of this two-phase project, the team will have demonstrated a replicable, community-driven implementation of the technology and how the approach can be tailored to the unique needs of communities across the US.

In Phase 1, the team will engage community leaders and conduct a feasibility assessment to build the business case, and develop an implementation plan for HTL-based waste disposal and energy recovery from wet wastes in the Detroit region. Community outreach will also include workshops and education. Through these engagements, the team will gather the necessary input and feedback to drive an implementation approach having the ability to re-lift a region once strong in manufacturing. The project will also explore expanding the HTL feedstocks to include other local wastes such as food wastes, yard wastes, and wastepaper. As part of the HTL feedstock study, the team will examine the impacts on local employment, waste collection, biosolids volume reduction, operation and maintenance of each system, impact on wastewater treatment operations, quality and value of energy (biocrude) generated, third party owner operations (including the availability of third-party operators), pollutant destruction, energy generation, GHG emissions, and process economics.

In the demonstration phase (Phase 2) the team will bring a mobile HTL reactor unit to GLWA to achieve 3 objectives: community engagement and education, technology demonstration, and regional feedstock conversion testing against the social, economic, and ecological impact metrics established in Phase 1. In community engagement and education demonstrations, residents and organizations in the region will have the opportunity to see HTL reactors and operations in person. Through technology demonstrations and engagement with eight of the largest WRRFs in the country on this project, we ensure the information is widely disseminated, that risks are addressed and incorporated and stakeholders are included in the feasibility analysis. Finally, the feedstock conversion tests will ultimately result in a fuel sample derived from a blend of local wastes which will be evaluated for suitability as a diesel fuel.

Pacific Northwest
NATIONAL LABORATORY

PNNL-37152

Evaluate Synergies of Using Hydrothermal Liquefaction and Anerobic Digestion Treatment Technologies for Wastewater Resource Recovery Facilities (CRADA 516 Final Report)

December 2024

Andrew Schmidt, Michael Thorson
Pacific Northwest National Laboratory

Xavi Fonoll, John Norton
Great Lakes Water Authority

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830

Pacific Northwest National Laboratory
Richland, Washington 99354

Cooperative Research and Development Agreement (CRADA) Final Report

Report Date: November 2024

In accordance with Requirements set forth in the terms of the CRADA, this document is the CRADA Final Report, including a list of Subject Inventions, to be provided to PNNL Information Release who will forward to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research. **PNNL acknowledges that the CRADA parties have been involved in the preparation of the report or reviewed the report.**

Parties to the Agreement:

Great Lakes Water Authority (GLWA)
Pacific Northwest National Laboratory (PNNL)

CRADA number: 516

CRADA Title: Evaluate synergies of using Hydrothermal Liquefaction and Anerobic Digestion treatment technologies for wastewater resources recovery facilities

Responsible Technical Contact at DOE Lab(PNNL): Andrew Schmidt

Name and Email Address of POC at Partner Company(ies):

John Norton

john.norton@glwater.org

Sponsoring DOE Program Office(s):

BioEnergy Technology Office

Joint Work Statement Funding Table showing DOE funding commitment:

	Funding Amounts			
CRADA Parties	**DOE Funding**	**Funds-In**	***In-kind**	**Total**
Great Lakes Water Authority	None	None	$465,750	$475,750
DOE Funding to PNNL	$275,000	N/A	N/A	$275,000
Total of all Contributions	$275,000	None	$465,750	$740,750

Provide a list of publications, conference papers, or other public releases of results, developed under this CRADA:

Cronin, Dylan, et al. "Comparative study on the continuous flow hydrothermal liquefaction of various wet-waste feedstock types." *ACS Sustainable Chemistry & Engineering* 10.3 (2021): 1256-1266.

Snowden-Swan, Lesley J., et al. *Wet waste hydrothermal liquefaction and biocrude upgrading to hydrocarbon fuels: 2021 state of technology*. No. PNNL-32731. Pacific Northwest National Lab.(PNNL), Richland, WA (United States), 2022.

Fonoll et al. "Using a Recirculating Anaerobic Dynamic Membrane Bioreactor to treat hydrothermal liquefaction aqueous by-product". Submitted to Frontiers in Chemical Engineering.

X. Fonoll*, A. Schmidt, A. Busch, M. Thorson, J. Norton. Using a Recirculating Anaerobic Dynamic Membrane Bioreactor to Treat Hydrothermal Liquefaction Aqueous By-Product: Reactor Performance and Microbial Community. 18th IWA World Conference on Anaerobic Digestion (AD-18). June 2028.

X. Fonoll*, A. Schmidt, A. Busch, M. Thorson, J. Norton. Great Lakes Water Authority research efforts on hydrothermal liquefaction to recover energy from sludge. MWEA biosolids conference. March 2023.

X. Fonoll*, A. Schmidt, A. Busch, M. Thorson, J. Norton. Using A Novel Anaerobic Technology to Treat Hydrothermal Liquefaction Aqueous By-product. 17th IWA World Conference on Anaerobic Digestion (AD-17). June 2022.

X. Fonoll*, A. Schmidt, A. Busch, M. Thorson, J. Norton. Reducing the Toxicity in Hydrothermal Liquefaction aqueous phase using a New Anaerobic Digestion Bioreactor to maximize resource recovery from sludge. Residuals and Biosolids Conference. May 2022.

X. Fonoll*, A. Schmidt, A. Busch, M. Thorson, J. Norton. Using A Novel Anaerobic Technology to Treat Hydrothermal Liquefaction Aqueous By-product. IWA LET 2022. March 2022.

X. Fonoll*, A. Schmidt, A. Busch, M. Thorson, J. Norton. Energy recovery from sludge through production of biocrude and methane using hydrothermal liquefaction and a novel anaerobic digestion bioreactor. European Biosolids & Bioresources Conference. November 2021.

X. Fonoll. Next Generation Biosolids. Eckenfelder Lecture Series 2024. Denton (TX), USA, November 2024.

X. Fonoll. Using A New Anaerobic Digestion Configuration to Treat Hydrothermal Liquefaction Aqueous By-product. IEA Bioenergy Task 36: Treating and valorizing the aqueous phase from hydrothermal liquefaction (HTL). Online presentation (2024).

X. Fonoll. Using A Novel Anaerobic Technology to Treat Hydrothermal Liquefaction Aqueous By-product. Hydrothermal Liquefaction in Metro Vancouver workshop. Vancouver, Canada, June 2022.

Provide a detailed list of all subject inventions, to include patent applications, copyrights, and trademarks:

None

Executive Summary of CRADA Work

The research focuses on utilizing a new anaerobic digestion (AD) configuration to treat the aqueous by-product generated by hydrothermal liquefaction (HTL) of sewage sludge. This report found that for Anaerobic Digestion for HTL By-product, Anaerobic biofilms can degrade some HTL wastewater contaminants, but co-digestion is essential to address nutrient deficiencies and optimize performance. Without AD, toxicity of HTL aqueous streams may limit broader adoption in wastewater treatment plants (WWTPs). Great Lakes Water Authority (GLWA) used an innovative reactor design, involving a dynamic membrane anaerobic bioreactor to promote biofilm growth, improving contaminant degradation. The tree-like structure inside the reactor supports biofilm development with recirculation enhancing microbial activity. Overall, a 70% chemical oxygen demand (COD) removal was achieved, although nutrient supplementation is required for stability. The reactor achieved a diverse microbial community, including methanogens and bacteria capable of degrading phenols and aromatics.

Summary of Research Results

1. Introduction

Municipal wastewater treatment generates substantial amounts of sludge, presenting both a disposal challenge and an opportunity for resource recovery. Traditional methods of sludge management, such as land application or incineration, have limitations due to environmental concerns and regulatory constraints. Hydrothermal liquefaction (HTL) has emerged as a promising technology to convert wet biomass like sewage sludge into valuable biofuels and bioproducts without the need for extensive dewatering. HTL processes sludge under high temperature and pressure in the presence of water, producing biocrude oil, gas, solids, and an aqueous byproduct (HTL-AB).

While HTL effectively transforms sludge into energy-rich products, the resultant HTL-AB contains a complex mixture of organic compounds, including nitrogenous substances like pyrrolidine and pyrazine. These compounds can be toxic to microbial communities and pose a challenge for downstream treatment processes. Traditional wastewater treatment systems often require significant dilution of HTL-AB to mitigate toxicity before biological treatment, which is impractical for large-scale implementation due to increased volume and associated costs.

Developing efficient methods to treat HTL-AB without excessive dilution is crucial to advancing HTL as a viable sludge management and resource recovery option. Anaerobic digestion presents a potential solution by converting organic contaminants in HTL-AB into methane-rich biogas, thus providing a pathway for energy recovery. However, standard anaerobic digesters may not effectively process HTL-AB due to its inhibitory compounds and nutrient imbalances.

The Recirculating Anaerobic Dynamic Membrane Bioreactor (R-AnDMBR) is a novel treatment system designed to enhance anaerobic biodegradation of complex waste streams. By promoting biofilm formation on a dynamic membrane, the R-AnDMBR increases microbial retention and resilience against toxic compounds. The system recirculates the feedstock through the biofilm-coated membrane, allowing prolonged contact between microbes and contaminants, which can enhance degradation efficiency.

This study explores the application of the R-AnDMBR for treating HTL-AB generated from municipal wastewater sludge. The primary objectives are to assess the system's efficiency in reducing chemical oxygen demand (COD) and toxic compounds without extensive dilution, to evaluate methane production for energy recovery, and to identify operational challenges such as nutrient limitations. By addressing these objectives, the research aims to contribute to the development of sustainable and integrated sludge management strategies that maximize resource recovery at wastewater treatment facilities.

2. Results

Substrate and Inoculum Preparation
A mixture of primary and secondary sludge was collected from the Great Lakes Water Authority (GLWA) Water Resource Recovery Facility (WRRF) in Detroit, USA and transported under refrigeration to the Pacific Northwest National Laboratory (PNNL). Upon arrival, the sludge was stored at 4°C until processing. The collected sewage sludge was subjected to continuous-flow hydrothermal liquefaction (HTL) at PNNL. The HTL system operated under subcritical water conditions at a temperature of 350°C and a pressure of 2900 psi. The sludge was processed as

a 15.5% (wt/wt) slurry at a flow rate of 12 L/h, resulting in a liquid hourly space velocity of 4 L L^{-1} h^{-1}, corresponding to a residence time of 15 minutes. The biocrude oil produced was separated by gravity from the aqueous phase without the use of solvents. The aqueous byproduct (HTL-AB) generated from this process was collected and shipped to GLWA for subsequent treatment in the R-AnDMBR. Other conditions, including lower temperature HTL were also tested with the HTL-AB being provided to GLWA.

Recirculating Anaerobic Dynamic Membrane Bioreactor Setup

The R-AnDMBR system consisted of a 7 L cylindrical bioreactor with a working volume of 5 L. It has a mesh pore size of 25 microns and was fed with a raw COD of 75gCOD/L, a feedstock concentration of 2-10gCOD/L, an organic loading rate of 0.2-2.1 gCOD/L_R/day and an HRT of 5-10 days (Table 1). The inoculum was sludge coming from digester treating food waste and sludge. Figure 1 provides a schematic of the reactor. The design of the RAnDMBr involves a tree-like structure submerged in the bioreactor which branches were surrounded by a stainless-steel mesh of 25 μm pore size. The goal of the tree-like structure if to build a high surface area biofilm to enhance the degradation of HTL-aq. The branches in the tree-like structure provided a very high surface area (19.79 m^2 $m_{reactor}^{-3}$) in the system where the biofilm (dynamic membrane) was developed. Contrary to common dynamic membrane bioreactors, the reactor bulk liquid was not permeated continuously through the dynamic membrane. To generate a biofilm on the branches of the tree-like structure and promote advective substrate transport, the bulk liquid was recirculated through the meshes. Therefore, the R-AnDMBR would work under cycles of recirculation and permeation (Figure 2). For a period of time of tR, the system would recirculate the bulk liquid through the stainless steel meshes and for a period of time tP the system would perform permeation. Permeation would take place by activating a three-way valve that would switch the direction of the fluid from recirculation to permeation (Figure S1B). Because the dynamic membrane permeability would not be constant, the time of recirculation and permeation varied during the study to keep the reactor at the desired HRT (5 or 10 days depending on the experiment stage, see Table 1). To determine how often the bulk liquid was recirculated through the dynamic membrane, the recirculation ratio was calculated by dividing the recirculation flow rate by the effluent flow rate. The R-AnDMBR operated under different organic loading rates by diluting the HTL-aq with DI water. The operating conditions of this study can be seen in Table 1.

Table 1 Reactor operating parameters

Time period (days)	0-25	26-75	76-115	116-166	167-359	360-473	474-521	522-600
OLR (g COD L_R^{-1} day^{-1})	0.5 ± 0.2	0.2 ± 0.0	0.4 ± 0.2	0.9 ± 0.1	0.5 ± 0.2	1.1 ± 0.4	1.5 ± 0.2	2.1 ± 0.3
HRT (days)	6.7 ± 2.1	11.5 ± 2.8	10.7 ± 1.6	10.3 ± 0.9	10.9 ± 2.0	5.6 ± 2.3	6.5 ± 0.6	6.0 ± 1.7
Dilution factor for HTL-AB	30.0	30.0	15.0	7.5	15.0	9.0	7.5	5.6
Feedstock (g COD L^{-1})	2.4 ± 0.2	2.4 ± 0.2	4.7 ± 1.1	8.6 ± 1.7	5.0 ± 0.4	6.0 ± 1.6	9.4 ± 1.3	12.5 ± 0.8
Recirculation ratio (L L_R^{-1})*	20.0	3.8-20.0	3.8	3.8-5.5	5.5	1.5	1.5	1.5

*The recycle ratio shows maximum and minimums used during the specific period (see figure 2)

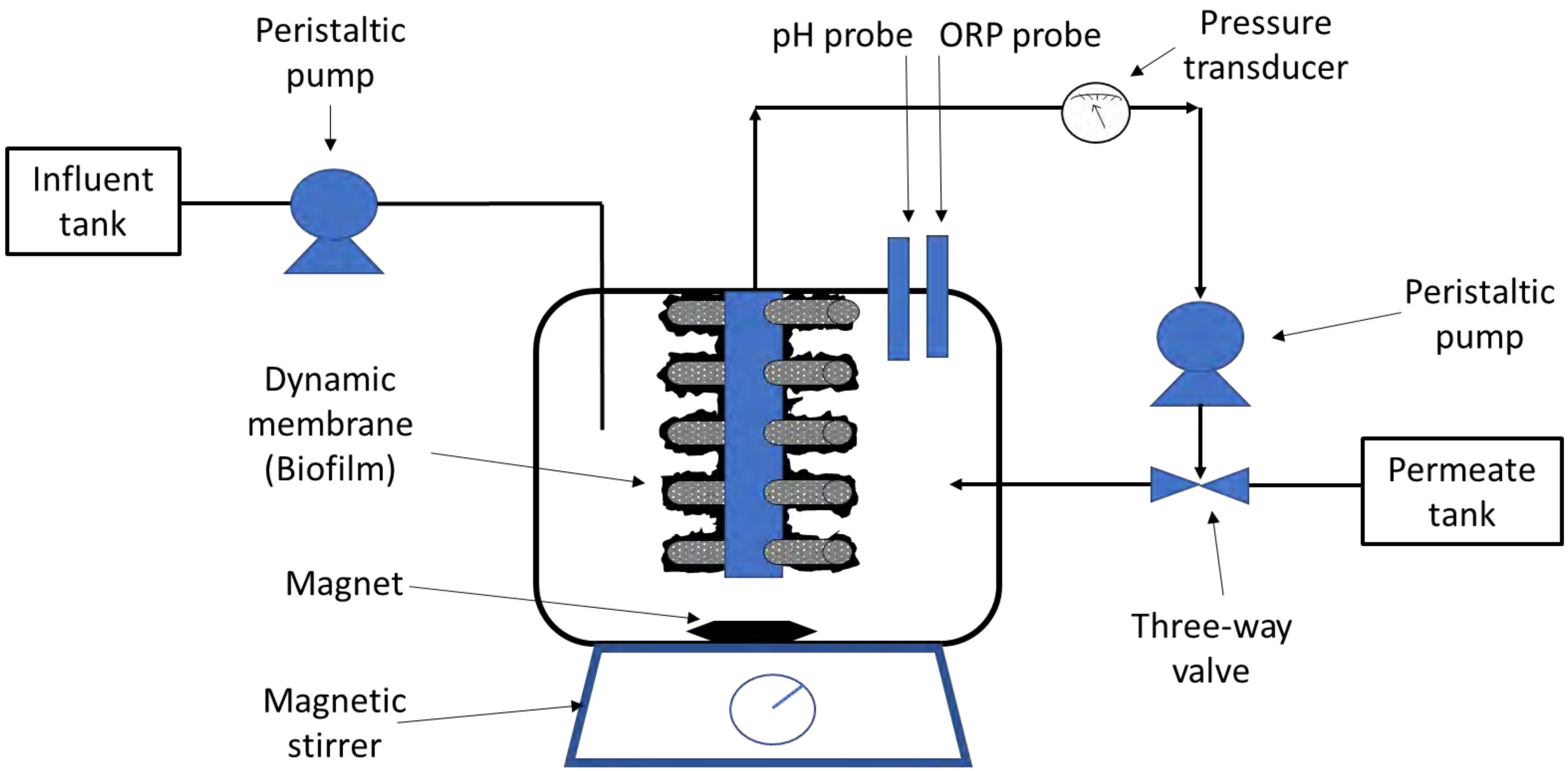

Figure 1. Schematic representation of the experimental apparatus

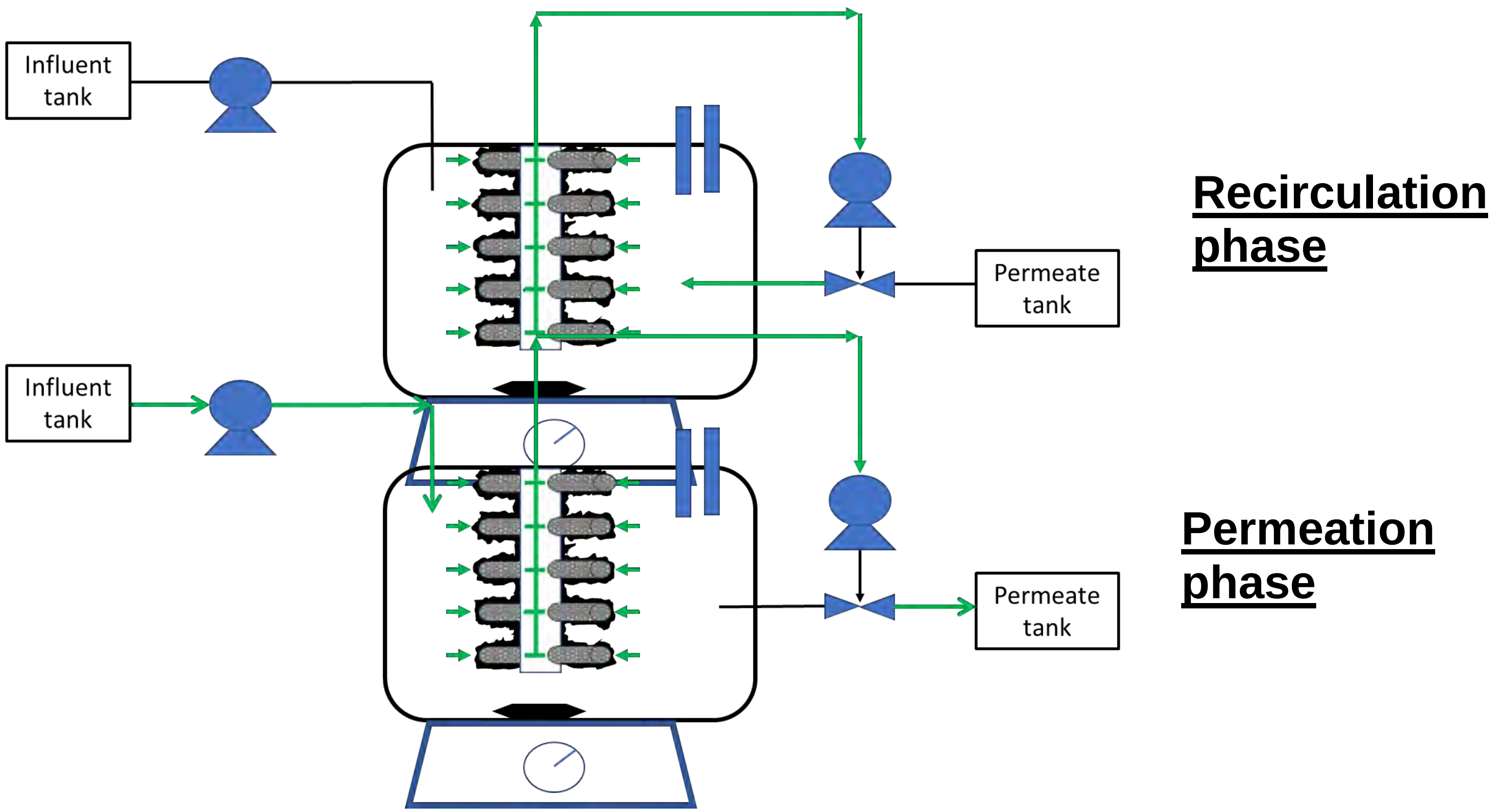

Figure 2. Schematic representation of the R-AnDMBR cyclic operational strategy.

The operating parameters and performance during the 600-day R-AnDMBR test are presented in Figure 3.

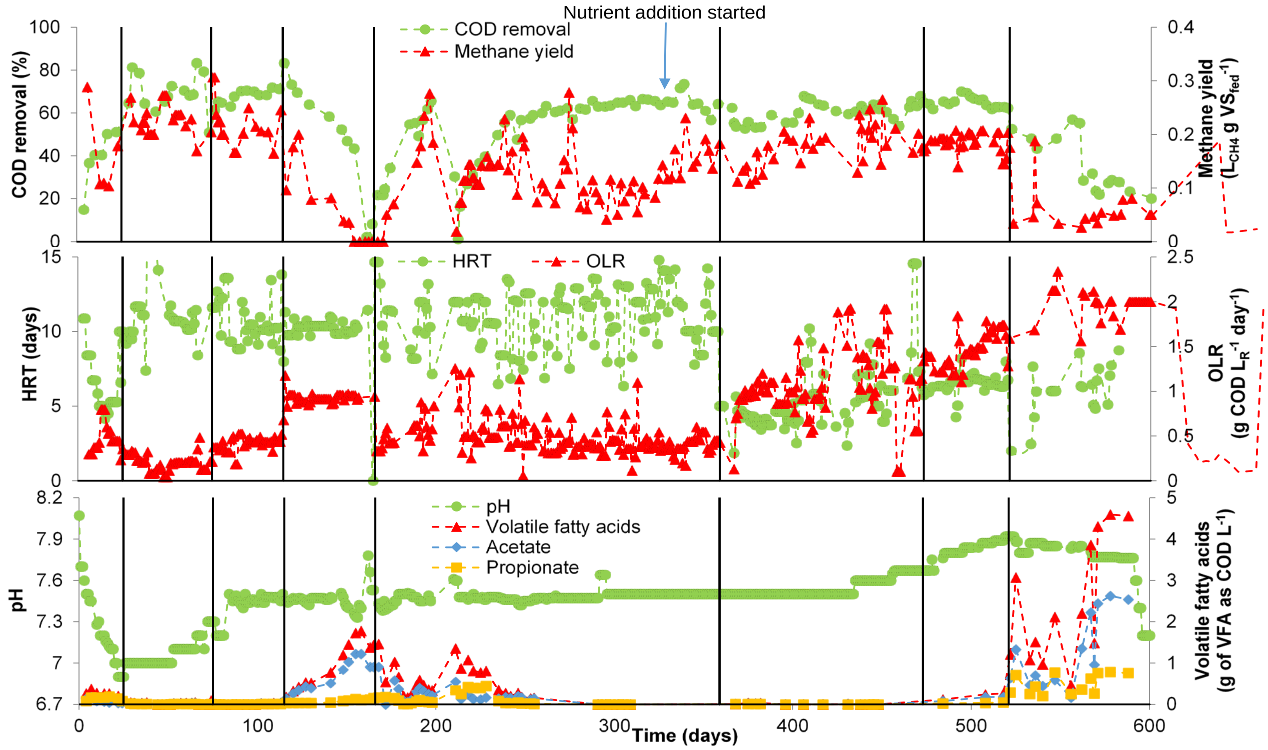

Figure 3. Chemical oxygen demand (COD) removal and methane yield (A), hydraulic retention time (HRT) and organic loading rate (OLR) (B), and pH and volatile fatty acids (VFA) accumulation (C). The vertical line indicates changes made to the OLR.

In the reactor, we achieved 70% COD reduction but at low organic loading rates as shown in Figure 3. COD reduction fell off when the organic loading was increased to 1.0 gCOD L_R^{-1} day^{-1} One of the reasons the R-AnDMBR could not work at an OLR higher than 0.5 g COD L_R^{-1} day^{-1} could be the low nutrients concentration in the substrate (Table 2). As seen in Figure 3 the COD:P of the substrate and the digester content was not in the ideal range for anaerobic digestion (400-17) (Thaveesri et al., 1995; Janke et al., 2017). In this study, the HTL-aq was provided by PNNL and their HTL system has a settling separation vessel to enhance the separation of inorganics from the biocrude/HTL-aq mixture. The settling vessel promotes the separation of phosphates from the HTL-aq, producing a hydrochar rich in P that can use as fertilizer and an HTL-aq with very low concentration of P for bioprocesses (Elliott et al., 2016). To avoid inhibition in the system due to the lack of P and trace metals, on day 332 we started to mix the feedstock with a solution rich in nutrients (details about the nutrient stock solution can be found in Table 3).

Table 2 Nutrient composition of the HTL aqueous phase

Compound	Concentration (ppm) HTL Aqueous phase	Reactor day 248	Reactor day 260
N	630 ± 15	642 ± 49	
P	1.2 ± 0.4	5.6 ± 0.1	
S	11	9	6
Na	8	6	8
Ca	62.2	9.4	10.9
K	22	24	24
Mg	3	3	3
Fe	1.8	5.8	3.6
Ni	< 1.6	< 1.6	< 1.6
Co	< 0.2	< 0.2	< 0.2
Zn	< 0.6	< 0.6	< 0.6
Mo	< 0.3	< 0.3	< 0.3
W	< 1	< 1	< 1
Cu	0.15	0.3	0.3
Mn	< 0.3	< 0.3	< 0.3

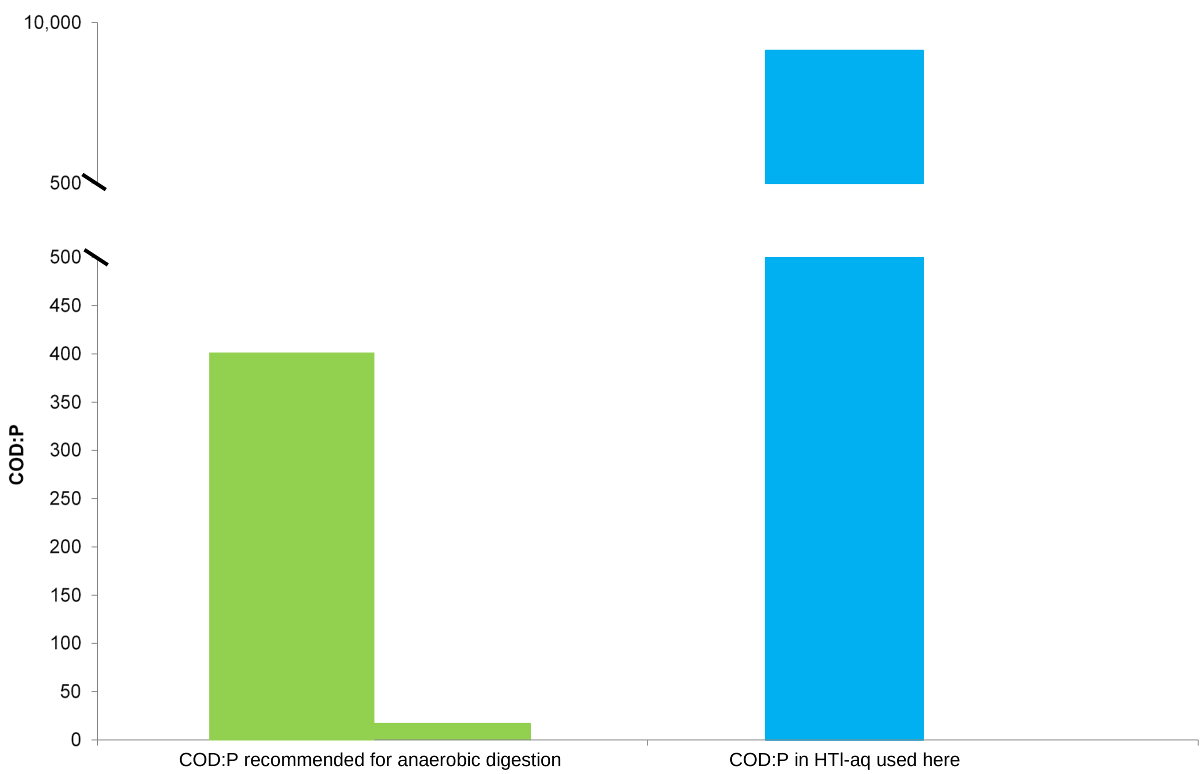

Figure 4. Ratio of Chemical oxygen demand over Phosphorous

Table 3. Description of nutrient solution used in this study

Solution A		Solution B		Solution C	
Compound	Mass or volume added to 1L distilled water	Compound	Mass or volume added to 1L distilled water	Compound	Mass or volume added to 1L distilled water
NaCl	10	$K_2HPO_4 \bullet 3H_2O$	200	$FeCl_2 \bullet 4H_2O$	2
$MgCl_2 \bullet 6H_2O$	10			H_3BO_3	0.05
$CaCl_2 \bullet 2H_2O$	5			$CuCl_2 \bullet 2H_2O$	0.038
				$MnCl_2 \bullet 4H_2O$	0.05
				$NiCl_2 \bullet 6H_2O$	0.092
				$ZnCl_2 \bullet 4H_2O$	0.05
				$(NH_4)6Mo7O_{24} \bullet 4H_2O$	0.05
				$ALCl_3$	0.05
				$CoCl_2 \bullet 6H_2O$	0.05
				Na_2SeO_3	0.1
				EDTA	
				HCl	1 ml

The final stock solution used in this study was prepared by mixing 10 ml of solution A, 2 ml of solution B and 1 ml of solution D in 987 ml of distilled water.

After adding the nutrient solution the system could operate with an OLR of 1.5 g COD Lr-1 day-1 without inhibition (dilution of 7.5)

The biofilm presented a diverse microbial community with important populations, including methanogens, aromatic and phenol compound degraders, and syntrophic bacteria as shown in Figure 5.

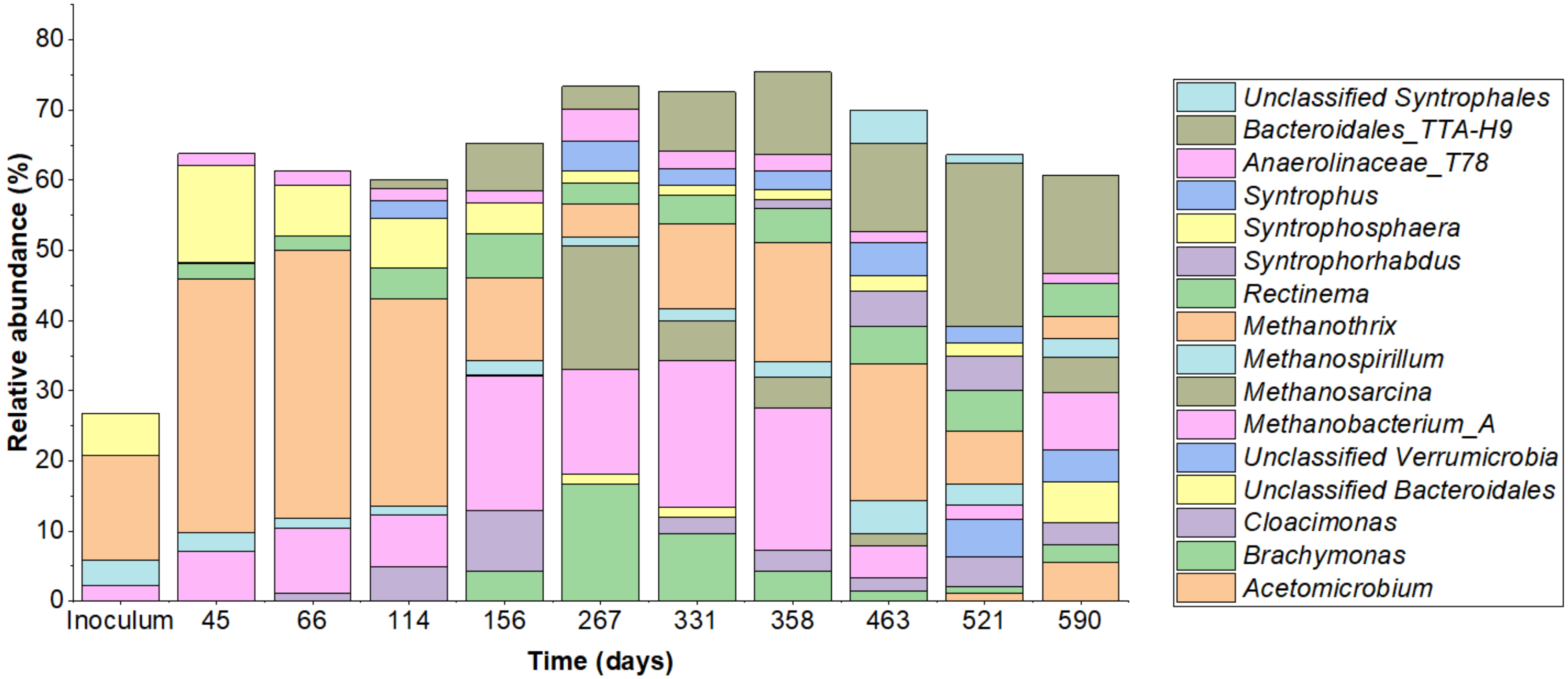

Figure 5. Relative abundance of dominant groups in the inoculum and biofilm samples collected from the recirculating anaerobic dynamic membrane bioreactor over time. Only genera present at relative activities greater than 1% in at least 6 samples or present at a relative abundance of 5% at least once are shown.

Overall, the R-AnDMBR was able to treat diluted HTL-aq (dilution factor of 7.5) and degrade 65% of the COD at 1.5 ± 0.2 g COD L_R^{-1} day^{-1} and 5.6 ± 2.3 days producing 0.19 ± 0.02 LCH4 $gCOD_{fed}^{-1}$. However, co-digestion with a substrate like sewage sludge or sludge centrate would be necessary to overcome the deficiency of P and other nutrients in HTL-aq. The system presented severe inhibition after the OLR increased to 2.0 g COD L_R^{-1} day^{-1}.

References

Elliott, D. C., Hart, T. R., Neuenschwander, G. G., Oyler, J. R., Rotness, J. L. J., Schmidt, A. J., et al. (2016). System and process for efficient separation of biocrudes and water in a hydrothermal liquefaction system.

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Thaveesri, J., Daffonchio, D., Liessens, B., Vandermeren, P., and Verstraete, W. (1995). Granulation and Sludge Bed Stability in Upflow Anaerobic Sludge Bed Reactors in Relation to Surface Thermodynamics.

Pacific Northwest
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Biosolids & Renewable Energy Innovation Technology Seminar

Hydrothermal Processing in Wastewater Treatment

James Oyler
President Genifuel Corporation
November 2017
jim@genifuel.com

Genifuel

Why Hydrothermal Processing?

- **Solids Management is a critical issue in wastewater treatment and a source of significant cost**
- **Hydrothermal Processing addresses this issue by converting solids to renewable fuels**
- **Eliminates solids disposal cost and generates significant revenue**
- **Renewable fuels offset fossil fuels and associated new GHG**

Why HTP

Background

- **Process developed over 30 years by the US Dept. of Energy at Pacific Northwest National Lab**
- **Licensed exclusively to Genifuel**
  - Both PNNL and Genifuel have contributed patents
- **Over 100 feedstocks tested**
  - Focus is now on wastewater solids

Technical Concept

- **HTP is similar to the formation of fossil fuels, but in minutes rather than millions of years**
- **Oil is similar to fossil crude but generally lower viscosity**

Brontosaurus by Charles R. Knight, 1897

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Hydrothermal Processing Overview

- **Hydrothermal Processing (HTP) uses temperature and pressure to efficiently convert wet organic matter to biocrude oil and methane gas in less than an hour**
  - Captures >85% of feedstock energy; uses <14% of fuel energy produced to run the system
  - T = 350°C; P = 200 bar (20 MPa)
- **Eliminates biosolids and reduces operational costs**
  - Significantly reduces GHG emissions vs. alternatives
- **Accepts any type of wastewater solids—primary, secondary, both together, or post-digester biosolids**
  - Can also co-process food waste and other wastes

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Hydrothermal Overview (cont.)

- **Unique process step precipitates phosphorus in the form of a dense clay-like solid; 98-99% removal**
  - Converts to fertilizer in same way as phosphorus ore
- **Effluent water clear and biologically sterile**
  - COD <60 mg/L, mostly small acids, e.g. formic, acetic
  - Large molecules destroyed, e.g. pharmaceuticals, estrogens, pesticides, fire retardants, etc.
  - Contains N as ammonia; ongoing R&D to recover
- **Systems or products often eligible for incentives**

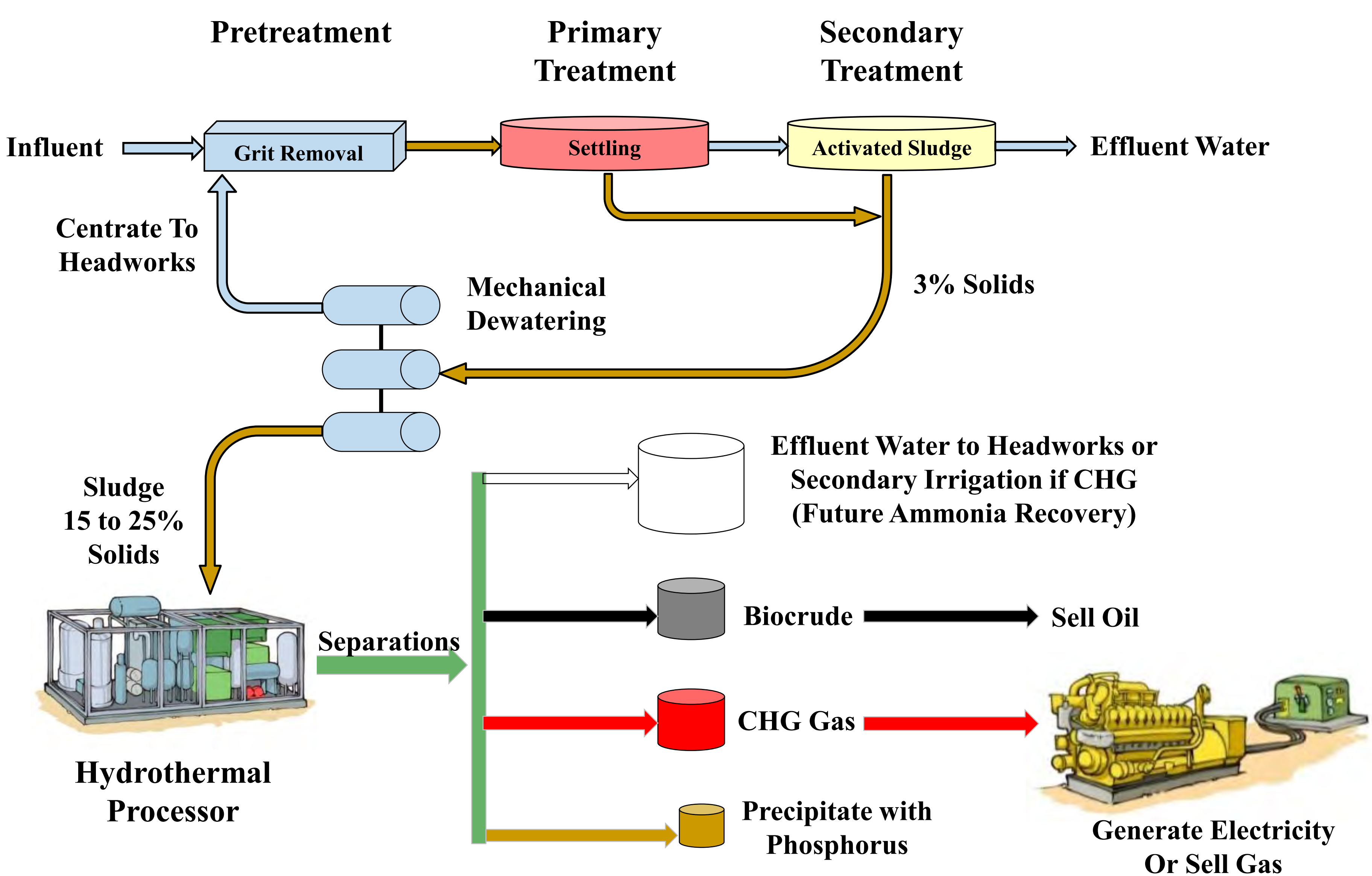
➢ **Solids management, P capture, valuable products, lower emissions, high efficiency, small size and incentives provide value to the plant owner**

An Installed HTP System and Outputs

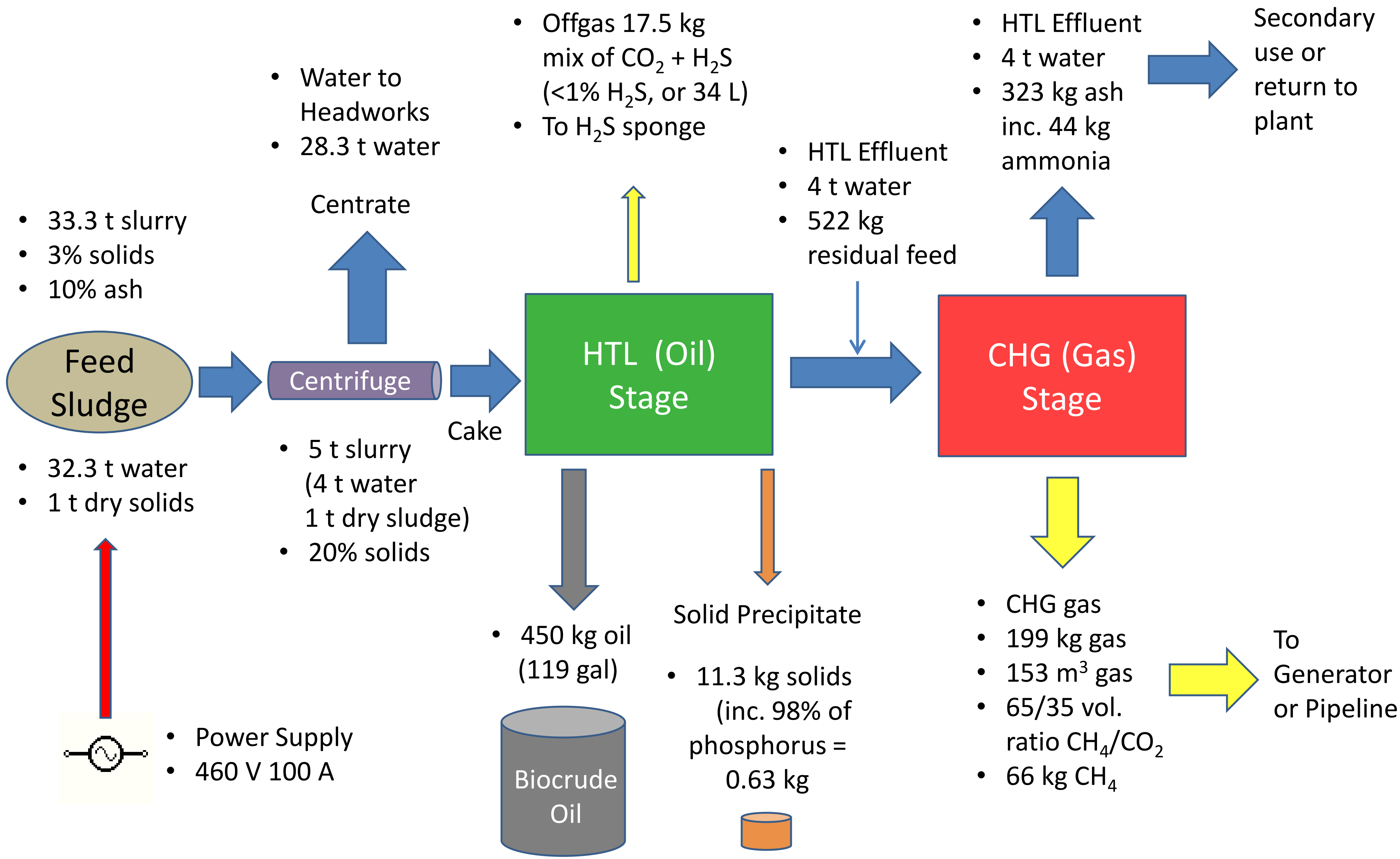
HTP Oil

Effluent Water

Wastewater Process Flow with Hydrothermal Processing

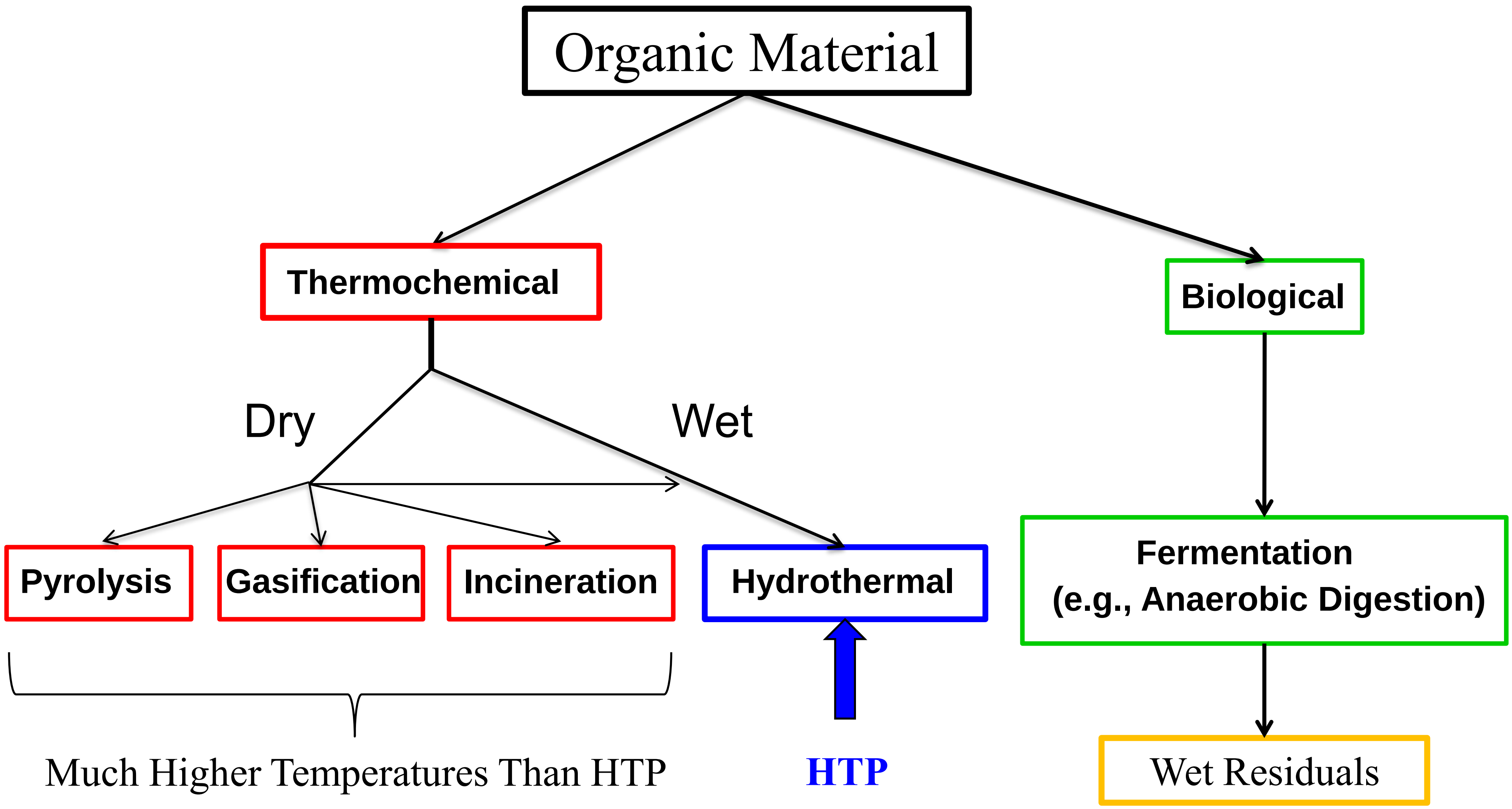


System is Well-Characterized:
Mass Flow Diagram for 1 t/d dry (equivalent) solids*



*All units metric unless shown otherwise. Mass unit of t/d = 1000 kg/day

Comparison to Other Technologies



Comparison to Other Technologies (cont.)

TECHNOLOGY	COMPARISON
Anaerobic Digestion	• AD app. 2x footprint of HTP • HTP one hour vs. 20-30 days for AD • HTP 80% to 120% more fuel energy • AD leaves 40-50% of feedstock as biosolids; HTP none
Thermal Hydrolysis (e.g. CAMBI)	• Pre-process for AD, not a conversion process • Increases yield and decreases time for AD • Increased methane needed for CAMBI, little net gain
Incineration	• Eliminates solids • Limited resource recover—some heat and some ash • Expensive to eliminate regulated air emissions
Pyrolysis or gasification	• Very high temperature can create reliability problems • Low yield and low quality if pyrolysis oil is produced • Produces syngas rather than methane—lower specific energy

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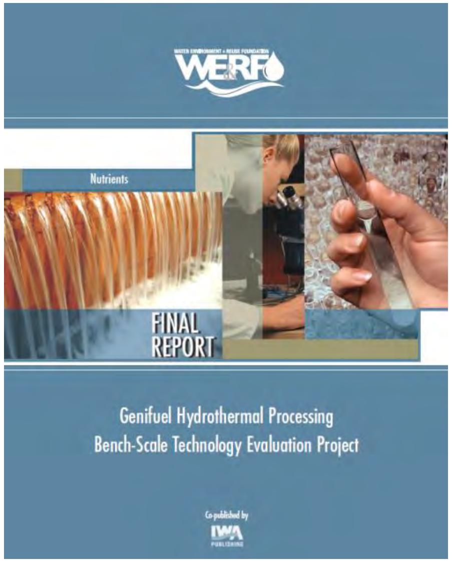
The LIFT Study of HTP by WERF

- **The LIFT study produced a 185-pg. third-party report by Leidos, Inc.**
- **The report was reviewed by utilities and industry experts…**



Available free from WERF

… and recommended installation at a utility

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Continuing Improvements in HTP

- **Pacific Northwest National Laboratory, which ran the LIFT test, ran additional tests with Detroit sludge, and installed major new test equipment**

Medium-Scale HTP System

Oil Upgrading System

Results from Wastewater Sludge Tests*

Measurement	Value
Oil as % feedstock solids (mass/mass)	35% to 45%
COD of effluent water after gasification	<60 mg/L
Feedstock carbon recovered into fuels	85%
% of output fuel energy needed to run the system	14%
Siloxane and H_2S levels in CHG gas	Negligible
Ammonia level in CHG water, before removal	1% to 1.5%
Complex molecules remaining (pesticide, pharma)	Negligible
Operating conditions	350°C, 200 bar
Preferred solids concentration	20% solids in water; range 15 to 25%

** Sludge samples from Metro Vancouver and Detroit*

Genifuel

Metro Vancouver's Interest in HTP

- **After working on LIFT, Metro Vancouver saw the HTP pilot project recommendation as a way to gain experience with solutions to key issues**
  - Rising cost of solids management and increasing distance to disposal sites
  - High cost of installing AD at smaller sites
  - New technology for future system upgrades to improve process and reduce cost
  - A pathway to meet environmental goals for lower emissions and greater energy recovery

Metro Vancouver's (MV) Project

- The MV system will process 10 metric t/d of sludge at 20% solids
- Serves satellite site with population of 30,000
- Initially oil only (875 L/d) , with gas later
- Commission late 2018

Annacis Island System Site

Genifuel

Analysis of MV Project—HTP vs. AD

MEASURE	VALUE
Footprint	HTP is 44% of AD
GHG Reduction	HTP reduces GHG 3X as much as AD
20-year NPV* Cost	HTP is 55% of AD Cost

*NPV = Net Present Value

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HYPOWERS Is the Next New Project

- HYPOWERS is a two-phase project partly funded by Dept. of Energy for demonstration with wastewater
- Size is planned at 20 metric tons/day, or 60,000 pop.
- Host facility is Central Contra Costa Sanitary District ("Central San"), east of San Francisco

Central San System Site

Genifuel

About Central San

- 145 Sq. Mile Service Area
- >480,000 Population Served
- >1,500 Miles of Sewer
- 19 Pump Stations
- 1 Treatment Plant
- Average Flow: 32 Million Gallons Per Day (MGD)
- Solids: ~200 Wet Tons Per Day

Central San Embarked on a Comprehensive Wastewater Master Plan

Aging Infrastructure	Capacity
Regulatory	Sustainability

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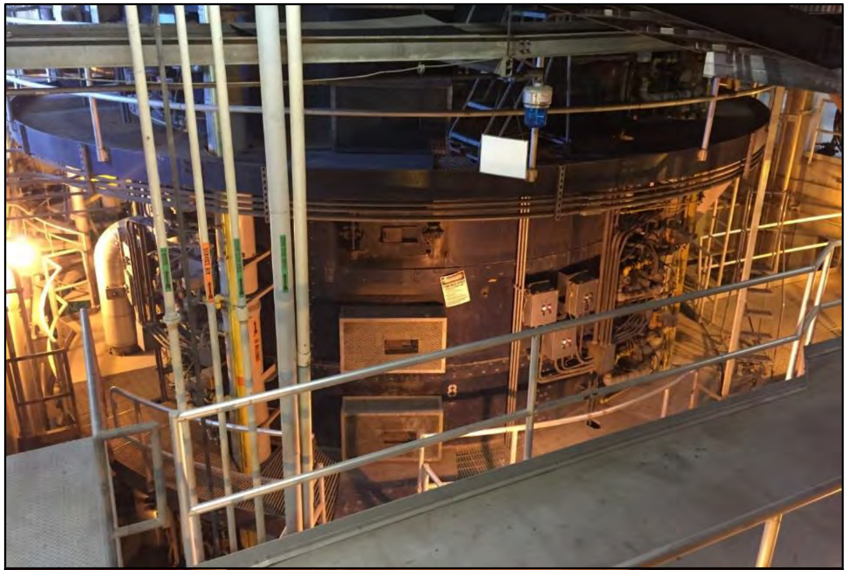
Existing Solids Handling System

- 1980s Waste to Energy
- Furnaces in Good Condition
- Support Equipment & Building Requires Upgrades
- Emissions Controls Improvements Needed
- Regulatory Risks
- Plans to De-couple Waste Heat Recovery System from Secondary Aeration Blowers



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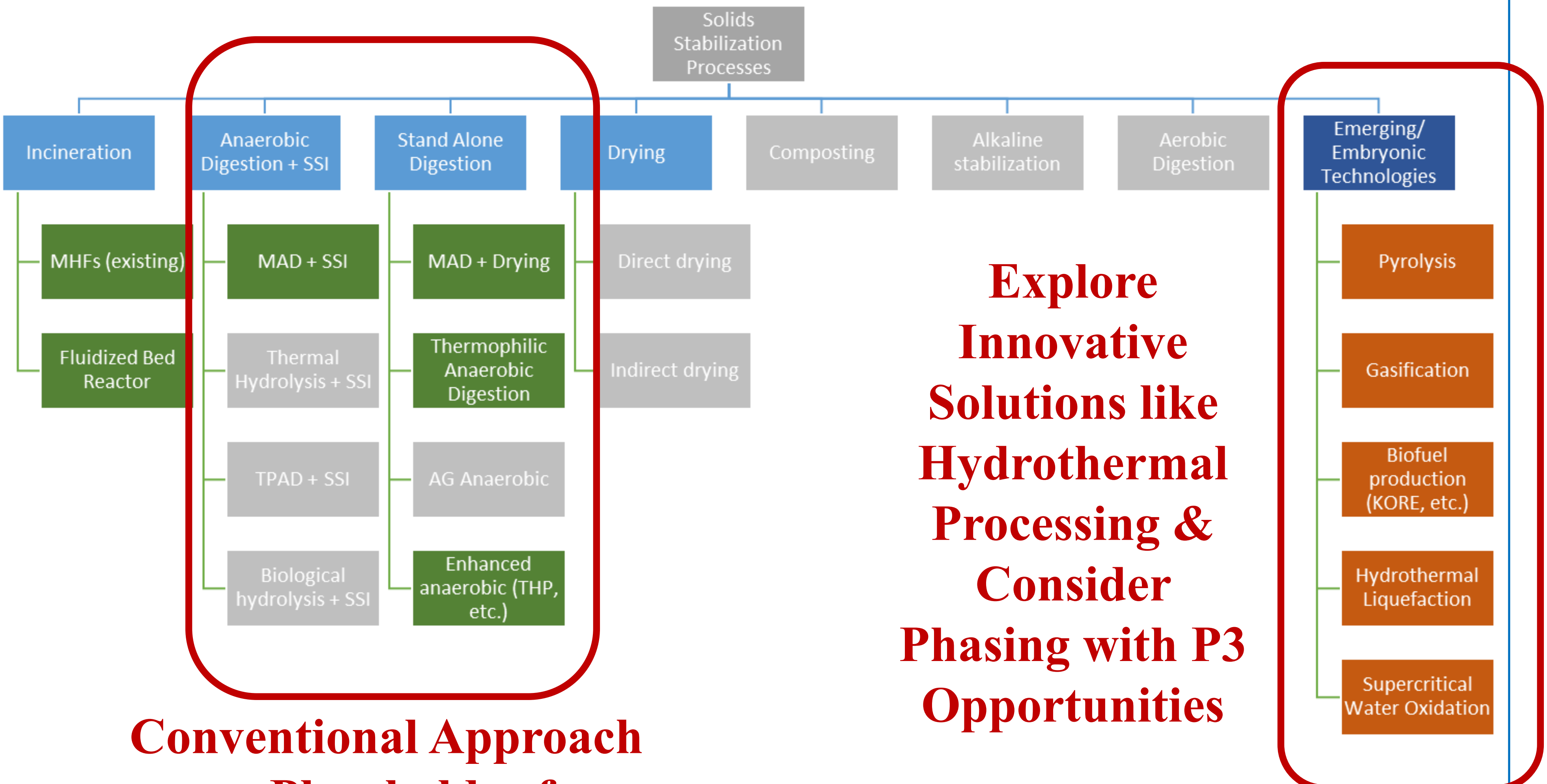
Solids Handling Goals

- **Continue with Furnaces**
  - Near-Term Upgrades
  - Address Vulnerabilities

- **Plan for Furnace Replacement (Possibly in Phases)**
  - Strive for Net Zero Energy
  - Reduce Greenhouse Gas Emissions
  - Embrace Innovation

Universe of Alternatives



Explore Innovative Solutions like Hydrothermal Processing & Consider Phasing with P3 Opportunities

Conventional Approach as a Placeholder for Master Planning

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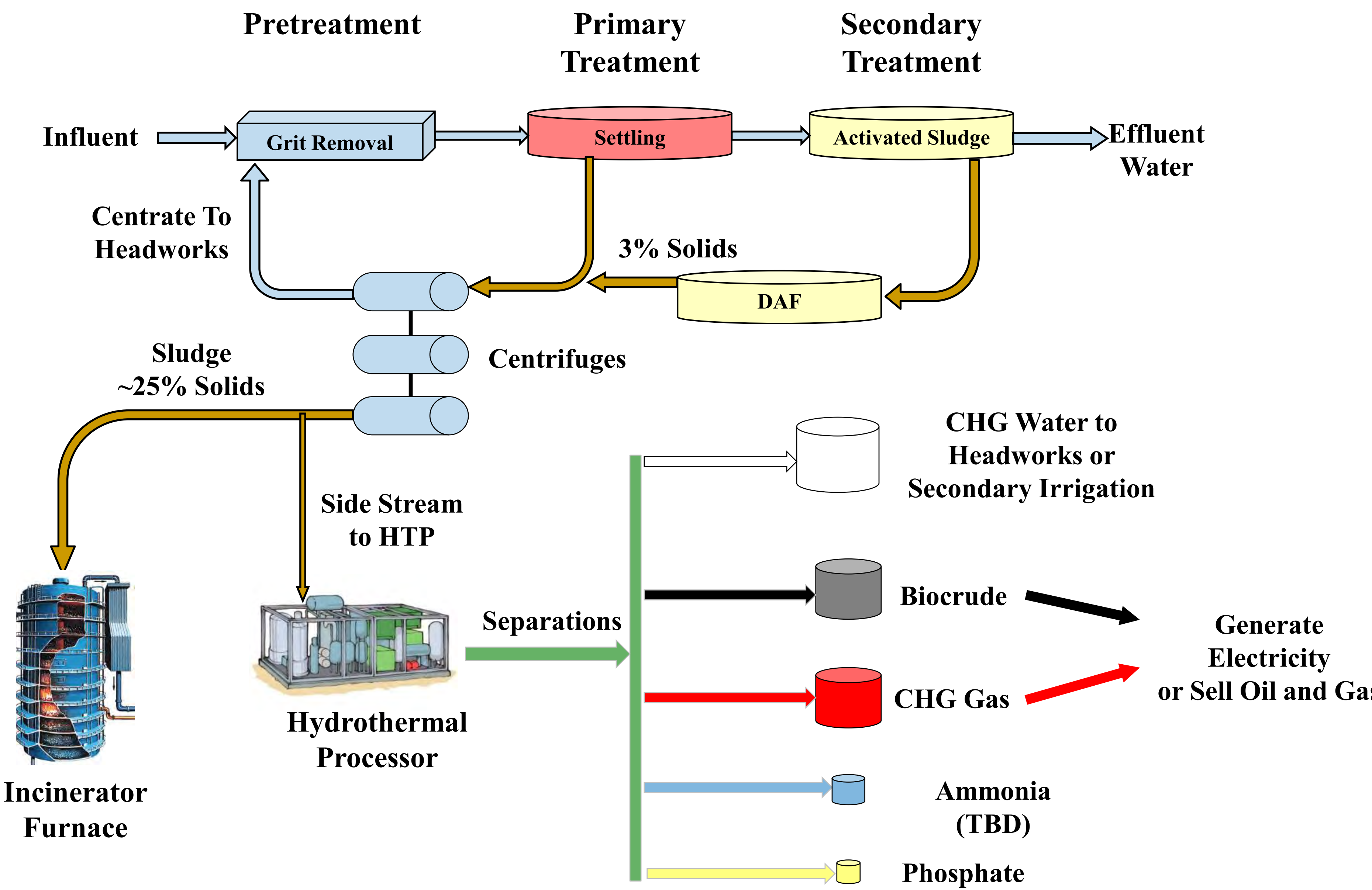
Central San Process Flow with Hydrothermal Processing



The HYPOWERS Team

WATER ENVIRONMENT & REUSE FOUNDATION
WE&RF

Pacific Northwest
NATIONAL LABORATORY

Genifuel
CORPORATION

MERRICK®
& COMPANY

Central Contra Costa Sanitary District

metrovancouver

SoCalGas
A Sempra Energy utility

BIO
MicroBio Engineering

TESORO

Brown AND Caldwell

CENTRAL CONTRA COSTA
1946 70 2016
YEARS
SANITARY DISTRICT

Equipment Installation for HTP

- **HTP system is skid-mount and factory-built**
  - Shipped to site by truck
  - May be containerized for sea shipment
- **Site installation requires pad, utilities (electricity, water, drain), and cover (roof or building)**
- **Need supply of sludge or biosolids**
  - Sludge can be delivered by pipe, biosolids likely not
  - Sludge will need to be dewatered to 20% (range 15-25%)
- **Need disposition of effluent water and storage tank for oil (weekly pickup)**
- **Odor control simple because very small amounts**

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Conclusion

- **Only hydrothermal process with both liquefaction and gasification in same system**
- **Optimized process produces high quality outputs**
  - Oil—no char, low oxygen
  - Gas—H_2S and siloxanes below detection limit
  - Water—no organisms or pharmaceuticals
- **Unique process step automatically captures phosphorus for direct conversion to fertilizer**
- **Successful scale-up now at small commercial size**
- **More than $50 million invested in R&D by both government and private parties**
- **All IP owned or licensed exclusively to Genifuel**

Genifuel

Hydrothermal Processing in Wastewater Treatment

Thank you!

Genifuel

Additional Slides

James Oyler, President—Brief CV

- Built and managed energy practice for Booz, Allen & Hamilton, worldwide consultants (1972-1976)
- Sector President for Harris Corporation, a Fortune 500 Company (1976-1993)
- President and CEO for E&S, a NASDAQ technology company sold to Rockwell Collins (1994-2006)
- BSEE 1967, M.A. Cambridge University (UK) 1969, Officer US Army 1972, Certified Mgmt. Accountant
- 24 issued or pending patents

Conclusion

- **Successful testing with wastewater solids has created significant learning for equipment design, expected performance, and cost reduction**
- **Critical next step is to demonstrate continuous 24/7 operation at operating wastewater utility**
  - Current longest operation is app. three months
  - Planned projects at MV and Central San
  - Sharing of data and results with wastewater industry
- **Will need new investment for operations**
- **Would like utility partner in UK/Europe for demonstration plant**

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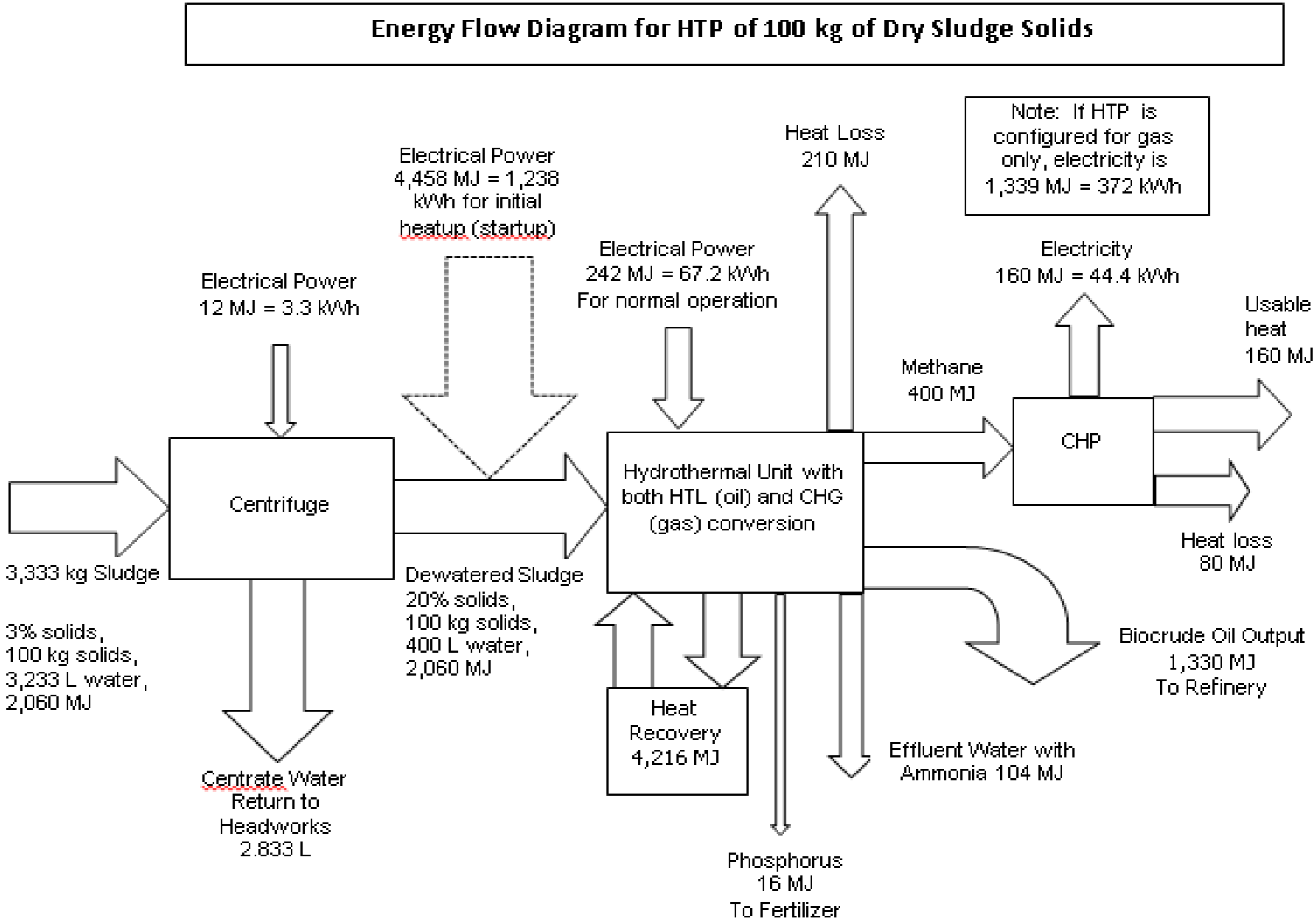
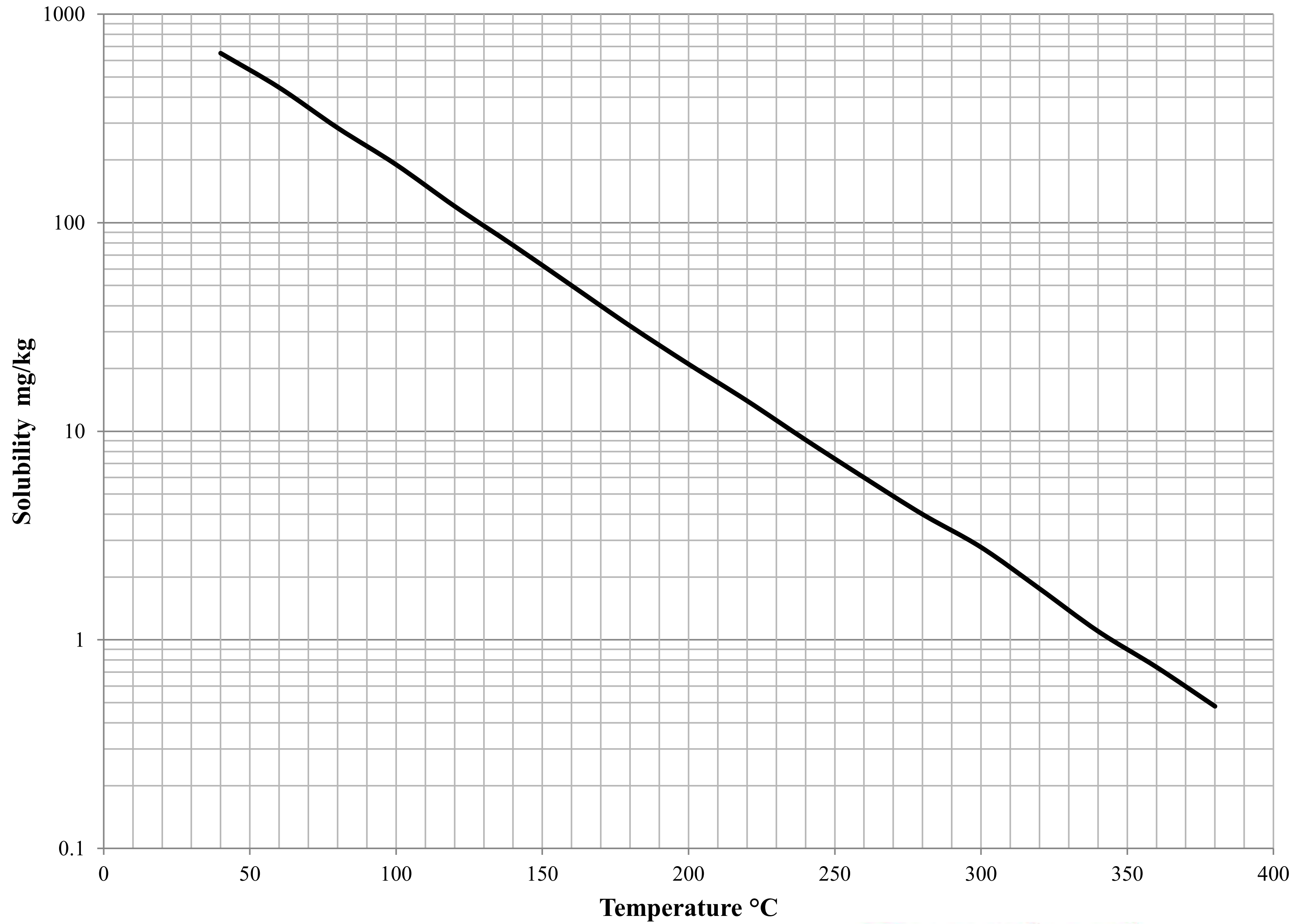
System is Well-Characterized:
Energy Flow Sankey for 100 kg/d dry solids



Solubility of Calcium Sulfate and Calcium Phosphate in Water



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ATTACHMENT 9

AgLoco® 150 Initial Technical Specifications[1]

Engine	
Rated power, kW (hp)	112 (150)
Max. power, kW (hp)	152 (204)
Crankshaft torque, N·m	7,920
Rated crankshaft speed, rpm	400
Cylinder bore, mm (in)	178 (7.00)
Stroke, mm (in)	275 (10.8)
Cylinders	2
Cycle	Regenerative Simple Expansion
Steam pressure, MPa (psi)	2.14 (310)
Steam temperature, °C (°F)	400 (752)
Transmission	
Speeds	2
Road gear, km/h (mph)	40 (25)
Field gear, km/h (mph)	20 (12.5)
Drive	
2WD	Standard
4WD	Optional
Hydraulics (Optional)	
Type	Closed centre, load sensing
Flow, L/min	120
Selective control valves	6
Power beyond	Optional
Wheels & Tyres	
Front	540/65R28
Rear	650/65R38
Capacities	
Rated towing capacity on 12% gradient, kg (lb)	30,000 (66,000)
Range with rated load in tow, km (mi.)	204 (128)
Bunker, solid biofuel (wood chip), kg (lb)	500 (1,100)
Feed tanks, water, L (gal)	2,000 (528)
Time between refuelling at 48% load factor[2], h	4
Cab	
Fully enclosed, air-cycle air conditioning (HFC free)	Standard
Open canopy	Optional
Dimensions	
Wheelbase, mm (in)	3,100 (122)
Width x height x length, mm	2,490 x 3,300 x 6,100
Ground clearance, mm (in)	500 (19.7)
Shipping weight, kg	4,000
Operating weight, full supplies, kg	6,500
Power Take-Off (Optional)	
Location	Front & rear
Drive	Independent v-twin engine
Speeds, rpm	0-1000 (Variable speed)
Max. power, kW (hp)	112 (150)
3 Point Hitch (Optional)	
Front	Optional
Rear	Optional
Category, front/rear	IIIN/II, IIIN or III
Max. lift capacity at hooks, front/rear, kg	4,000/6,500
Brakes	
Engine (dynamic service brake)	Counter-pressure steam brake
Engine (service)	Hydraulic flywheel disc brake
Rear axle	Independent hydraulic drum brakes
Front axle	Hydraulic drum brakes
Pneumatic trailer brake	Optional
Hydraulic trailer brake	Optional
Suspension	
Front axle	Hydro-pneumatic, double wishbone
Steering	
Type	Hydrostatic
Turning radius, m (ft)	4.7 (15.4)
Autosteer	Optional
Various	
ISOBUS ready	Optional

[1] All specifications are subject to change.
[2] California Air Resources Board, *Analysis of California's Diesel Agricultural Equipment Inventory according to Fuel Use, Farm Size, and Equipment Horsepower*, California, 2018.

Powerful, Practical & Resilient

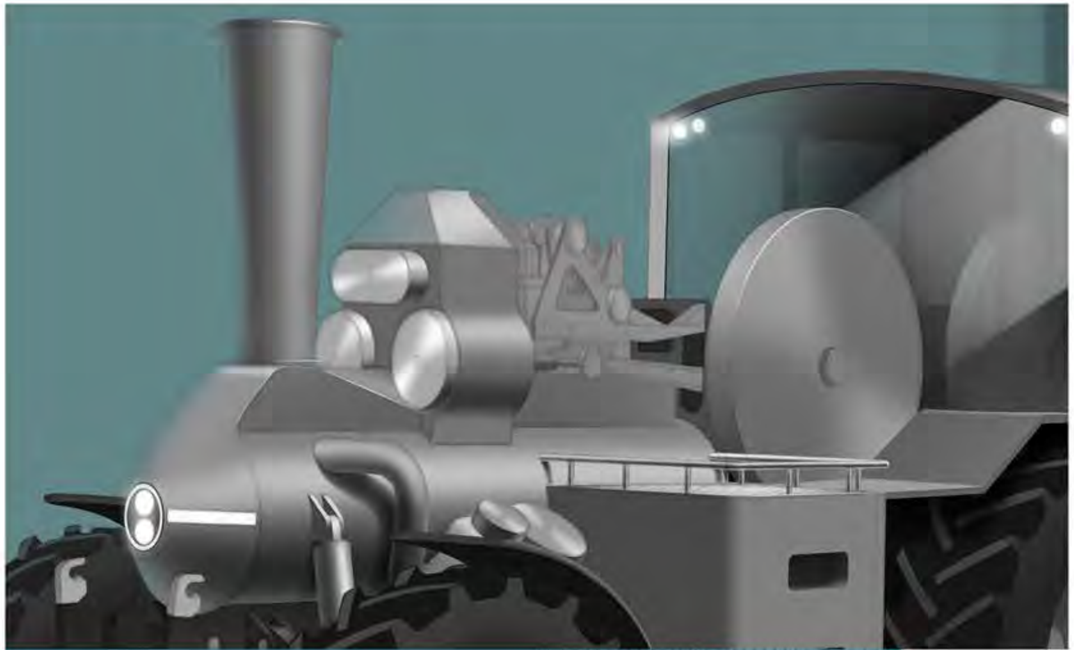
AGLOCO® 150

THE FUTURE OF TRACTION

agloco.co.nz - info@agloco.co.nz - +64 3 669 3366

150 Horsepower

10x the torque of a diesel engine



No excuses...

- 10 minutes to reach full pressure
- Reduces fuel costs by up to 90%
- 4 hour range at an average 48% load
- Refuel in less than 10 minutes
- Front and rear 112kW PTOs
- Front three point hitch
- Haul 30 tonnes
- 4wd optional
- Self feeding fuel system
- Spacious and air conditioned cab
- Autosteer option

"The AgLoco® 150 is a significant investment in your future..."

... A future of self reliance, where you grow your own regenerative fuel and put it to work.

The 150 is powered by solid biofuels such as cord wood, wood-chip, wood pellets and crop residues.

Fuel it yourself
Fix it yourself

The 150 is both durable and simple to repair,
using basic farm workshop equipment,
hand machined parts and locally available skills.

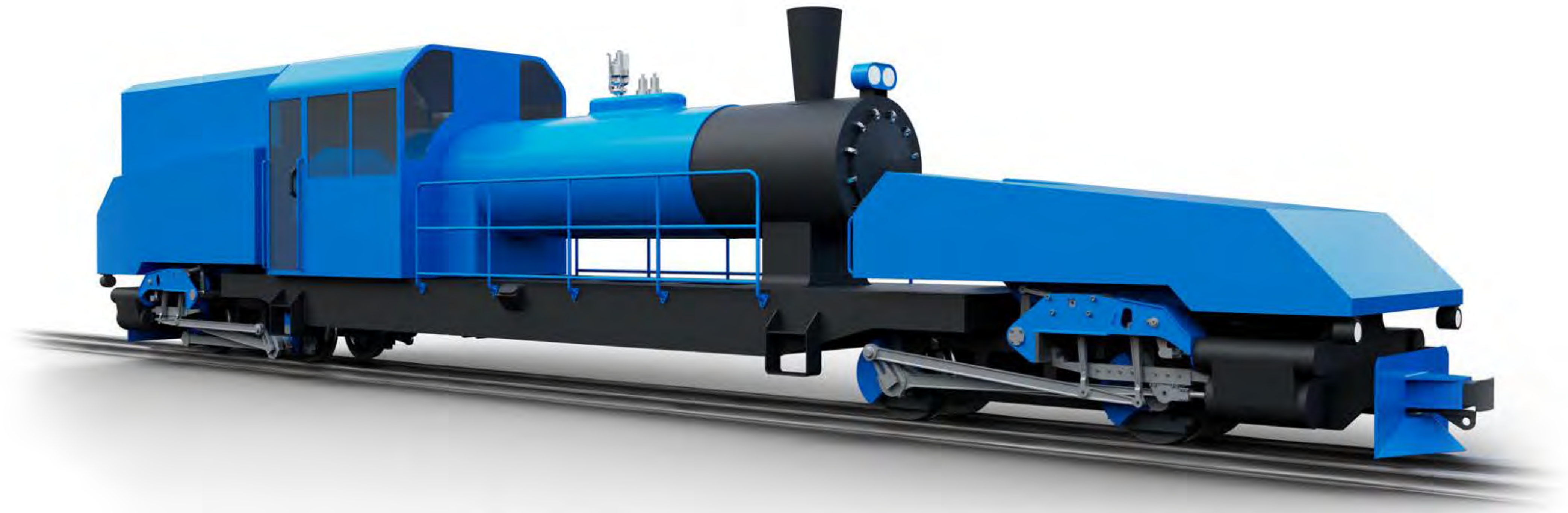
Regenerative carbon cycles
Complete combustion
Future resilience

As solid biofuel is produced, carbon dioxide is captured and stored.

The 150's advanced steam boiler technology utilises complete combustion resulting in a highly efficient, clean, spark and smoke free combustion.

The next round of solid biofuel growth simply recaptures emissions released during combustion.

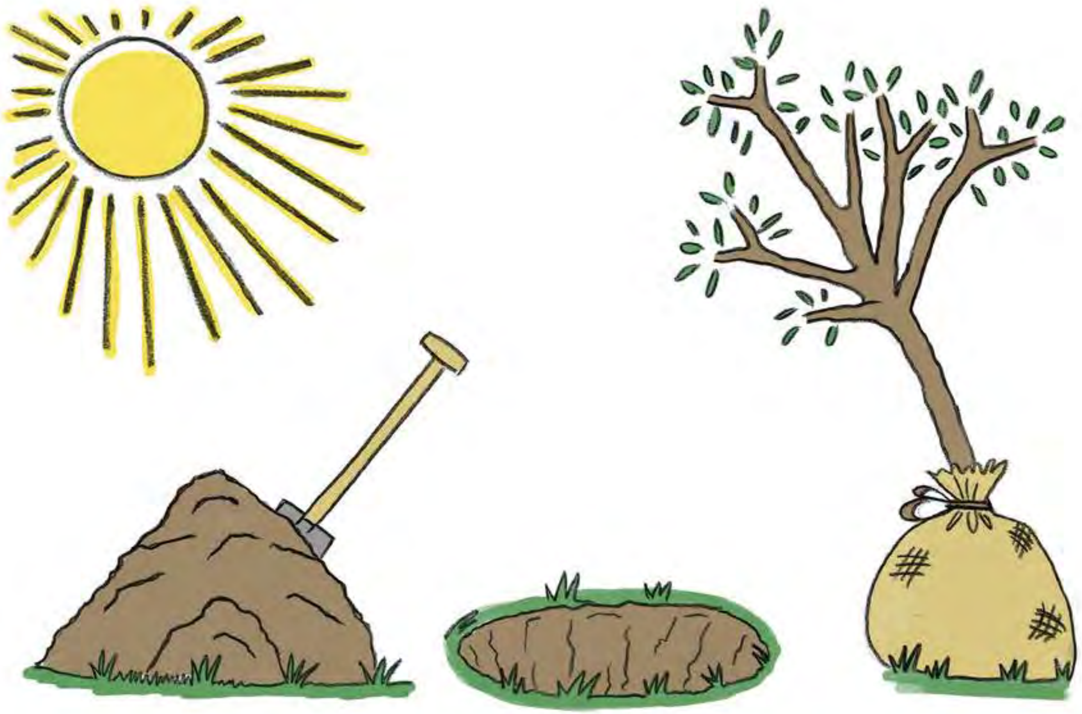
Mackwell Locomotive Co.



ZEROLOCO™ 400

SELF-SUFFICIENT TRANSPORT

mackwelloco.com - info@mackwelloco.com - +64 3 669 8607

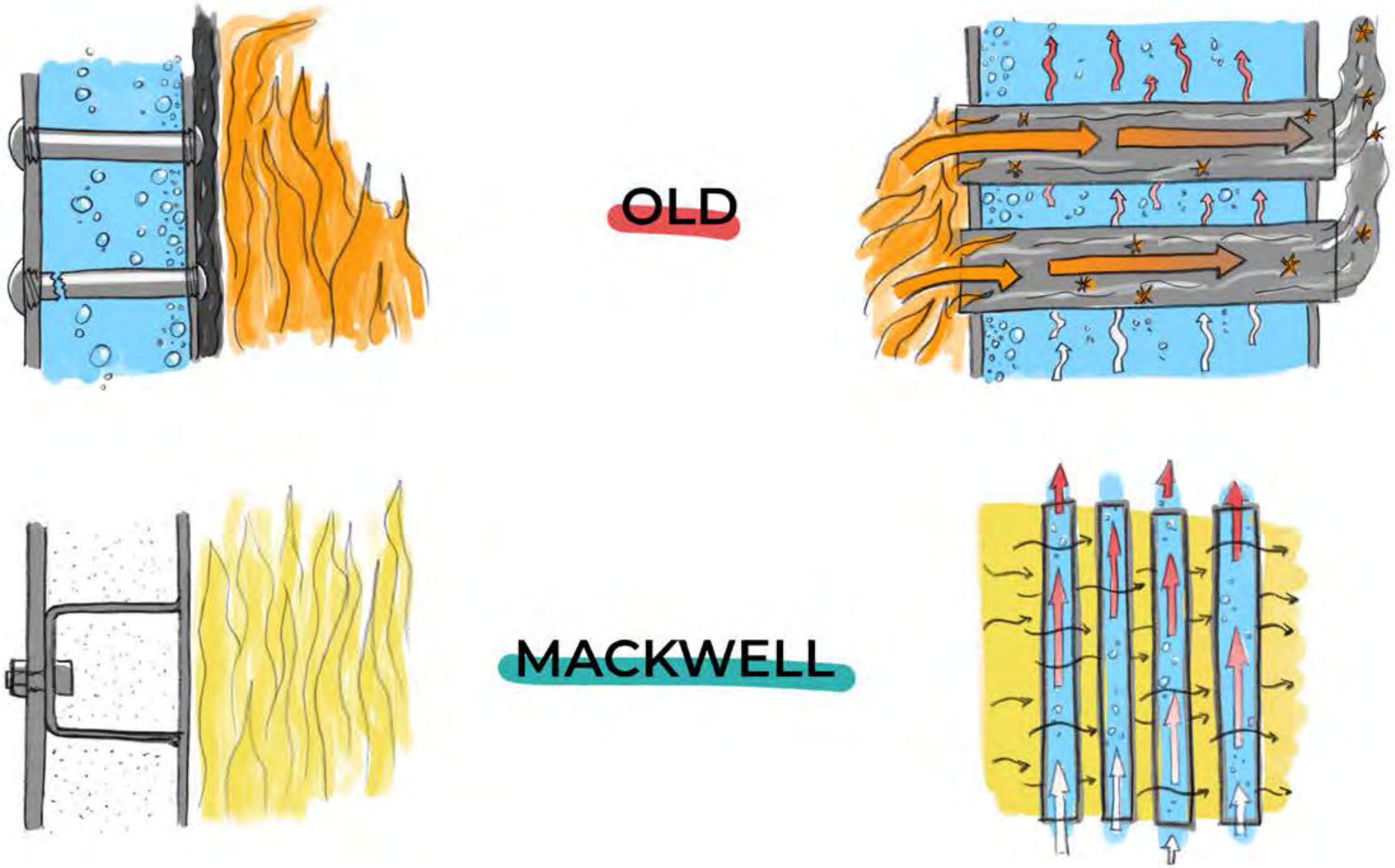


We believe energy for transport must be affordable, for everyone.

Affordability is not just about money. **Environmental impact**, **energy availability** and **community resilience** are equally important.

Solar energy, **captured and stored** by nature as **solid biofuel**, will provide affordable energy for transport.

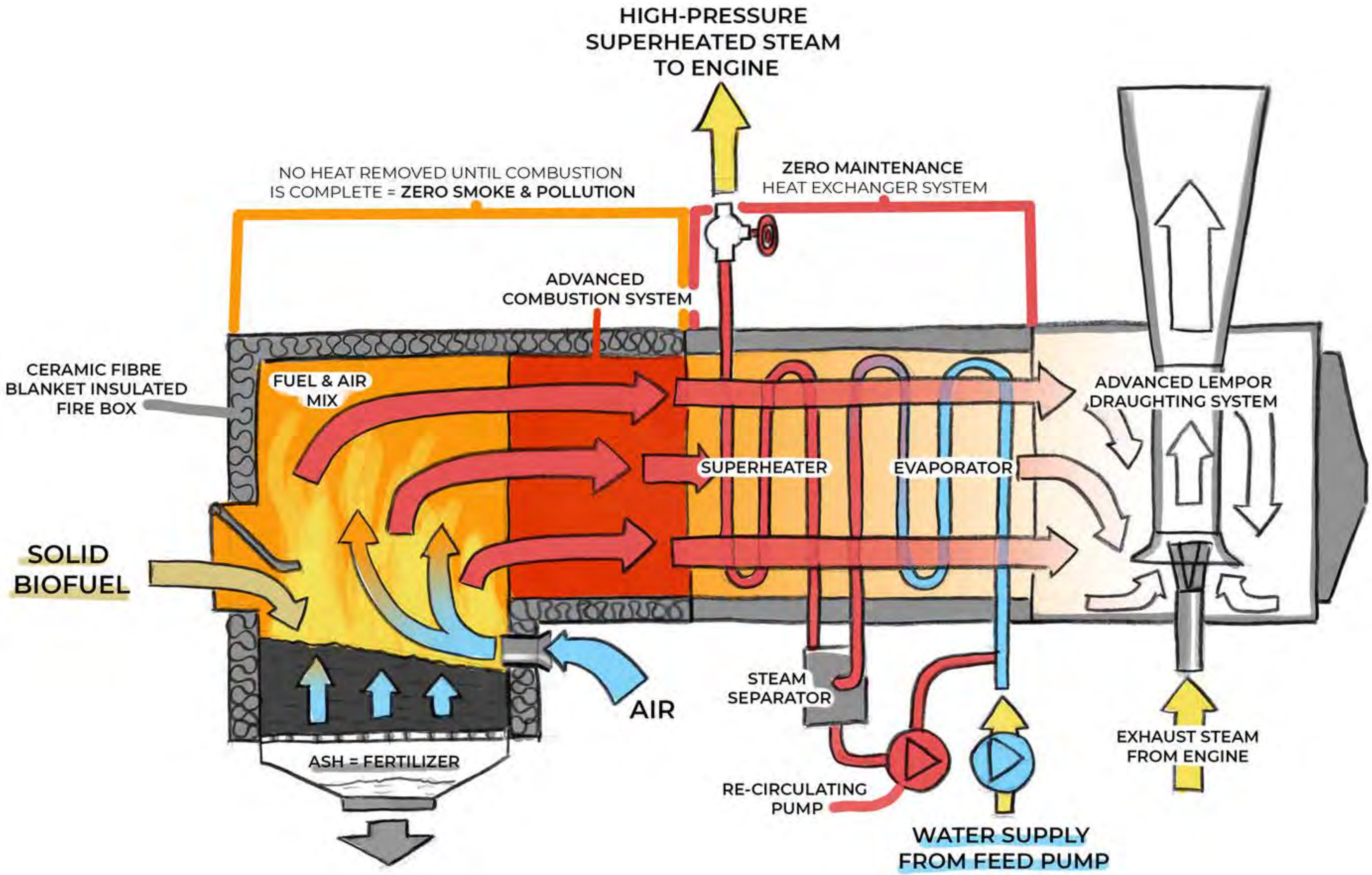
Advanced steam locomotives use solid biofuel responsibly by transporting loads on **highly efficient railway systems**, using raw solid biofuel directly and requiring few resources to build and maintain.



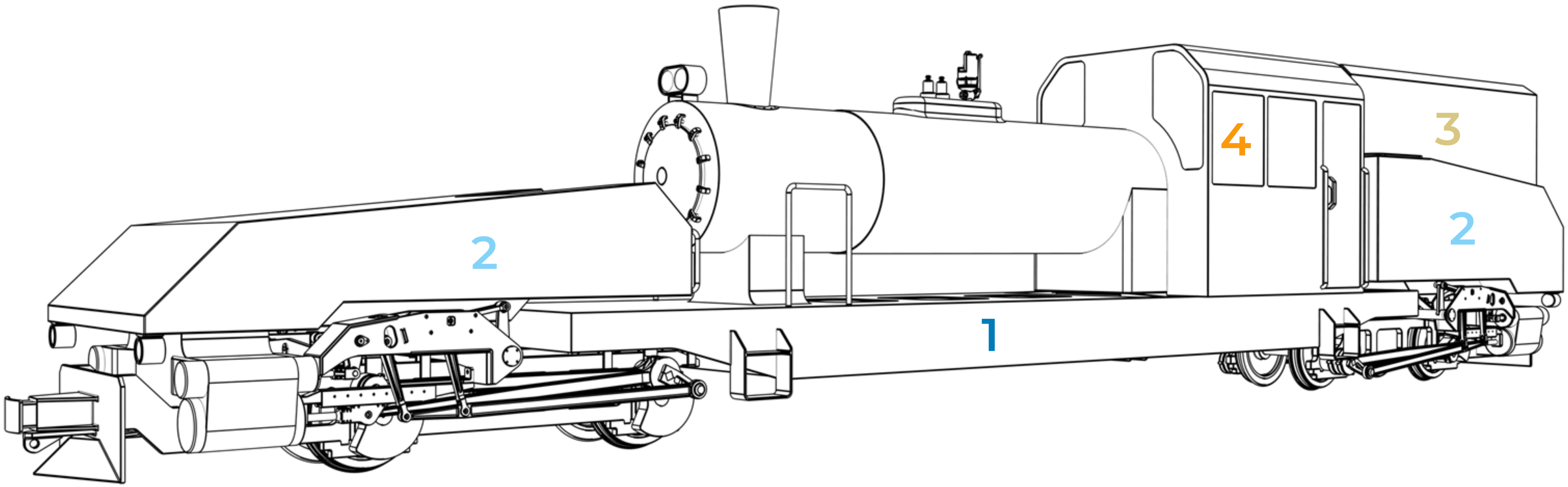
Two key principles underpin the Mackwell boiler technology:

1. **No heat is removed until combustion is complete.**
2. **Fast-moving water is heated inside small robust tubes.**

We have reinvented the locomotive boiler, **eliminating the sparks** and **smoke** that traditional boilers emit when fed solid biofuel.



Mackwell Locomotive Co's advanced steam boiler technology



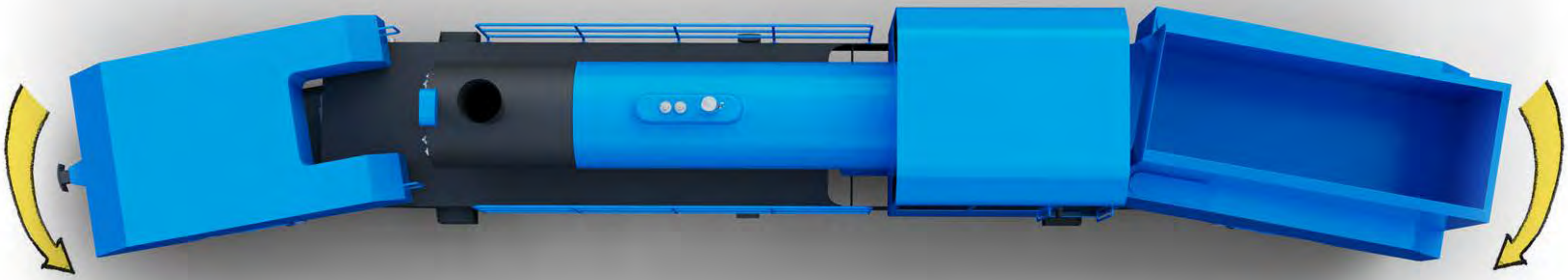
ZeroLoco™ combines Mackwell boiler technology with a highly successful articulated locomotive concept and state of the art mechanical design.

1. The long **articulated wheelbase** ensures an extremely stable ride allowing the ZeroLoco™ to glide around the tightest curves and climb steep grades. The **high power-to-weight** ratio of ZeroLoco™ gives **maximum drawbar power** with the minimum of steel. ZeroLoco™ is designed for **bi-directional operation**, no turning facilities are necessary.

2. **Large water capacity** is provided beyond typical service requirements, allowing the **locomotive's weight** to be **actively adjusted** to accommodate sections of lightly laid track.

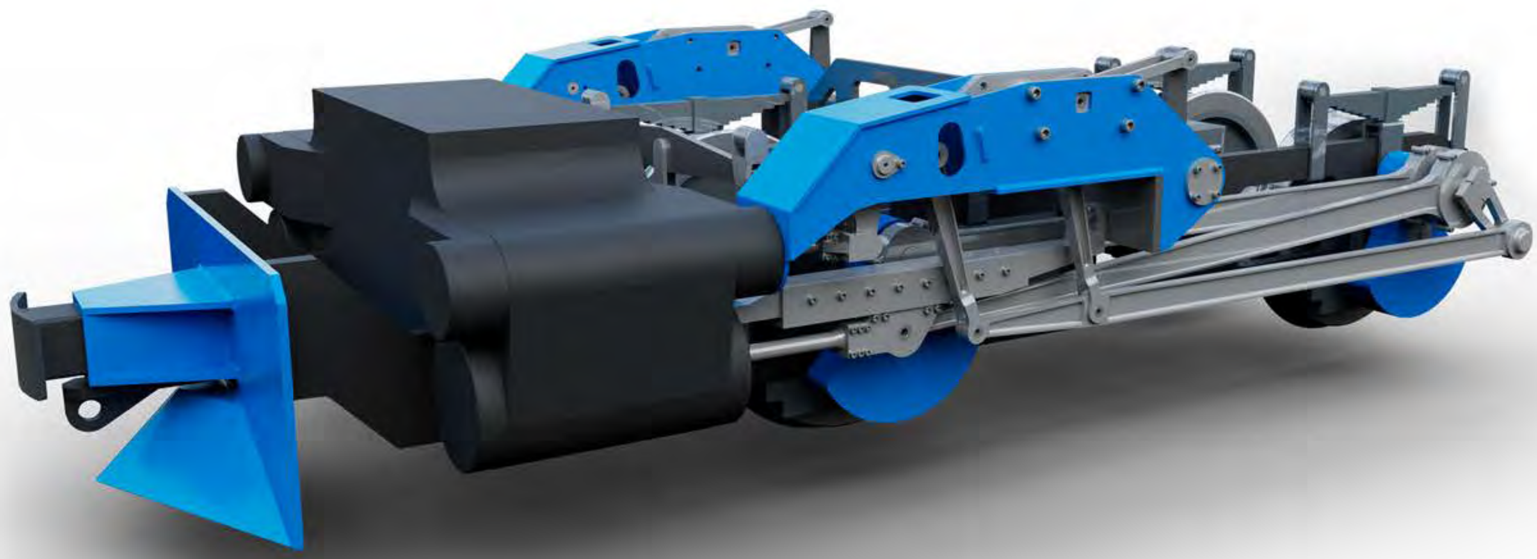
3. **Fuel bunker capacity** is large to enable the use of the **lowest-cost grades of solid biofuel** without compromising the **useful range** of the locomotive

4. An enclosed, **climate controlled cab** is provided, eliminating the hot working conditions experienced on traditional steam locomotives. **Air suspended seats** are fitted to minimise operator fatigue. **Facilities** are provided for using the heat of the boiler to **prepare hot beverages and cook food**.



The ZeroLoco is **articulated** on a highly successful pattern invented in 1908 by Herbert William Garratt. On curves, Garratt's invention results in the locomotive's **centre of gravity** moving inwards, aiding **stability**, especially on **narrow gauge** lines.

Supplies of solid biofuel and water **are carried by the driving wheels**, improving **adhesion**. The ZeroLoco's design **distributes its weight** over a long length, **reducing bridge stress.**



Tightly sealed **lightweight pistons** convert **superheated steam** into kinetic energy to haul trains. Piston thrust is transferred through **rolling element bearings** and **alloy steel rods** to crankpins on each axle.

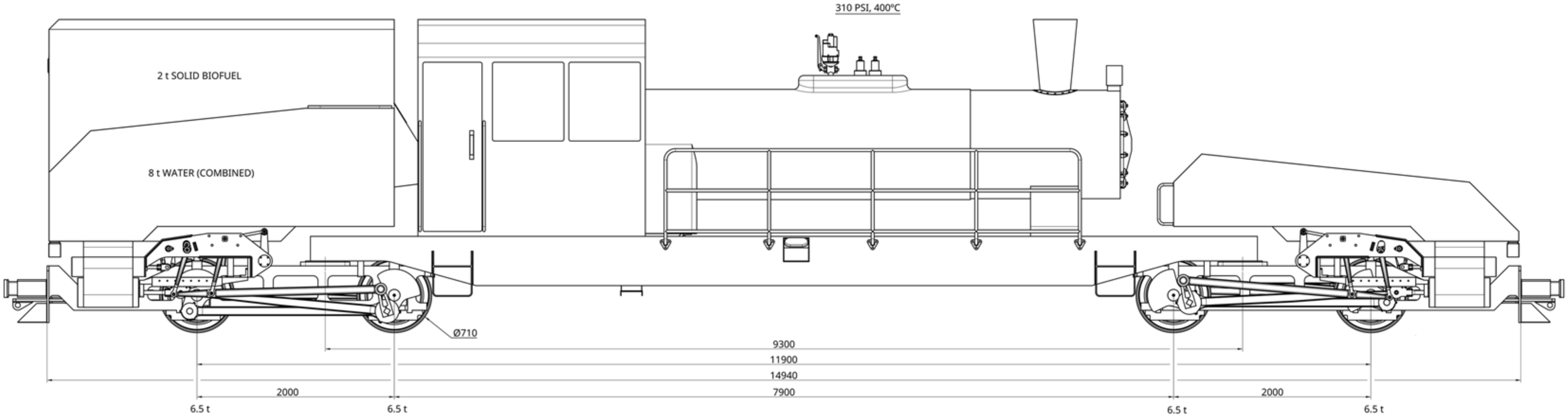
A simple mechanism named **Southern valve gear** controls the direction and power output of the locomotive. Being external, the moving parts of the transmission are simple and time effective to maintain.

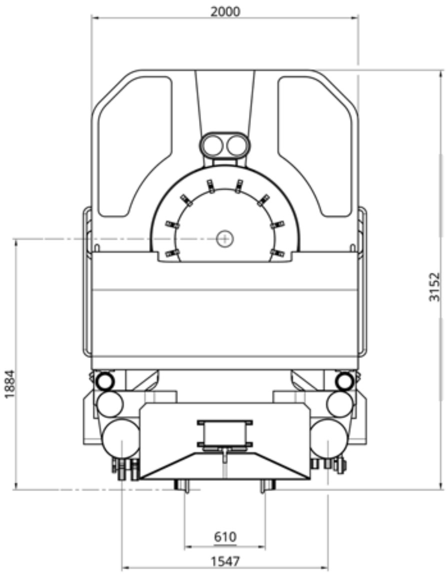
The ZeroLoco can be quickly **reversed without stopping** and **dynamic counter-pressure braking** is provided to minimise brake wear.

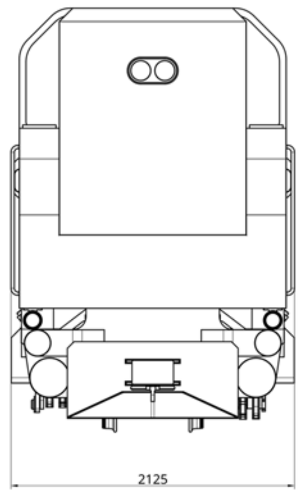
ZeroLoco™ 400 Technical Specifications[1]

Propulsion	
Max. wheel rim power, kW (hp)	298 (400)
Wheel rim tractive effort, kN (lbf)	49 (11,000)
Rated speed, km/h (mph)	60 (40)
Cylinder bore, mm (in)	170 (6.7)
Stroke, mm (in)	355 (14)
Cylinders	Four
Cycle	Regenerative Simple Expansion
Steam pressure, MPa (psi)	2.14 (310)
Steam temperature, °C (°F)	400 (752)
Grate area, m^2 (ft^2)	0.99 (10.7)
Valve gear	Southern
Driver diameter, mm (in)	710 (28)
Capacities	
Load capacity on a 1.5% gradient, tonnes (tons)	240 (265)
Load capacity on the level, tonnes (tons)	1120 (1230)
Typical range with rated load in tow, km (mi.)	300 (190)
Bunker, solid biofuel (hog fuel etc.), m^3 (ft^3)	8 (283)
Feed tanks, water, L (gal)	8,000 (2110)
Comfort	
Cooling	Air-cycle air conditioning (HFC free)
Heating	Steam heat
Seating	Air suspended, fully adjustable
Ride stability	Long flexible wheelbase with hydraulic stabilisers
Amenities	Provision for cooking on boiler & preparing hot drinks
Dimensions	
Wheel arrangement	0-4-0+0-4-0
Rigid wheelbase, mm (in)	2,000 (78.7)
Overall wheelbase, mm (in)	11,900 (469)
Width x height x length, mm (in)	2,130 x 3,150 x 14,900 (83.7 x 124 x 588)
Max. axle load, tonnes (tons)	6.5 (7.2)
Min. axle load, tonnes (tons)	4 (4.4)
Shipping weight, tonnes (tons)	16 (17.6)
Operating weight, full supplies, tonnes (tons)	26 (28.7)
Adhesion aids	Air sanding, steam rail head conditioning
Gauge, mm (ft)	610 (2.0)
Brakes	
Engine (dynamic service brake)	Counter-pressure steam brake
Engine (service)	Air, clasp brakes acting on all wheel treads
Engine (park)	Spring apply, air release
Train	Automatic air or to suit operator
Various	
Minimum curve radius, m (chains) degrees	27 (1.33) 65
Drawgear	To suit operator

[1] All specifications are subject to change.







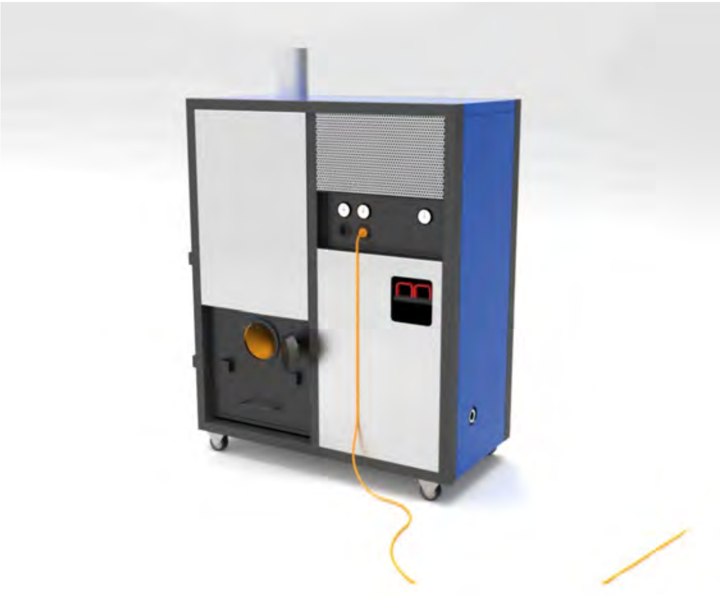
GENERAL ARRANGEMENT
ZEROLOCO™ 400-610

ATTACHMENT 10

Technology

The prototype for the first-generation Cobber is already generating up to 5kw electricity, and 20 kW heating. And it makes this power through the efficient combustion of renewable and locally sourced biomass.

The Cobber is a small-scale, compressed gas engine that works by making steam and using it to drive a reciprocating engine. At the foundation of this technology is our patented engine, in which every stroke is a power stroke, delivering incredible torque and outstanding fuel efficiency.



High Efficiency Furnace

Because of the rugged nature of our technology, this 21st century steam engine can be powered with all manner of low-grade woody fuel. The Cobber's mini- furnace combusts solid fuel in the most efficient manner possible and very little of the heat is lost to the environment. Low-grade fuels suitable for the Cobber include nut shells, woody weed species, wastepaper and cardboard, carpenters and builders' off-cuts and forest litter.

Patented Boiler and Water Tube Flash Steam Boiler

At the heart of the Cobber are two patented technologies, the water tube flash steam boiler and the compressed gas engine. The small scale water tube boiler, which requires only 20 litres of water to start, generates dry steam which, after passing through the compressed gas engine is then condensed and returned to the feed water tank for reuse.

240V Electricity

The engine turns a flywheel, producing high-torque mechanical power. This flywheel then turns an alternator and produces up to 5kw of steady 240-volt electricity. The electricity produced is enough to power a homestead, workshop, or even a small energy conscious community.

More than just electricity – The Cobber's Heat Energy Recovery Unit (HERU)

As well as producing up to 5kw of electricity, the Cobber also produces useful heat. The exhaust steam leaving the engine still contains thermal energy. This thermal energy is recovered from the steam by our Heat Energy Recovery Unit (HERU) – a water cycling heat exchanger. When the Cobber is connected to a thermal storage tank and

hydronic heating circuit it provides bountiful space heating. The HERU also provides potable hot water for all the normal uses – showers, baths, laundry, dishwashing – or any other situation where hot water is required. Please click here to see the heating circuit and hot water setup at our Renewable Energy Demonstration Site (REDS).

The Cobber can be integrated with other renewable energy technology and energy storage systems

The Cobber has been designed so that it can stand alone as a totally independent off grid' system. But the Cobber is also designed to integrate with other renewable energy systems.

Many off-grid renewable energy and battery systems have a back-up diesel or petrol generator as an essential part of the system. These fossil-fuelled generators are there to provide the system with power when solar or wind power aren't available, and to condition and recharge battery banks. The Cobber is the first truly renewable alternative to these fossil-fuelled generators and is designed to replace these generators, making so called hybrid renewable' systems fully independent pure renewable systems.

Water Distillation Circuit in Development

Work has already begun on the design of a water distillation circuit for the Cobber.

According to the latest figures from the World Health Organisation, around one third of the world's population still does not have access to clean drinking water. Uniflow is dedicated to providing a system that can give communities in developing countries access not only to electricity and hot water, but clean drinking water too.

Rotary Mechanical Power

Thanks to Ted Pritchard's patented engine, every stroke of the Cobber's engine is a power strok

This means that the heavy flywheel of the Cobber provides an incredibly stable and powerful source of high torque rotary power.

The rotary mechanical power produced by the Cobber will be similar to the PTO (Power Take Off) systems on small farm tractors. This system will be able to provide rotary mechanical power to separate attachments or applications such as direct drive water pumps, seed sorting machines, air compressors, hydraulic systems, industrial cement mixers, and many more.

Multiple Use Steam Circuit

The Cobber is capable of producing dry and wet steam. Steam and high-pressure water are used for many applications, such as the dry steam sterilisation of medical equipment (field autoclave), dry cleaning, steam ovens, pressure washers, and more.

Research and design work still needs to be done in order to equip the Cobber with an optional modular steam circuit capable of delivering the diverse benefits of on-demand process steam.

About Us

Uniflow Power was created by a Board of Directors passionate about renewable energy, and a group of investors dedicated to breathing life into this vision.

Uniflow Power was first incorporated in order to acquire the global and exclusive rights to all of the technology, inventions, and intellectual property of the late Ted Pritchard.

A small group of investors have supported the development and testing of several prototypes of the generator. Uniflow is accepting investment as we progress through product finalization towards manufacture.

The Directors

Paul Murphy
Director

As a safety, health, environment, and quality coordinator, Paul currently manages onsite safety protocols, risk assessments, and government audits, ensuring compliance and a secure work environment on large construction projects. He has also served as a construction foreman, leading teams of up to 150 people, managing projects, and consulting with stakeholders.

Previously Paul has been a commercial pilot conducting corporate, government, and private charters.

Additionally, he has written and produced films, overseeing script development, fundraising, writing, and production.

More recently in his own entrepreneurial life he has created a team-building scenario room (a submarine simulator) to enhance team dynamics, helping businesses foster stronger, more productive teams. His diverse experience brings a unique perspective on leadership and operational success.

Paul's bread and butter is all about recognising and managing risk, not being risk adverse.

Sylvia Tulloch
Director

Sylvia Tulloch is a materials scientist (UNSW) with many years experience in the establishment and management of advanced technology businesses. She was the founding managing director of the solar company Dyesol (ASX.DYE), and is now Chairman of Zeotech (ASX.ZEO).

Sylvia has been on the boards of several cleantech industry associations. She was a member of the Future Manufacturing Industries Innovation Council, and chaired its working group on Capital for Innovative Companies. She has be

on several government Boards advising on the allocation of grants for renewable energy companies, and was a judge for the Australian Technology Competition.

As Chair of Griffin Accelerator Holdings and a member of the CBRIN Board, she is an active member of the Canberra innovation ecosystem. Companies in which Sylvia is a shareholder, angel investor and Director include: Lava Blue, an advanced materials company with a mine-to-market business plan for hgih purity minerals; Balance Mat, commercialising fibre optic sensor systems for measuring balance; and Sundrive Solar, which is developing next generation conductor systems for photovoltaics.

Michael Mccann
Director

Michael McCann has had a lifetime involvement in the development of sustainable technology and processes, and has worked across the Australian energy sector for 30 years since being a founding member of Canberra based energy efficiency specialists, Energy Partners, in 1991.

Michael has been an active investor and hands on developer of new technology and systems for most of his professional life and began working on the core technology that underpins the Cobber, alongside the inventor, in 2005.

The Team

Dr Philip Hutchinson
Management (Financial)

Dr Philip Hutchinson holds a Bachelor of Science, with a major in mathematics, a PhD in Environmental Design, a Graduate Diploma in Resource and

Environmental Management, and a Graduate Diplomas in Financial Planning.

Philip initially worked in the public service with stints in the Department of Finance and Environment Australia. Philip had a career as a landscape architect which transitioned into a ten-year stint lecturing in landscape architecture at the University of Canberra. Philip ran the Landscape Architecture Program for 2 years and was on the Australian Institute of Landscape Architect's ACT committee.

After leaving academia, Philip had a career change that led to research position on financial markets and the economy with a financial planning office, a role that combined a long-term personal interest in markets with a proven research background. Philip also was on the board of Regional Development Australia (ACT) for many years until a restructure of RDAs in early 2024.

Philip is interested in development and commercialisation of eco-logical technology and believes that the Cobber has a fundamentally sound role in off-grid energy independence, and in poverty alleviation and economic development.
Philip will manage our government relations and the Future Made in Australia opportunities at Federal and State level.

Jenny Priest
Management (Operations)

Before retiring from the ACT Government in August 2023, Jenny was the Executive Branch Manager of Business and Innovation, under the Chief Minister, Treasury and Economic Development Directorate. She served as the Branch Head of ACT Sport and Recreation between 2011 and 2018, with responsibility for policy, programs and infrastructure across community and elite sport, and for managing both white and blue collar workforces. Prior to that Jenny worked for almost two decades in the ACT leasehold and planning system.

One of her most recent career highlights include mobilising operations and delivering the ACT Government's Business Support Grants during COVID-19,

providing ACT Businesses with over $236 million in financial assistance. Jenny was awarded a public service medal by the Governor-General for this achievement. She also led the major project between 2018 and 2020 that culminated in the ACT Government and the University of New South Wales (UNSW) signing an agreement to deliver a new UNSW Canberra City Campus, worth over $1b to the ACT Economy.

Jenny as a long-term shareholder in Uniflow Power, and in a new chapter of her career, has taken to the project management of our creative and engineering team with gusto. Everyone is enjoying and benefitting from her steely eyed commitment to articulating objectives and implementing outcome driven project delivery systems.

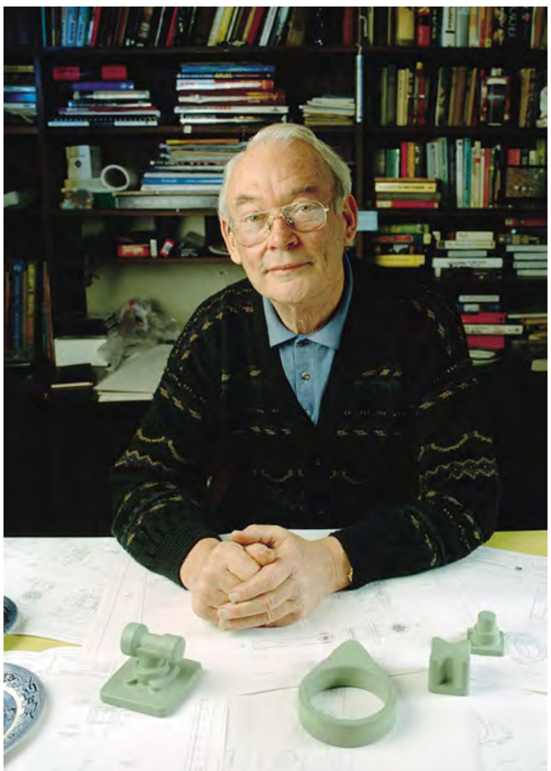
Paul Stewart
Engineering and Manufacturing

Paul holds First Class Honours in Mechanical Engineering from Curtin University Western Australia, a degree he earned while in his forties following a life of practical on farm engineering and practice.

Paul's lifelong interest in many areas of science, including manufacturing, mechanics, software programming, and electronics, brings a diverse skill set to the team. For 10 years, Paul ran a commercial mushroom farm with his wife. This involved designing and fabricating extensive customised machinery and electronics systems to improve production efficiency and quality. Before this, Paul gained years of experience in fabrication and mechanics while studying and working part time as an unqualified mechanic. Paul has developed an exceptional problem-solving ability as a result of his extensive occupational experience. Paul built the first fully functional Cobber in 2015 building on the lessons learned from the first two only partially operational prototypes.

Paul runs the Perth workshop from his farm in the Perth Hills and when not making metal parts on his own lathes and presses he does the calculations.

Ted Pritchard



Edward "Ted" Pritchard (28 August 1930 – 16 August 2007) was an Australian mechanical engineer, inventor and developer of small scale modern steam engines. Pritchard was obsessed by the virtues of modern steam as compared to the internal combustion engine. He believed that for a fraction of the investment in the development of internal combustion engines, modern small-scale steam, externally fired engines, could prove to be of far greater efficiency and utility, exhibit better combustion characteristics, have lower emissions, greater fuel efficiency, higher torque and better power-to-weight ratios.

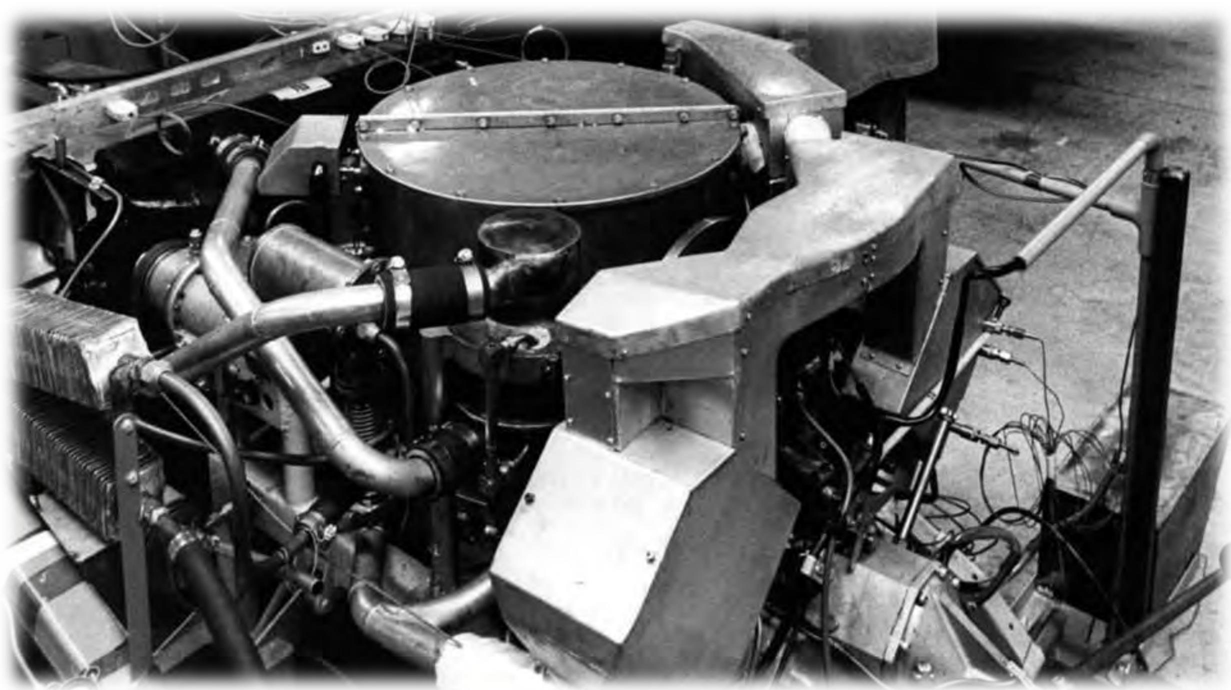
His commitment saw him nearly single-handedly attempt to launch a steam driven car industry in Australia in the 1970s. Towards the end of his life, he continued to refine the engineering principles and designs of his engines and he left a design for what he referred to as "the best small steam engine the world has ever seen". Pritchard claimed that he had, "done for the steam engine what IBM did for the computer, made it small and personal". It is from these final designs that we at Uniflow Power have built our prototype combined heat and power generator – The Cobber.

https://en.wikipedia.org/wiki/Edward_Pritchard_(engineer)

Ted invents a new kind of steam engine

Pritchard Steam Power System – Basis for Uniflow Power Ltd. Cobber CHP Unit

Available at http://www.virtualsteamcarmuseum.org/makers/pritchard_steam_power_pty_ltd.html



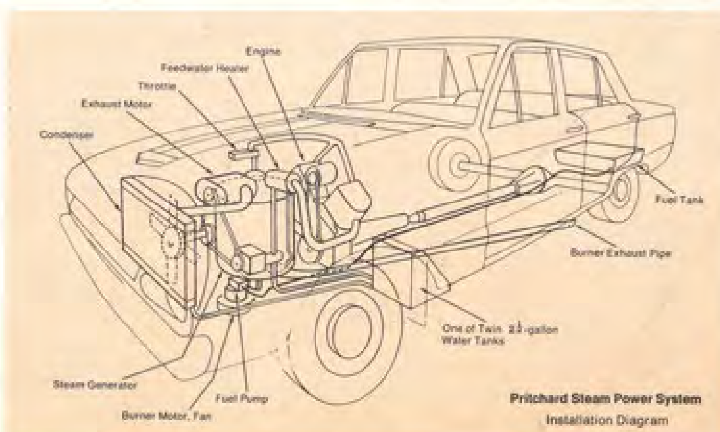
PRITCHARD

STEAM CAR

Australia's Own Design

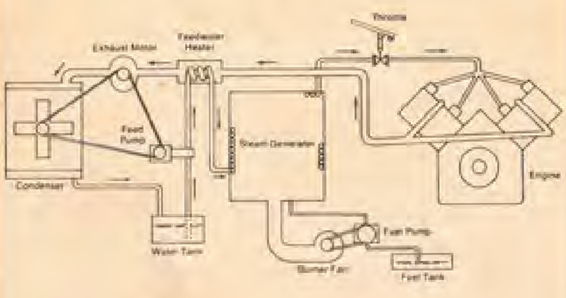
Pritchard Steam Car being airlifted to U.S.A. for special auto industry demonstrations November 1972.

The Installation Diagram shows the steam generator located centrally under the bonnet. The vee twin engine, behind the steam generator, drives the rear wheels through the propeller shaft. No gearbox is required.
The exhaust motor, mounted above the steam generator, drives the condenser fan and feedpumps positioned towards the front of the under-bonnet space.



Pritchard Steam Power System
Installation Diagram

Pritchard Steam Power Pty. Ltd.



Pritchard Steam Power System Schematic Diagram

Schematic Diagram

Capacity of the WATER TANKS located at the rear wells of the two front mudguards is 5 gallons. A FEED PUMP lifts water from the storage tanks to a FEED-WATER HEATER, where the water is pre-heated before entering the monotube STEAM GENERATOR. High-pressure steam is supplied from the generator to the uniflow ENGINE, the amount of steam being regulated by the THROTTLE.
Exhaust steam from the engine is utilized to drive the EXHAUST MOTOR, which powers both the feed pump and the condenser fan. Exhaust steam is condensed in an automotive-type radiator, which serves as the CONDENSER. The resulting condensate is returned to the water tanks by gravity, thereby completing the cycle.
Fuel and air are supplied to the BURNER MOTOR by an electrically driven FUEL PUMP and BURNER FAN. Fuel currently being used in the FUEL TANK is ordinary household kerosene.

SPECIFICATIONS

Engine type	Two cylinder 90° vee, double-acting full Uniflow. Self starting, reversible, provides emergency braking.
Cylinder Bore	2.3/8" (60 mm)
Piston Stroke	2 in (51 mm)
Displacement	17.6 cub. in. (288 cc)
Maximum Speed	4000 r.p.m.
Maximum Torques	360 lb. ft. Late cut-off (for starting) 240 lb. ft. Medium cut-off (low speeds) 160 lb. ft. Early cut-off (normal running)
Horsepower	36/40
Lubrication	Crankcase — all roller and ball bearing — splash. Cylinders — mechanical pump.
Steam Generator type	"Monotube". ("Once — through") No pressure vessels.
Water content	4 pints.
Casing size	15 in. dia. (38 cm) by 16½ in. high (42 cm)
Control	Automatic by temperature, pressure and built-in proportioning controls.
Steam pressure	1400 p.s.i. — Burner off. 1200 p.s.i. Burner on
Burner type	Cold starting from "ignition" key, pressure atomising.
Combustion chamber	Gas turbine type.
Power Unit Seals	All non-adjustable.

PERFORMANCE

AT PRESENT STAGE OF DEVELOPMENT

Starting up time	1 — 2 minutes
Cruising speed	60 m.p.h.
Fuel tests at 40, 50, 60 m.p.h.	19.6 m.p.g. (kerosene)
Water consumption	40/50 m.p.g.

POLLUTION COMPARISON

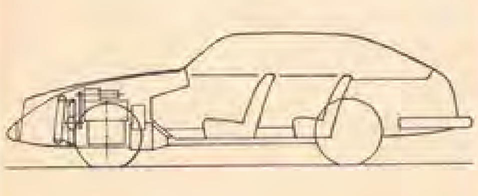
Pritchard Steam Car	Burner "Steady State"
Petrol Car	Typical uncontrolled engine.

	Petrol Car	Pritchard Steam Car
Carbon Monoxide	0.5 to 7%	0.013%
Hydrocarbons. Parts per million	200 to 3000	Less than 1
Nitrous Oxide. Parts per million	500 to 1000	115
Lead Compounds	Yes	None

THE COMPANY

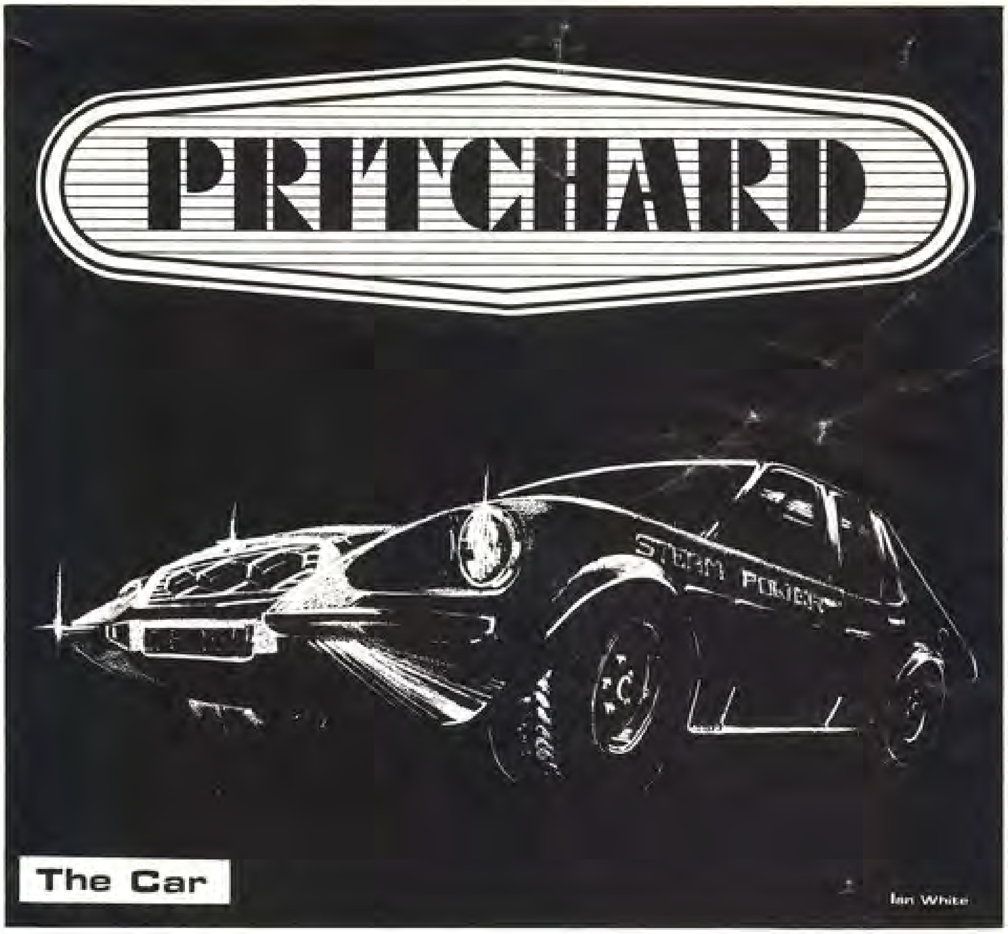
PRITCHARD STEAM POWER PTY LTD an Australian controlled Company was formed to develop modern steam power units primarily for automobiles. The result is the compact steam power unit at present fitted to an early Ford Falcon body. The cover shows this car on its way to the United States where 24 demonstration runs were given to interested bodies.
It is known that a steam car produces little smog. It does not require a gearbox. What else, then, is required for a modern steam car?
One answer is that a compact steam power unit must be used. (Boot space must not be taken up by the components of the power plant.) Only a small amount of water should be carried in the steam generator. We have made much needed break throughs in the control of pressures and temperatures in a tiny steam generator containing only 4 pints of water. It should be noted that this type of steam generator is not subject to inspection by boiler authorities.
A special feature of our design is the use of exhaust driven auxiliaries which assist in obtaining fuel consumption competitive with modern petrol-engined vehicles. The use of low grade fuel confers additional economy. Until recently, development work was carried out in a small factory at Caulfield. Operations have now been transferred to a centre at Bayswater. Here, three advanced units are to be made and subjected to intensive testing.
A production batch will then be made available for sale to the public. Your further enquiry regarding the development of this engine is invited.

Modern Steam Power for the Car of the Future



The Pritchard Steam Power Unit is a long-life, low pollution type. The engine has low mechanical drag. These are ideal characteristics in an engine for a car of the future, with low fuel consumption taking advantage of advanced body design.
Energy Crisis Steam engine burner fuel is of a wide "cut" or distillation range. This means greater flexibility in the operation of the oil refinery enabling the best possible useage of the available crude oil.
In the event of a petroleum oil shortage, fuel used can be other liquid, gaseous, solid fuel or fuels derived from solid fuels.
There is no "octane" ("pinging" or "detonation") requirement for the steam engine fuel. There is no need for high volatility. (A safety feature). There are possibilities with shale oil, and solar energy crops such as eucalyptus, peanut oil, wood and wheat.

Pritchard Steam Power PTY. LTD.
Unit 11 176 Canterbury Road, Bayswater Vic. 3153 Phone: 729 3766



The Company

PRITCHARD STEAM POWER PTY. LTD. is an Australian controlled Company formed to develop modern steam power units primarily for cars.
Patents have been issued in a number of countries on such subjects as — steam generator, burner control and engine improvements.
Mr. Pritchard has presented two papers to the Society of Automotive Engineers describing his work to date. These are —

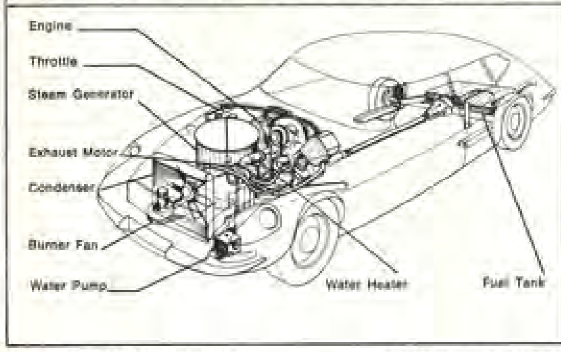
(1) "The Steam Car — Fact and Fantasy", See "SAE-Australasia", Sept.-Oct. 1971 (Winner of Hartnett Award for "An outstanding contribution to Automotive knowledge or Practice")and
(2) "Progress on the Pritchard Steam Car", See "SAE-Australasia", July-Aug. 1974.

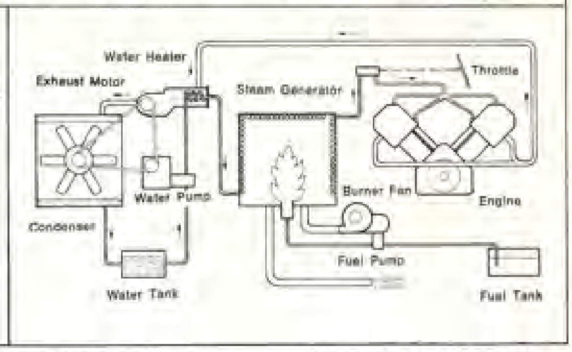
Three power units of improved design are being built at the Bendigo Ordnance Factory. One is to be mounted in the PRITCHARD aerodynamic car body, one for dynamometer testing and the other is a spare. After the test programme on these engines we will be ready to produce a pre-production batch of power units and cars for sale to interested persons.

PRITCHARD STEAM POWER PTY LTD

Factory 11, No.176 Canterbury Road Bayswater Vic. 3153 Phone: 729 3766

MODERN STEAM POWER - The answer to today's Energy and Pollution problems





GENERAL LAYOUT **PRITCHARD STEAM POWER SYSTEM** **SCHEMATIC DIAGRAM**

Features demonstrating superiority of the PRITCHARD power unit over current internal combustion engines.

* **Multi-fuel capability:** Alcohol from sugar cane, "Grown crop" oils, or petroleum based liquid fuels can be used. Economic use of solid fuels is being investigated for stationary and marine applications.
* **Environment:**
  (a) **Pollution** is virtually non existent. Fuels do not need to be leaded.
  (b) **Noise.** Steam has always been noted for its quietness in operation, and the PRITCHARD power unit is no exception. This is most essential for trucks, buses, construction and agricultural equipment. Many plant operators and farmers have had their hearing affected by noisy machinery.
* **Safety:**
  (a) **Reluctant Flammability.** Fuels used in the PRITCHARD power unit do not need to be highly volatile. This is a great advantage in marine applications, where spilt or leaked petrol can collect in bilges and causes explosions.
  (b) **Collision.** The Steam Generator consists of coiled tubing, which, in a heavy front end collision acts as an impact absorbing crushable structure; unlike the rigid cast iron cylinder block of an internal combustion engine. There are no pressure vessels to cause explosions.
  (c) **Elimination of "Runaway" danger.** In the event of brake failure, the reverse torque of the Steam Engine can easily halt the vehicle. This is an important advantage for all vehicles, especially buses and trucks.
* **Generally:** The engine is self starting and reversible. High torque from the relatively small engine eliminates the need for a manual gearbox and clutch, or automatic transmission. Easy manoeuvering and driving is thus obtained. Low engine friction loss — about one-sixth of a petrol engine — enables development in conjunction with low drag car bodies toward further increases in fuel economy.
* **Summing up:** **The PRITCHARD is a very safe, low pollution, multi-fuel power unit. It has characteristics most desirable for use in automotive, marine, construction and agricultural machinery; and stationary applications such as sawmilling and electric power generation.**

SPECIFICATIONS — CAR ENGINE

ENGINE:

Type	Two cylinder 90° vee. double acting full Uniflow Self starting, reversible: provides emergency braking.
Cylinder Bore	66 mm.
Piston Stroke	60 mm.
Displacement	410 cc.
Max. r.p.m.	4000.
Max. torques	Late cut-off (for starting)(500 lb.ft.) 678 Nm. Medium cut-off (low speed)(340 lb.ft.) 461 Nm. Early cut-off (normal running) (225 lb.ft.) 305 Nm.
Power	33.5 kw (45 H.P.).
Lubrication	Crankcase — all ball and roller bearings — splash. Cylinders — mechanical pump

STEAM GENERATOR:

Type	Monotube ("Once-through")
Water Content	2.2 litres.
Casing Size	410 mm dia. x 470 mm high.
Controls	Automatic by temperature, pressure and built-in proportional controls.
Steam Pressure	9646 k Pa (1400 p.s.i.). Burner off. 8268 k Pa (1200 p.s.i.). Burner on.

BURNER:

Type	Cold starting from "ignition" key, pressure atomising.
Combustion Chamber	Gas turbine type.

(**Note:** *Specifications are subject to change without notice.*)

POLLUTION COMPARISON

PRITCHARD Steam Car.... Burner "Steady state"
Petrol Car ....Typical uncontrolled engine.

Exhaust Emission	Petrol Car	PRITCHARD Steam Car
Carbon Monoxide	0.5 to 7%	0.013%
Hydrocarbons (parts per million)	200 to 3000	Less than 1
Nitrous Oxide (parts per million)	500 to 1000	115
Lead compounds	Yes	None

Note: *PRITCHARD steam car passed pollution requirements easily for Australian 1976 standards in test on 21st May, 1974.*

PERFORMANCE DATA. PRITCHARD STEAM POWERED UNITS

Parameter	*Early Truck 5 Ton*	*Experimental Car. 6 Passenger*	* *New Car 6 Passenger*
Cruising Speed	64 kph (40 mph)	104kph (65 mph	136kph (85 mph)
Fuel Consumption (kerosene)	28-47 L/100kmz (6-10 mpg)	11-14 L/100km (20-25 mpg)	9-11 L100km (25-30 mpg)
Water Consumption	28 L/100km (10 mpg)	to 1.66 L/100km (170 mpg)	Negligible (semi-sealed)
Start up time	4 minutes	1½ minutes	45/50 seconds
Acceleration	Good	Capable of improvement	Good

*Figures subject to confirmation by testing programme.

PRITCHARD STEAM POWER PTY LTD

Factory 11, No.176 Canterbury Road Bayswater Vic. 3153 Phone: 729 3766

(LA3) THOUSAND OAKS, Cal., Dec 14--STEAM AUTO ENGINE UNVEILED--Edward Pritchard, an Australian inventor, shows off his steam automobile engine in a demonstration Thursday in Thousand Oaks, Cal. Pritchard, who built the system into a Ford Falcon , said he's driven the car up to 60 miles per hour and says the engine could meet pollution emission standards set up for 1975. (AP Wirephoto)(rhs51410stf-dfs) 1972

Pritchard Steam Car – Drive Article (2022)

Available at https://www.drive.com.au/caradvice/the-australian-designed-car-built-to-steamroll-the-establishment/

You could be forgiven for not knowing of The Pritchard, an obscure, yet ambitious automotive marque founded by a Melbourne-based engineer, who'd go on to have his 'steamer' air freighted to Detroit to show it to the 'big boys'. Mad about steam engines from an early age when he and his father used to build them for fun, Edward 'Ted' Pritchard was a well-credentialed mechanical engineer and visionary. A Fellow of Melbourne's Technical College (now the Royal Melbourne Institute of Technology) and a member of the Institute of Engineers Australia, he believed that steam could power anything and do so economically. To prove his beliefs, he set about commercialising a steam power unit for use in everything from the agricultural to automotive sectors.

A labour of love for Ted and his father, the self-named, designed and engineered Pritchard Steam Power System was, in essence, a steam crate motor that could be retrofitted, or engineered from the outset as a primary power source for any machine requiring motive force. To demonstrate the flexibility, compact size, and practicality of the steamer, Ted decided to fit it to a 1963 XM Ford Falcon.

Over four years, Pritchard refined the drivetrain and packaging to suit the Falcon, with the final steamer featuring a 288cc, 90-degree, V-twin which developed approximately 40 horsepower and a mighty 360Nm of torque, with peak revs reached at 4000rpm. This was enough to return a fuel efficiency of 9.4 litres per 100km. Compare that for a moment to the standard six-cylinder XM Falcon – which would consume close to 15 litres of fuel per 100km – and you start to understand why the Pritchard had potential.

The Pritchard also had fewer moving parts, could run on any type of combustible fuel from cooking oil to kerosene, and weighed less than its combustion-powered contemporary. Most interesting was the fact that the car did not need a transmission as the engine could be thrown into reverse at the flick of the column-mounted shifter for immediate 'reverse-torque,' or as Ted called it an additional 'safety device.' The car was also self-starting, featured a closed-loop boiler, made use of the standard Falcon radiator as a condenser and could cruise at 120km/h.

By 1967, Ted and his 'Green Stripe' XM – named for the green centre stripe Pritchard fitted to the vehicle – were ready to undertake proof on concept and field trials. Conducted around Melbourne, Pritchard's field trials were described as 'convincing' by the media of the time. So widespread was the interest in the 'steam-powered car' that several news networks covered the vehicle trial at the time.

Buoyed by enthusiasm from the successful trials, Ted refined his offering and by 1971 his 'Green Stripe' had attracted the attention of US auto manufacturers, who undertook extensive local testing in Australia. So impressed were the Americans, that in November of 1972, the car and its inventor set off for the United States. Landing in L.A., the company embarked on 24 demonstrations over three weeks to the likes of Ford, General Motors, American Motors and a host of other interested parties, with all leaving the events impressed according to the inventor.

Upon return to Australia, Ted was made aware that 'Green Stripe' was the cleanest vehicle ever evaluated by far, already surpassing the incoming 1975 US Emissions Regulations.

These forthcoming emissions standards, which we now know as Corporate Average Fuel Economy (CAFE) regulations, would see a slew of new emissions measures thrust onto American manufacturers – including Exhaust Gas Recirculation, recognition of NOx emissions and the adoption of catalytic converters. Pair this with the oil shock of 1973 and automakers moved quickly to clean up their act, in turn stifling interest in Pritchard's work.

Undeterred, Ted continued to refine his drivetrain and by 1974, interest had reignited in Pritchard's work, with Ted presenting the vehicle for further testing at Ford's Geelong testing facility. At first, Ford's engineers thought their testing equipment was mis-calibrated, so they reset the equipment, but the result was the same. Pritchard's drivetrain was able to meet emissions regulations that we would not see until 1999 – known as Euro 2 – but Ford passed on the tech once again.

It was by this time that media interest was again piqued, and the engineer-come-advocate appeared on the iconic Australian TV series Leyland Brothers World (if you don't know who they are, just Ask the Leyland Brothers) this time with the Falcon sans the green stripe. It is during this interview with Mal Leyland is told of a second-generation Pritchard steamer that is under development. That second vehicle was first shown to the public at the 1975 Melbourne International Auto Show as a model (below), debuting as the Advanced Pritchard Steam Car. So compelling was the proposition that the then Federal Minister for Manufacturing and Industry awarded a grant to Pritchard to build three prototypes.

Based on a 'restyled' Holden Torana donor vehicle, progress on the prototypes was slow and funds began to run out. To keep the program alive, Ted sold one of the original steam trucks he and his father worked on in the early days, but it was not enough. Fortunately, in July of 1977, State and Federal Governments injected further funds into the company just as it was on its knees. This cash lifeline was enough to finish the prototype drivetrains and get them to the bench testing phase, but again the program began to run behind schedule and was bleeding cash.

In short, by 1981 the company went broke and despite growing international interest in the powertrain, for both motive and stationary purposes, the company just didn't have the means to finish its development work. But Ted wasn't about to give up on his dream and passion. Finding work as a Lecturer at the Royal Melbourne Institute of Technology (RMIT) Ted taught the finer points of engineering and thermodynamics by day, and whiled away at his drawing desk by night investing five years and 6000 hours into his new S5000 steam engine – named so because of its ability to generate 5000 Watts of power.

Between 1992 and 2002 Ted Pritchard remained committed to his cause, lobbying governments and publishing articles on the advantages of steam power. By 2003, Pritchard Power Australia had been formed to further develop and license the S5000 power unit, but it was never to be. In 2006, with Ted now 77 years old, he signed the technology over to an Australian company that embarked on commercialising the engine, but he died before it was finished. Today, Pritchard's S5000 lives on via the Victorian-based company Uniflow Power which has developed the steamer into a consumable product dubbed the 'Cobbler'. Able to produce electricity, steam, hot water, distilled water and rotary mechanical power, the Cobbler is everything Ted Pritchard envisioned his powerplant could be.

Additional details on Pritchard Steam Engine Patents can be found at:
http://www.rexresearch.com/pritchardsteam/pritchard.html

Pritchard Steam Power System Patent Information
Available at http://www.rexresearch.com/pritchardsteam/pritchard.html

US2008184944
Water tube boiler

A steam generator for generation of steam in a water tube boiler having first and second upright headers (16,18) in sealed communication with lower (12,14) and upper (13,15) inclining banks of tubes communicating therebetween. An end portion of the tubes in the upper bank (13,15), changes to a declining angle toward its communication with the upright header (16). The declining angle provides for increased separation of steam from hot water in the tubes.

[0001] This application claims the benefit of U.S. Provisional Patent Application No. 60/720,210, filed Sep. 23, 2005.

BACKGROUND OF THE INVENTION

[0002] 1. Field of the Invention

[0003] The invention disclosed and described herein relates to steam generators. More particularly the apparatus and method of employment herein disclosed relates to an improved design for a water tube boiler and steam generator which provides for improved separation of steam from residual water and enhanced protection from overheating of water tubes. The unique inclined design with curved end portions can be employed in any number of fields using steam including driving steam engines, for process steam, for steam heating, for hospital sterilizers, for most commercial power plants, for nuclear generators using steam boilers, or in any application where steam is employed.

[0004] 2. Prior Art

[0005] Water-tube style boilers for steam generation have been in use for decades and generally consist of natural-circulation style and submerged style water tube boilers. Water tube boilers were developed to satisfy the demand for large quantities of steam at pressures and temperatures far exceeding those possible with fire-tube boilers.

[0006] Water tube boilers have a low risk of disastrous explosion compared to fire box boilers or fire tube boilers, and they are space saving. They also provide for rapid steam raising and ease of transportation. However, water tube boilers have required that supply water should be substantially pure and specially treated to protect the steam tubes and may require special maintenance procedures for this reason.

[0007] Because of their safety and large production capacity for steam, water tube boilers are employed in products from steam engines to nuclear power plants and are considered an especially safe design for steam generation in a steam powered system. A wide variety of sizes and designs of water tube boilers are used in power stations, nuclear reactors, ships and factories. Well known designs such as those by Babcock and Wilcox have been in use for decades and those skilled in the art will understand the positioning and employment of the included water tube device herein, in proper communication with a heat source, for use in all such boilers.

[0008] Heating the water tubes of a water tube boiler or steam generator requires that fuel is burned inside a furnace, creating hot gas. The hot gases are communicated to the water tubes in various ways known in the art to heat up water in the steam-generating tubes.

[0009] Submerged water-tube boilers generally employ a means to heat water or fluid in the steam generator. The heat from fossil fuels, nuclear power, natural gas, or other sources, is communicated to a lower bank of inclined tubes through a first substantially upright header. The first or lower bank of tubes is inclined to communicate steam upwards through a plurality of the vertical headers. In such submerged boilers, the lower bank of tubes is substantially submerged in the heated water being communicated from the first upright header. Each of the lower bank of tubes communicates at an inclined end with a second substantially vertical header wherein steam rises in the second header and water will return to the reservoir below feeding the first header.

[0010] An upper bank of tubes communicating with the second header above the water line, receives the steam communicated through the second header from the lower bank of tubes, and communicates that steam through the upper bank of tubes at an inclined angle from the second substantially vertical header back to the first header. A preferred inclining angle for the first and second bank of tubes is at an angle between 11 and 15 degrees with a current especially preferred mode being substantially 12 degrees.

[0011] Various patents such as U.S. 309, 282, (Babbitt) describe such conventional submerged water-tube steam generators and all suffer from inadequate separation of remaining water from the steam which has been communicated to the upper bank of tubes. As such, there exists a need for an improved water-tube style boiler or steam generator which both dries and separates water from the steam. Such a device should also minimize the danger of overheating the water tubes which damages the apparatus and in doing so, results in an increased power rating for the steam generator device. Such a device should provide steam for turbines and the like which is substantially free of water droplets which can severely damage turbine blades.

SUMMARY OF THE INVENTION

[0012] The disclosed device and method of forming the device provide for an improved water-tube boiler or steam generator, which overcomes the above-noted deficiencies of prior art. The disclosed device is suited for use wherever water tube type steam generator devices are employed in combination with a properly communicated heat source to produce steam whether it be a liquid or gas communicating the heat from a heat source to the water tube boiler.

[0013] The device features water tubing which is divided into two sections or banks. A lower section features a plurality of tubes each of which angle upward from a first end, which is in sealed engagement with a first vertical header. Each of the plurality of tubes in the lower section is in sealed engagement at the upper end, with a second substantially vertical header. In one mode of employment, the device is in operative communication with a heat source in the form of hot gases from a furnace. In other modes of employment, the device may be employed with the entire lower tube section, submerged in water as a submerged water tube boiler.

[0014] In operation, heated water is communicated into an upright first header and thereafter into the inclined tubes of the lower section of tubes. Steam, and the hottest portions of water from the lower section of tubes reaching the axial passage of the second upright header, will naturally rise in the second header where it is thereafter communicated to a second bank of inclined tubes in sealed engagement between the axial cavities of the second header and first header.

[0015] The second bank of tubes is also angled upward from a lower end engagement with the second header to an upper sealed engagement of the opposite end of each tube, with the first header. Steam and/or water communicated from the lower tube section into the second header is thereon communicated into the tubes making up the second bank of inclined tubes where it will naturally rise toward the upper end of the first header.

[0016] Thus, the device features two banks of tubes, with all of the tubes of the lower bank or section angled upward from a respective starting end to respective termination ends at the second header. All of the plurality of tubes in the upper bank angle upward from starting end in sealed communication with the second header, to their termination-in sealed engagement with the first header. The upper or second bank traverses the distance between the first and second headers in the opposite direction as those of the lower bank.

[0017] In the preferred embodiment of the device, at the upper end portion of each tube member of the upper bank of tubes, adjacent to their individual engagement points with the first header, every tube is curved to angle downward to its sealed engagement with the second header. Consequently, an upper end portion of each tube in the upper bank of tubes changes direction from an upward angle to a downward angle just adjacent to a sealed engagement point with the first header.

[0018] Currently, this change in the angle of the upper ends of the tubes making up the upper bank changes around the curve from the noted upward angle to a declining angle. A current preferred angle of the upward incline is substantially 12 degrees relative to the substantially perpendicular second header to a declining angle of between 20 and 30 degrees with approximately 25 degrees being the especially preferred angle at their juncture with the substantially perpendicular first header.

[0019] The change in direction resulting in a downward or declining approach of the upper end portions of the tubes making up the upper bank of tubes has been found to provide an excellent increase in the efficiency of the device in separating water from steam which is to be communicated from the upper end of the first header to the device requiring the steam. Steam in the pipes of the inclining tubes of the upper bank of tubes naturally rises toward the top of each inclining tube. Consequently, at the point at the upper end of each tube where the direction or angle of the tubes changes from an incline to a decline toward the second header, steam is separated and accelerated into the first header in an upward direction. The water portion of the mixture which is already on the lower half of each tube, continues down the declining slope of the tubes entering the first header. This bifurcation of steam and water achieves an extremely high degree of separation of steam from water not heretofore provided by the simple horizontal or inclining tubes of prior art.

[0020] It is therefore an object of the present invention to provide a water tube component for a water tube boiler which provides increased boiler efficiency and steam generation which can be employed in all types of water tube boilers using a heat source generating steam for power.

[0021] It is a further object of this invention to employ downward curved portions of substantially all upper tubes of the water tube component to achieve increased separation of steam communicated to a device requiring it, from water.

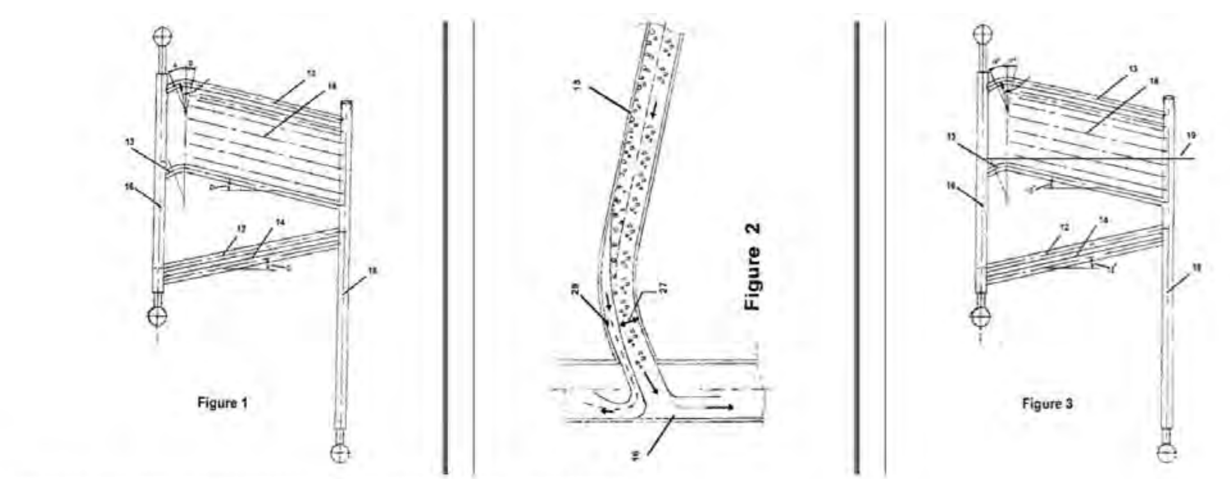
[0022] These together with other objects and advantages which become subsequently apparent reside in the details of the construction and operation of the invention as more fully hereinafter described and claimed, reference being had to the accompanying drawings forming a part thereof, wherein like numerals refer to like parts throughout.

[0023] With respect to the above description, before explaining at least one preferred embodiment of the invention in detail, it is to be understood that the invention is not limited in its application to the details of construction and to the arrangement of the components or steps set forth in the following description or illustrated in the drawings. The various apparatus and methods of the invention are capable of other embodiments and of being practiced and carried out in various ways which will be obvious to those skilled in the art once they review this disclosure. Also, it is to be understood that the phraseology and terminology employed herein are for the purpose of description and should not be regarded as limiting.

[0024] Therefore, those skilled in the art will appreciate that the conception upon which this disclosure is based may readily be utilized as a basis for designing of other devices, methods and systems for carrying out the several purposes of the present buoyancy engine. It is important, therefore, that the objects and claims be regarded as including such equivalent construction and methodology insofar as they do not depart from the spirit and scope of the present invention.

[0025] Further objectives of this invention will be brought out in the following part of the specification wherein detailed description is for the purpose of fully disclosing the invention without placing limitations thereon.

BRIEF DESCRIPTION OF DRAWING FIGURES



DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS OF THE DISCLOSED DEVICE

[0026] FIG. 1 depicts a view of the water tube apparatus herein described showing the improved configuration for use in as a segment of a water tube boiler or steam generator and adapted for engagement with a heat source to generate steam.

[0027] FIG. 2 depicts a view of the device of FIG. 1 employed as a submerged water tube boiler, showing angles of incline of both banks of tubes, and the especially preferred downward angles of the upper end portions of the second bank of tubes. Also shown is the submerged lower bank.

[0028] FIG. 3 depicts the improved separation of steam from water in the fluid flow when the upper end portion of the tubes of the upper bank communicates in a downward angle at their engagement with the first vertical header.

DESCRIPTION OF PREFERRED EMBODIMENTS OF THE DISCLOSED DEVICE

[0029] As depicted in FIGS. 1-3, the device 10 herein provides a steam generator or water-tube boiler which is adapted for operative engagement with a heat source such as a conventional furnace or other means for communication of heat to the device 10. Most such steam generators are formed of multiple segments of similar construction grouped to form a larger steam generator with the tubular components of the segments being substantially inline and parallel to each other. The device 10 with the aforementioned improved water and steam separation will provide significant improvement when used in any type of water tube boiler over the prior art. The device 10 adapted more mounting in operative communication with the chosen heat source to generate steam and features a plurality of tubes 12 and 13 for communicating steam and water through the device. The two inclining pluralities of tubes 12 and 13, are formed in two distinct banks.

[0030] A lower bank 14 features a plurality of tubes 12 which in the current mode are substantially parallel with each other, and having a fluid capacity sufficient for the intended purpose. Each of the tubes 12 of the lower bank 14 angle upward at an inclining angle "C" from a lower first end which is in sealed engagement with a first vertical header 16. Each of the plurality of tubes 12 in the lower bank 14 proceeds to a sealed engagement at an upper end, with a second, substantially vertical header 18. The first and second vertical headers 16 and 18 in the current preferred mode of the device 10 are substantially perpendicular to a level support surface, and parallel; however, it is anticipated that other angles for the vertical headers 16 and 18 to both the support surface, and each other, may be employed.

[0031] The device as shown in FIG. 2, in a particularly preferred mode may be installed as a steam generator in a submerged water tube type boiler configuration with the entire lower tube section submerged in water below the water level 19.

[0032] In operation for steam generation, heated water is communicated into the first header 16 and thereafter into the inclined tubes 12 of the lower bank 14 wherein steam and the hottest portion of water from the lower bank reaching the second upright 18 header will naturally rise in the second header 18. This steam and high temperature water is therein communicated to the second or upper bank 15 of inclined tubes 13 where it proceeds upward in the inclined tubes 13 from the second header 18 toward the first header 16.

[0033] The upper bank 15 of tubes 13 is angled upward at an angle of incline "D" from a first or lower end engagement with the second header 18 to a transition point (shown as line between "A" and "B") at a curve and then downward to a sealed engagement at a second end with the first header 16. Steam and/or water communicated from the lower tube bank 14 into the second header 18 is thereon communicated through the plurality of tubes 13 of the upper bank 15 where it will rise toward the second end engagement to the first header 16.

[0034] As noted, in an especially preferred mode of the device 10, which experimentation has shown to operate with improved efficiency, an end portion of each tube 13 of the upper bank 15, from a curve at a transition point adjacent to their respective individual engagement points with the first header 16, is angled downward in a declining angle "A" from a curved point along the transition point in each tube 13. This reversal in the angle at the upper ends of the tubes 13 of the upper bank 15 from the noted preferred incline to a declining angle or path in the end portion of each tube, has shown to provide unexpected results in steam and water separation and efficiency of the device 10. Currently the inclining angle of the tubes 13 yielding most favorable results when combined with the upright parallel first and second headers 16 and 18, is substantially 12 degrees relative to the substantially perpendicular second header 18. The declining angle of the end portion between the curved portion and the second end works very well at substantially 25 degrees heading toward the sealed engagement with the substantially perpendicular first header 16.

[0035] This improved efficiency in separating steam from water is yielded by a means for enhanced separation of water from steam being carried in the upper tubes 13 provided by the declining approach of the end portions of the tubes 13 at their sealed engagement to the upper portion of the first header 16. The improved separation of the steam and water in the tubes 13 provided by the declining end portion of the tube 13 is provided by the steam which rises toward the top of the tube 13 and the water on the bottom of the tubes 13 being accelerated during the decline. Steam in the tubes 13 at the sealed engagement to the header 16 already on the upper portion of the tube 13, is accelerated upward into the first header 16 as it reaches it. Water, which is already on the lower half of each tube 13 due to lower heat content and higher density, is also accelerated by the declining slope of the tubes 13 entering the first header 16. As the water is denser and being accelerated in a declining angle of velocity, it continues in the downward angle imparted by the end portions of the tubes 13 and into the first header 16.

[0036] The declining angle of the end portions of the upper bank of tubes 13 thereby results in a much hotter and drier steam being communicated into the upper portion of the first header 16 and onto the blades of a turbine, or for any other purpose requiring high pressure, dry, steam.

[0037] The method and components shown in the drawings and described in detail herein, disclose arrangements of elements of particular construction and configuration for illustrating preferred embodiments of structure of the present invention. It is to be understood, however, that elements of different construction and configuration, and using different steps and process procedures, and other arrangements thereof, other than those illustrated and described, may be employed for providing a steam generator or water tube boiler in accordance with the spirit of this invention.

[0038] As such, while the present invention has been described herein with reference to particular embodiments thereof, a latitude of modifications, various changes and substitutions are intended in the foregoing disclosure, and will be appreciated that in some instance some features of the invention could be employed without a corresponding use of other features, without departing from the scope of the invention as set forth in the following claims. All such changes, alternations and modifications as would occur to those skilled in the art are considered to be within the scope of this invention as broadly defined in the appended claims.

US3892502
Control of expansion ratio in rotary motors

A rotary motor driven by a pressurised working fluid such as steam or compressed air having a series of working chambers around the periphery of the motor, an inlet port and an exhaust port oppositely disposed at the periphery of the motor for the inlet and outlet of the working fluid and a further port or ports between those ports admitting further working fluid bled from the supply to the chamber past the inlet port but before the exhaust port to significantly increase the amount of working fluid in the motor at low speeds or high load.

BACKGROUND OF THE INVENTION

This invention relates to rotary motors of the type using steam or compressed air or other expansible gas or vapor. In particular the invention relates to the provision of a device for varying the expansion ratio of rotary motors of the type specified and which are not fitted with intake valves such as rotary inlet valves or inlet valves operated by means of link motions or cam shafts.

In a rotary motor or reciprocating engine which is used over a wide range of speeds as, for example, from zero to the maximum design speed, it is desirable to use a small expansion ratio or "late cut-off" of the high pressure working fluid in order to obtain more positive starting, high overload torque and better smoothness on starting. A smaller expansion ratio or "later cut-off" is also desirable, apart from when starting, in order to run against loads heavier than normal. Under normal loads, it is desirable to run on a higher expansion ratio (early cut-off) so as to obtain more economical use of the working fluid.

In some rotary and reciprocating engines, changes of cut-off are obtained, for example, simply by varying the arrangements of link motions or by changing the positions of cams or, on engines fitted with rotary valves, by changing the position of rotary valve sleeves.

However it is advantageous if intake valves can be eliminated and to rely solely upon porting of the rotary engine thereby reducing initial and ensuing maintenance costs.

SUMMARY OF THE INVENTION

This invention has for its principal objective to provide a rotary engine of the type specified in which the expansion ratio can be varied in accordance with load and speed requirements.

With the principal objective in view there is provided according to the present invention in a rotary motor driven by a working fluid introduced through an inlet port under pressure the improvements comprising, a bleed or bypass passage leading the working fluid to a later expansion stage in the motor, thereby increasing the amount of working fluid within the motor to do work.

Conveniently a pressure sensitive valve is provided in said bleed passage, the valve being sensitive to variations in pressure of working fluid in the bypass line and the main supply line leading to the inlet port. It will be understood that the external load on the motor is proportional to the degree of pressure of working fluid in the motor. With an increase in load the pressure of working fluid in the motor must increase to maintain speed.

The bleed passage may be restricted and provided in parallel to said valve to provide a continuous flow of working fluid which is particularly effective at low motor speeds to substantially increase the amount of working fluid and decrease the expansion ratio. Alternatively the bleed restriction may be incorporated into the valve construction so that even when closed the valve continues to pass working fluid to a later expansion stage.

Said pressure sensitive valve is conveniently sensitive to working fluid inlet or expansion stage pressure, or a pressure differential between inlet and expansion stage inlet pressures. When a differential is apparent the valve is opened to transmit increased quantities of working fluid to a later stage so that effects of later cut-off are achieved. The inlet pressure represents a datum pressure and the expansion stage inlet pressure is dependant for its value upon the load on the motor. Accordingly, at low speeds and high load a pressure differential will exist across the valve to open said valve. The datum pressure and thus the pressure differential between inlet and expansion stage inlet pressures may be further increased by manual control of the engine throttle, however, this aspect forms no part of the present invention.

It will be understood that according to the invention re-introduction of the working fluid may take place at several succeeding stages of expansion to a lower pressure in the motor.

A practical arrangement of the invention will be described with reference to an extensible vane or blade type rotary motor having variable volume chambers, with said blades being driven by steam or air, however, it will be understood that the invention can be applied to various types of rotary motors in which there is at least two stages of expansion of the working fluid. The arrangement is described having reference to the accompanying drawings which depicts a schematic form of the invention.

BRIEF DESCRIPTION OF THE DRAWING

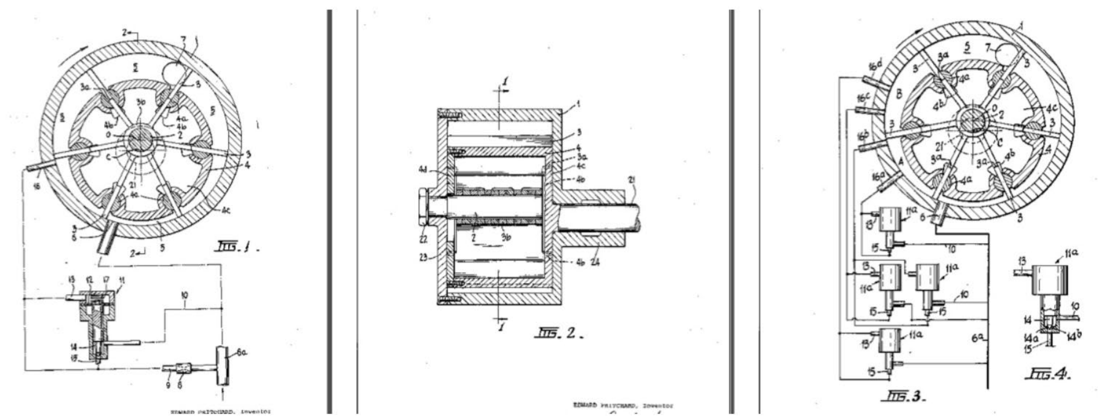


FIG. 1) End sectional view on line I-I of FIG. 2.

FIG. 2) Sectional elevation taken on line II-II of FIG. 1.

FIG. 3) Sectional elevation of a modified engine with a plurality of late admission ports for working fluid.

FIG. 4) Partial sectional view of a modified pressure sensitive valve.

DETAILED DESCRIPTION OF THE INVENTION

There is provided a stationary cylindrical ported chamber 1. In sealing contact with said chamber 1 a plurality of blades 3 are provided which extend radially from bearing bosses 3b mounted on shaft 2 about centre 0 enabling said blades 3 to move about centre 0 independently of each other in the direction of rotation shown. The blades 3 are constructed with their inner portions and bosses 3b forked to fit inside each other along the shaft 2. The blades 3 pass through sealing segments 4a mounted in a rotatable cylindrical structure 4 which is integrally formed with an end flange 4c at the drive end and with a removable flange 4d at the opposite end. The blades 3 are stepped down at 3a in overall width (taken along the axis) to clear inner portions 4b of the end flanges of the structure 4. At the driving end of the structure 4 an output shaft 21 on centre C extends from the end flange 4c.

Shaft 2 is held into end wall 23 of chamber 1 by means of a nut 22. Output shaft 21 runs in bearings machined into an extension 24 of the opposite end wall of chamber 1.

The ports, inlet 6 and outlet 7 in the chamber 1 are placed approximately opposite one another.

It is preferred that a sufficient number of radial blades 3 are provided so that at least two expansion stages or chambers are formed before exhausting through the exhaust port 7.

Accordingly smooth running of the motor is obtained despite the lack of intake and exhaust valves as well as providing a greater expansion ratio.

Referring to FIG. 1 bypass or bleed fluid passes through a restricting orifice or passage 8 of a definite predetermined minimum control area in bleed line 9 leading from the main supply line 6a to a later expansion chamber supplied by inlet pipe 16. The amount of bleed fluid is increased by opening up an additional passage area controlled by means of a pressure sensitive valve 11 which may be diaphragm controlled and interconnects passage 10 to passages 9 and 15 through needle valve 14. The diaphragm 12 may be sensitive to the pressure existing at a datum point such as at the fluid intake (not shown) or to a pressure differential such as the difference between the pressures at the intake 6 and at the point of readmission to a later expansion chamber as at pipe 16 of the working fluid as shown in FIG. 1. In this arrangement the diaphragm 11 is subjected to the pressure in passage 10 (datum pressure) on one side and the pressure in passage 13 (chamber pressure) on the other side. The diaphragm is adapted to move in response to the bias created by the pressure differential whereby the needle valve is moved to open or close passage 15. If necessary a compression spring 17 may be provided to ensure that the needle valve 14 is closed at the appropriate time.

A major controlling factor over the maximum expansion ratio on the type of rotary motor illustrated is the number of blades 3. The larger the number of blades, the greater the expansion ratio obtainable.

It will be appreciated that the bleed fluid flowing in the restricted passage 8, 9 will have little effect at normal running speed, the volume of flow being of but a small proportion of the total flow of working fluid through the motor. Thus the bleed passage is mainly effective at starting and low speeds as desired. Also, while the restricting orifice or passage 8 is of definite predetermined controlling area, this is to be understood to be for a given set of circumstances relating to the input fluid pressure and relative size of the main supply line and the bleed or bypass line. Accordingly, it is understood that such restricting passage may be of a selectively variable type to achieve a predeterminable control area therethrough for different conditions.

Referring to FIG. 3, a modification of the embodiment described with reference to FIG. 1 is illustrated showing a plurality of bypass passages controlled by a pressure sensitive valve 11 feeding into more than one expansion stage. In this Figure similar reference numerals refer to like integers. The internal construction together with the function of the valve 11 is similar to that previously described with reference to FIG. 1 or alternatively similar to that described here-below with reference to FIG. 4.

The arrangement shown in FIG. 3 depicts explicitly multiple bypass of working fluid to two expansion stages enhancing the amount of late cut-off working fluid that may be supplied to the motor. Having reference to the first stage after inlet pipe 6 (reference A), two inlet pipes 16a and b are arranged to feed into this stage at the particular point in time represented by the diagram. The spacing of the inlet pipes 16a, 16b, 16c and 16d is selected by the designer to achieve optimum benefit from the late admission of working fluid. For instance, the spacing of inlet pipe 16c from pipe 16a provides that chamber A will receive working fluid from all three inlets 16a, 16b and 16c for an instant in time during its passage around housing 1. Similarly chamber B would receive steam from 16b, 16c and 16d for an instant in time slightly preceding chamber A. It will be understood the phasing or spacing of the bypass inlets may be chosen according to needs and the operating conditions of the motor provided always that working fluid is not admitted when a chamber is being exhausted through port 7. The valve 11a may operate in identical fashion to that already described with reference to FIG. 1. Namely, a diaphragm 12 is provided, which is subject to a pressure differential between working fluid pressure in expansion stages cut-off from the working fluid inlet pipe 6 and the working fluid pressure in the inlet pipe 6a. In the arrangement shown in FIG. 1 the pressure sensitive valve 11 is provided in parallel circuit with bleed restriction 8 in pipe 9 leading from inlet pipe 6a to a later expansion stage.

The pressure sensitive valve may be modified as shown in FIG. 4 by the provision of a non-closable valve and valve seat 14, 14a. All other parts of the valve 11a are identical in construction to that previously described with reference to FIG. 1. The seat 14a includes small slots or recesses 14b spaced therearound through which working fluid may pass even when valve element 14 is in engagement with the seat 14a. Accordingly, lifting of the valve element 14 off its seat merely allows for an increase in flow of fluid into line 15 and thence to a later expansion chamber. It is preferred but not essential that valve 11a be utilised in feeding working fluid to a plurality of later expansion stages as shown in FIG. 3.

US7536943

Valve and auxiliary exhaust system for high efficiency steam engines and compressed gas motors

A steam engine with improved intake and exhaust flow provided by separate pairs of intake and exhaust ports located at both ends of a steam drive cylinder. A slide valve located adjacent to the drive cylinder provides for timed sealing of intake and exhaust ports during operation. Exhaust is facilitated by the provision of two paths of exhaust from the cylinder and the exhaust ports may be adjusted for a flow volume to meter exhaust steam flow to significantly reduce back pressure only at low speeds of said engine.

FIELD OF THE INVENTION

The invention relates to steam engines. More particularly, the invention herein disclosed relates to an improved design of the valve and auxiliary exhaust system for steam engines of both the double-acting and single-acting designs and in particular for uniflow steam engines with auxiliary exhaust. The design can be employed upon fixed timing engines or with added means for timing adjustment, upon variable timing steam engines.

BACKGROUND OF THE INVENTION

Single-acting and double-acting steam engines have provided power for industry and other uses for a long time. The single-acting steam engine may resemble a two and a four-stroke internal combustion engines in that a piston, connecting rod and crank are used per cylinder set. With the double-acting form of steam engine, straight line reciprocating motion is described not only by each piston, but also by each piston rod and crosshead. Motion is transferred from the crosshead via a connecting rod to the crank. The piston rod passes through a seal in the end of the cylinder and the steam is valved to work on the piston from above and also below it. This gives a “one stroke” action. With two double-acting cylinders, only four valves are required on a “full” uniflow engine of conventional design as against 16 valves being required for an 8-cylinder 4-stroke engine which exerts the same number of power impulses per revolution.

The uniflow engine exhaust system uses holes in the cylinder which are exposed to the top end of the cylinder adjacent to the piston near the bottom of its stroke. The same row of holes are exposed to the bottom or crank end of the cylinder adjacent to the piston near the top of its stroke. The length of the piston adjacent to the cylinder wall is equal or approximately equal to the stroke minus the diameter or length of the exhaust holes. (The exhaust holes in the cylinder can be seen in one of the photos on display). Clearance volume is provided at each end of the cylinder to allow for reasonable compression to take place at each end of a stroke.

A semi-uniflow engine is one in which exhaust valves are used to supplement the action of the exhaust holes in the cylinder wall. By employing the exhaust valves, the point at which compression begins on the return stroke of the piston can be delayed. Such an auxiliary exhaust feature is useful especially where exhaust is at atmospheric pressure rather than into a vacuum and/or, further, where compounding is utilized. Further, in single cylinder engines which are not necessarily self-starting, the auxiliary exhaust makes the engine easier to start. This is because it is easier before the admission steam starts the engine to rotate the engine against compression since with an auxiliary exhaust system compression acting against the piston begins later on the compression stroke.

In some early uniflow engines with auxiliary exhaust systems, the auxiliary or secondary exhaust steam traveled out through the same ports and passages through which previously admission steam entered. A disadvantage of this design is that the cooling effect of the exhausting steam lowered the efficiency of the engine. In other early semi-uniflow engines the auxiliary or secondary exhaust steam exhausted through special ports in the cylinder wall at positions between the main uniflow exhaust and the admission passages, the latter located near the cylinder ends.

Special valves such as poppet valves controlled these auxiliary exhaust passageways. These engines, if of the double-acting type, were fitted with four valves: two for inlet steam—one at each end of the cylinder, and two for auxiliary exhaust—one for the upper part of the cylinder and one for the lower part of the cylinder. A disadvantage of this design with its four valves plus the respective valve motions required for their operation is relative complexity. [See Skinner. P271. “Power from Steam,” R. L. Hills.]

PRIOR ART

U.S. Pat. No. 3,967,535 (Rozansky) while disclosing that the device relates to uniflow steam engines having a novel valving means for controlling the introduction of steam into the cylinders, is not concerned with auxiliary exhausting.

U.S. Pat. No. 3,651,641 (Ginter) discloses an engine system and thermogenerator therefor. Ginter in teaching a valving system seems primarily concerned with an internal combustion engine with water internal cooling and there are no uniflow exhaust ports and no auxiliary exhaust ports disclosed.

U.S. Pat. No. 3,967,525 (Rosansky), while disclosing that the device relates to uniflow steam engines having a novel valving means for controlling the introduction of steam into the cylinders, is not concerned with auxiliary exhausting.

U.S. Pat. No. 3,991,574 (Frazier) discloses a uniflow exhaust system in a rather complex structure. However, Frazier does not teach the employment of an auxiliary [uniflow] exhaust.

U.S. Pat. No. 3,788,193 (O'Conner) discloses a spool type slide valve for controlling both admission and auxiliary [uniflow] exhaust. However, O'Conner requires the employment of a complex system of powered cams to operate the disclosed valve. O'Conner teaches a complex double cam driven system, the cams having positive lift and drop as in “desmodromic” systems with complex chain drives to achieve variable valve timing. In the mid-position of the slide valve it appears that the admission and auxiliary exhaust ports are both closed. The variable engine “timing” or valve events are controlled by phase changes in their relative positions of the double cams and also with the angular displacements of the camshafts with the “variable” chain drive.

As such, there exists a need for an improved auxiliary exhaust valving system on steam engines with fixed timing which employs a simple mechanical operation to achieve the desired result. Such a device should utilize simple harmonic motion from a simple eccentric and should provide the required valve events by careful selection or design of the required bobbin admission and exhaust “laps” or the eccentric radius and also the phase relationship between the eccentric valve drive and the crank. Still further, such a device and system should be easily adaptable to a variable timing steam engines.

With this design, the valve events can be worked out using conventional valve diagrams, e.g. “Bilgrams Valve Diagram”. Still further, such a design should control the auxiliary exhaust in a manner similar to the conventional steam engine which exhausts through the common admission/exhaust ports. Employing such a control, the auxiliary exhaust should then be communicated through ports and passages separate from the admission passages which could be said to be in the correct uniflow tradition. Main central uniflow exhaust should also be utilized.

As can be seen and readily discerned by those skilled in the art, this invention can also be employed, if desired, to obtain variable valve timing using conventional valve gears such as Stephenson's link, Allan's link motion, Joy valve gear, Walschaert, etc. This enables forward and reverse operation plus changes of cut-off.

SUMMARY OF THE INVENTION

The disclosed device provides for an improved valve and auxiliary exhaust system when employed and yields a high efficiency steam engine or compressed gas motor. For fixed timing, as may be utilized for a stationary engine, a preferred embodiment utilizes movement for the slide valve in harmonic motion derived from a simple eccentric and connecting rod and obtains the required valve events by careful selection or design and inter-related functions of the required bobbin admission, and auxiliary exhaust “laps,” and the eccentric radius and the phase relationship between the eccentric and the crank. The slide valve would be adapted to move in a direction controlled by an eccentric set at between 90 to 180 degrees ahead of the crank controlling the piston. The design procedure for valve event timing is similar to that of a conventional non-uniflow outside-admission slide valve or other slide valve engine. Conventional valve diagrams such as Reuleaux's Slide Valve diagram can be used to assist in the design of this invention.

It should be noted that the device as herein disclosed shows employment for use in combination with a fixed timing engine for ease of illustration of the novel properties of the device and the great utility provided in steam or compressed air engines. However, those skilled in the art will no doubt realize that inclusion of a means to vary engine timing, such as a camshaft, could be added to the design disclosed herein, thereby providing a variable timing engine with improved efficiency, and all such modifications are anticipated to be within the scope of this invention.

The embodiments herein provide for forward and reverse control and change of cut-off to facilitate start-ups and obtain normal operation at more efficient early cut-offs as is usually required for a mobile engine. Again, conventional slide valve driving mechanisms such as Stephenson's Link Motion and Walschaert's Valve Gear can be utilized to drive the valves of this invention.

The embodiment further provides for built-in easy starting with low compression plus phasing out auxiliary exhaust under more load and speed. This is achieved with the area of the auxiliary exhaust ports designed so that, on start-up and at slow speeds, the steam flow is adequate to hold cylinder exhaust pressure close to exhaust pipe discharge pressure. This assists with easy starting of the engine and makes for smooth running at low speeds. However, with rising speeds and bigger throttle openings, more steam will pass through the engine. There will consequently be greater pressure drop through the auxiliary exhaust ports with the amount of pressure drop depending on the flow areas. The latter are designed to achieve the desired metering of the steam flows. This will lead to higher cylinder pressures and higher compression pressures, i.e., the engine will run more like a “full uniflow” type and higher efficiency can be realized.

The above design provides a device which is much simpler than alternative systems of controlling the extent and timing of opening of the auxiliary exhaust ports. This latter more complicated type of arrangement may be activated by devices sensitive to engine speed and/or amount of steam flowing through the engine.

The valve functions for controlling inlet steam and auxiliary exhaust steam are provided by a slide valve, preferably of the slide valve type. Slide valve designs were commonly used in conventional types of counter-flow steam engines, but in the device and method herein disclosed, the valve is used in a different manner in keeping with the uniflow principle. In keeping with that principle, one area of the valve controls one inlet steam function and a different area of the valve controls an auxiliary exhaust function. The two areas control steam flow through separate inlet and auxiliary exhaust ports and passages. Thus, the flows of hot inlet steam and the relatively cooler exhaust steam are kept apart. A single slide valve can be used to control both inlet and auxiliary exhaust steam in a single-acting engine and also in a double-acting engine.

In the device herein described and disclosed, the simplicity of the slide-valve design is retained. The slide valve may be driven by valve gear giving the valve simple harmonic motion or an approximation to it. The valve gear, as in conventional steam engines, may be designed to give reverse operation plus changes in cut-off. A valve and drive system similar to that described herein is suitable for use in an engine without central “uniflow” exhaust ports which are uncovered by the piston near the ends of its stroke. In this case, the “auxiliary” exhausts described herein will be the main exhausts.

With respect to the above description then, it is to be realized that the optimum dimensional relationships for the parts of the invention, to include variations in size, materials, shape, form, function and manner of operation, assembly and use, are deemed readily apparent and obvious to one skilled in the art, and all equivalent relationships to those illustrated in the drawings and described in the specification are intended to be encompassed by the present invention. Therefore, the foregoing summary is considered as illustrative only of the principles of the invention. Further, since numerous modifications and changes will readily occur to those skilled in the art, it is not desired to limit the invention to the exact construction and operation shown and described, and accordingly, all suitable modifications and equivalents may be resorted to falling within the scope of the invention.

Accordingly, it is the object of this invention claimed herein to provide a steam engine having an improved slide valve and drive cylinder design wherein one area of the slide valve controls one inlet steam function and a different area of the valve controls an auxiliary exhaust function.

It is another object of this invention to supply the disclosed steam engine wherein two areas of the slide valve providing improved operation control steam flow through separate adjacently located inlet and auxiliary exhaust ports and passages. It is another object of this invention to supply an improved steam engine providing a slide valve control of overall operation which is much simpler than alternative systems of controlling the extent and timing of opening of the auxiliary exhaust ports. These and further objectives of this invention will be brought out in the following part of the specification, wherein detailed description is for the purpose of fully disclosing the invention without placing limitations thereon.

BRIEF DESCRIPTION OF DRAWING FIGURES

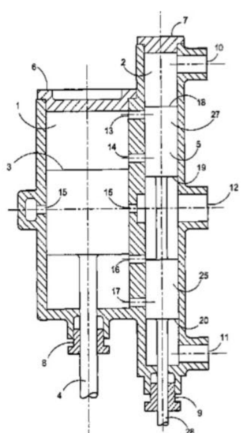


FIG. 1

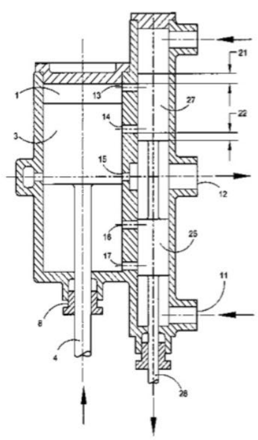
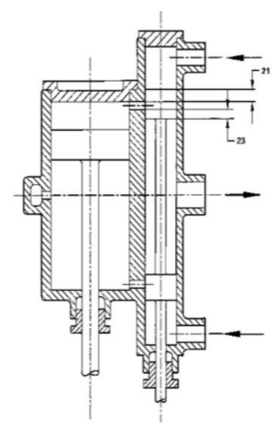


FIG. 2a



(PRIOR ART)
FIG. 2b

FIG. 1) Sectional view of the device featuring a cylinder arrangement for a Uniflow, double-acting type steam engine.
FIG. 2a) New design showing the engine of FIG. 1, depicting the valve laps of the present device.
FIG. 2b) Prior art in the form of a valve design for a conventional non-uniflow steam engine and the conventional admission lap and an exhaust lap thereof.

DESCRIPTION OF PREFERRED EMBODIMENTS OF THE DISCLOSED DEVICE

FIG. 1, shows the cylinder arrangement for an embodiment of the device for employment with a uniflow double-acting steam engine including the herein disclosed and described novel valve design, which used in conjunction with a conventional harmonic valve drive mechanism, forms the main part of this invention. Not shown is the crankcase containing the connecting rod, crosshead, valve motion and other attendant parts of the engine for which the disclosed device is adapted for engagement. These latter parts may be conventional in design.

The main parts shown are the cylinder 1, the valve chest 2, and the piston, 3, which would best be fitted with piston rings (not shown). Also shown in FIG. 1 is the piston rod 4, and the slide valve 5, showing the continuous exterior surface to contact the valve chest and which also would be fitted with sealing rings but which are not shown. Number 6 depicts the cylinder head and the valve chest cap is shown as number 7. The piston rod sealing assembly is identified by number 8 and number 9 represents the valve rod sealing assembly.

In the preferred arrangement of the disclosed device as shown, the valve chest 2 is adapted for outside admission. Two steam inlet ports are shown as numbers 10 and 11 and the exhaust port is shown as number 12. The cylinder upper inlet steam passage 13 is shown at the upper area of the cylinder adjacent to the cylinder upper auxiliary exhaust steam passage 14.

In a central section of the cylinder 1 is the cylinder uniflow or central exhaust steam ports 15. At a lower end of the cylinder 1, is the cylinder lower auxiliary exhaust steam passage 16 and the cylinder lower inlet steam passage 17. It should be noted that steam inlet passages 13 and 17 and steam exhaust ports 14 and 16, while depicted as single passages, may be one or a plurality of passages to provide the volume communication required. It should also be noted that use of the terms upper and lower are for convenience sake and those skilled in the art will realize that positioning and operation of such engines is possible using different manners of positioning of the components described herein. Therefore the invention herein described and disclosed is employable for steam engines of any position and angle of operation.

In the position shown in the drawing FIG. 1, the piston 3 is shown as it would be moving downwards toward the lower end of the cylinder 1 and the slide valve 5 would be concurrently rising in the opposite direction of the piston 3. The upper part of the slide valve 5 at the face 18 is moving away from the piston 3, and has just cut off the inlet steam supply though the upper steam inlet 13 to the upper portion of cylinder 1 and to the top of the piston 3 which continues to travel downwards under pressure from the expanding steam in the upper portion of the cylinder 1. The length of the continuous side edge of the upper piston 27 of the slide valve 5 and the speed of the slide valve 5 in reciprocal motion to the piston 3 during each engine cycle to determine the length of time it will maintain this cut off of steam so long as it covers the inlet 13. Steam under the piston 3 in the lower portion of the cylinder 1 is exhausting through lower exhaust passage 16 and out the exhaust port 12, until cut off by the piston 3 moving downward wherein the piston's continuous side edge covers the exhaust passage 16. At this point in the timing of the device, compression of the residual steam in the lower portion of the cylinder 1, under the piston 3 will then begin.

When the piston 3 reaches the bottom of its stroke, steam above the piston 3 in the upper portion of the cylinder 1, will exhaust through the main uniflow or central exhaust ports 15. The side of the upper piston 27 of the slide valve 5 bounded by the lower face 19 will uncover its sealed engagement over the auxiliary upper exhaust port 14 which will vent exhaust steam also thereby emptying the upper portion of cylinder 1 through two routes of exhaust increasing efficiency of this operation. It has been found through experimentation that the total aggregate area of each set of the exhaust ports 14, and 16, may be adjusted to provide a means for metered steam flow such that the flow is adequate to significantly reduce back pressure only at low speeds, while at higher speeds and larger throttle openings, the engine will operate more similarly to that of a full Uniflow engine. This can be done through adjusting the sizes of the exhaust ports so that the volume of exhaust vented at lower speeds of the engine being built for use at desired speeds and loads has the desired reduced back pressure at the determined low speeds.

The slide valve 5 will uncover the lower steam intake 17 and allow admission of steam past rising lower face 20 at the bottom of the second or lower piston 25 opposite the upper piston 27, and communicate it to the underside of the piston 3. The piston 3 will then begin to rise from the force of the steam. In reciprocal action, the slide valve 5 with the first or upper piston 27 and the second or lower piston 25 operatively engaged by the valve rod 28 at an operative distance, now begins to descend, and the lower end slide valve 5 bounded by face 20 of the lower piston 25 passes the lower inlet steam passages 17 wherein the continuous side edge of the lower piston 25 seals the lower inlet steam passage 17 and causes cut-off of the steam communicated to the lower end of the cylinder 1. The duration of the cut off is determined by the length of the side surface of the lower piston 25 in the same fashion of the sealing operation of the upper piston 27 combined with the speed of the valve rod 28. The piston 3 is now moving upwards from the force of the steam in the lower end of the cylinder 1, and the slide valve 5 is concurrently descending in the opposite direction. This reciprocal cycle now continues similarly to that described above but for an “up” power stroke of the piston 3, rather than for a “down” power stroke.

Drawings FIG. 2a and FIG. 2b illustrate the improvement of the disclosed device and operation over conventional valve design for the disclosed uniflow engine by employment of auxiliary exhausts 14 and 16, compared with valve design for a conventional engine with outside admission slide valves as shown in FIG. 2b. Also shown in FIG. 2a is the unique admission lap 21 and uniflow auxiliary exhaust lap 22 of the disclosed device which is provided by the length of the continuous side wall of the piston at the upper cylinder 27 and lower cylinder 25. The continuous sidewalls of both the upper and lower cylinders of the slide valve 5, cover both their adjoining respective inlet and exhaust ports during each cycle for a lap period determined by the length of each of the two cylinders of slide valve 5 which are operatively engaged by the valve rod 28 therebetween and thereby define the admission lap 21 and exhaust lap 22 shown in FIG. 2a.

FIG. 2b to the contrary shows the close proximity of the admission lap 21 and the conventional exhaust lap 23 in a non-uniflow steam engine and the short duration therebetween and limitations on adjustment. Employing the discloed device, the full diameter part of each bobbin is extended so as to control exhaust steam flow separably through the auxiliary exhaust ports rather than through common admission and exhaust ports as in conventional designs. The disclosed design also does not require any special cams, chains, or valves in its connection of the slide valve 5 to the control system. The design may be carried out using conventional valve diagrams which incorporate specifications for eccentric radius and eccentric phase difference with the engine crank.

US3818699
FEED AND INJECTION WATER CONTROL FOR STEAM GENERATORS

A steam generator control system including a once through steam generator, a superheater thermostat sensing the temperature of superheater steam in the generator and controlling a fluid injection circuit connected in parallel to a portion of the steam generator coil to supply injection water to the coil and also, controlling the supply of feed water supplied to the steam generator, the feed water supply being controlled substantially proportional to the amount of exhaust steam issuing from a steam consuming apparatus together with extra water when called for by the thermostat, said control being provided by a positive displacement motor such as a rotary motor driven by the exhaust steam, and including auxilary governing means for the rotary motor to ensure more accurate proportionality between the speed of the rotary motor and the supply of feed water requirement to the steam generator so that full utilization of steam generator burner output is obtained for any given requirement.

This invention relates to the control of feed water and injection water flow into steam generators of the type known as flash boilers and once through steam generators having single or parallel coils. Fluids other than water can be used in similar "vapour" generators. It is pointed out, therefore, that "fluid" can be read for "water" and "vapour" for "steam."

One of the main problems in the development of compact steam generators as used for automotive steam engine systems is in the control of the generator. A large percentage of experimental steam car projects have failed because of the inability of the designers to solve the control problem. The aim is to obtain reasonably constant steam pressure and temperature at the outlet of the steam generator. During normal operation over a wide range of loads, control should not be at the expense of a reduction in burner output which causes undesirable reduction in steam generator pressure, in order to maintain safe temperatures throughout the steam generator.

The principle of the once through steam generator appears deceptively simple. Water is pumped in at one end and superheated steam is led away from the other end. A survey of the rather voluminous patent literature on the subject of control systems shows, however, that a wide variety of control "schemes" are proposed. It is clear to the applicant from extensive experimental trials and an appraisal of prior proposals that the correct control of a steam generator is not obvious even to those supposedly skilled in the art. Some of the problems involved are:

Control of the burner is not a difficult problem. Quick response or feed back can be obtained with either pressure or temperature control.

CONTROL OF WATER SUPPLY

This is a more difficult problem. Although, for example, an increase in feed water supply will cause an almost immediate response on the feed water heating or economiser section of the steam generator in which the fluid is largely incompressible, there will be a delay in the feed back to a thermostat fitted to the steam generator in a steaming or superheater zone in which case there exists compressible fluid (steam) between the feed pumps and the thermostat.

SEVERAL PRIOR ART CONTROL SYSTEMS ARE REFERRED TO IN A GENERAL WAY:

a. Pressure Control of feed pumps (e.g., early White steam car). A disadvantage of this system was excessive blowing of the safety valve especially when delay in the pressure control caused too much water to be fed into the steam generator. The burner, under thermostat control, would endeavour to bring temperature back up, even at zero power output.

b. Temperature Control of feed pumps and water supply. Burner main control was usually a pressure type with an overriding high temperature cut-off. Some variations in temperature control systems as outlined in (b) are:

I. final Thermostat type. Control thermostat is situated in the superheater zone. Disadvantage -- too much response delay.

Ii. thermostat at end of evaporative zone. (e.g., British Patent 254,774, 1926, W. M. Cross.) Disadvantage -- Too much response delay.

Iii. thermostat(s) in evaporative zone. (e.g., U.S. Pat. Re 20045, 1936, J. Fletcher). Disadvantages -- Too much response delay. Also effected by inherent changes in boiling point temperatures with steam pressure changes. The latter applies in particular to automotive systems, where certain steam pressure changes take place in normal operation.

Iv. thermostat in feed water heating zone. Small response-delay with this system but thermostat is situated so far away from the final steam generator zone that poor control can result from secondary effects such as soot on generating coils modifying water-steam zone positions.

V. thermostat plus water injector. In British Patent Specification 568,722, 1945, M. H. Lewis states that up to 5 percent only of total feed water capacity is fed to the water injector nozzle in the superheater zone. Otherwise there is a danger of a high temperature peak before the injector point. See later for argument showing that this amount would be insufficient to result in good control but that, in some systems, additional increments of "base" water can be fed equal to the quantity of water injected.

There have been tried and proposed various combinations of thermostatic and water injection systems. Estimates are made later which show that a thermostatic and injection system alone cannot provide sufficient basis for a correct control but, from certain considerations, can be used to control up to only approximately 65 percent of the total water. An additional form of control must therefore be provided.

Early systems using variable capacity vaporising burners proportioned water and fuel. (e.g., -- Serpollet, later White steam cars.) Note that, with the type of vaporising burners used, roughly proportional air-to-fuel ratios were maintained. With modern pressure atomising burners, systems using variable fuel and air supplies are complex and relatively expensive, particularly as applied to small units.

There have been systems using auxiliary reciprocating engines or turbines driving feed water pumps (and other auxiliaries) in order to assist in matching water flow with burners demand. Some systems use water metering valves, sometimes dependent on hand adjustment. With some water injection systems, relatively large amounts of water, which are sometimes relatively cool, are injected into superheated steam causing thermal shock to the piping system. Thermal shock is a serious problem particularly under the difficult conditions encountered with the varying power requirements of an automotive steam power system where frequent operation of the injection control may be required. Thus with such systems it is undesirable to inject into the superheater zone.

Main engine-driven pump systems have the disadvantage that, at low speeds, particularly with a cold engine, the feed pumps pump insufficient water. Some prior systems are not fundamentally sound, in that they will not cope with a wide range of power demands. On some, to prevent local overheating, the burner is cut. This may reduce available power.

Applicants earlier Australian Patent No. 226,096, "Improvements in Steam Plants for the Control of Plant Auxiliaries proportional to the Steam Consumed," stated that, . . . "preferably the drive arrangement according to the invention is operated in conjunction with conventional temperature actuated means (thermostat) controlling a secondary feed pump, which is cut-in to boost the primary pump, responsive to changes in steam temperature within the steam producing unit." In practice, such conventional means did not prove adequate. Very considerable experimental and theoretical work was carried out before the control system according to the present invention was evolved.

As described in Applicants earlier U.S. Pat. No. 226,096, water quantities bear a direct relation to exhaust steam quantities rather than to burner rates. This means that steam generator water control can be largely independent of burner operation. Thus, boosting of the burner will not directly effect the water control system.

It is a principal objective of the present invention to overcome the abovementioned problems and provide a steam generator control system in which the quantitative components affecting the operation of the system namely the feed water pump means, feed water injection system and burner are controlled.

It is a further objective of the invention to provide a steam generator control system in which the auxiliaries are driven by an improved proportional exhaust steam motor drive in combination with a water injection system in which feed water flow rates and injector flow rates are controlled within certain proportions calculated empirically.

It is a further objective of the present invention to provide a steam generator control system in which known definite quantities of water are automatically fed into the base of the steam generator coils by proportionally driven feed pumps or controlled metering means and known definite quantities of water are injected (as required) into a known desired evaporator zone point of the steam generator coil, thus resulting in a fast response and stable control with minimum thermal shock at the injection point, and enabling full utilisation, under normal operation, of the burner output for a given steam generator capacity.

There is provided according to the present invention a steam generator control system comprising a steam generator, a burner, a once through coil heated by said burner supplying superheated steam to a steam consuming apparatus, a superheater thermostat disposed on the coil at or near the outlet end of the coil in proximity to said burner arranged to sense the temperature of superheated steam, a water injection circuit connected in parallel to at least a section of said coil and arranged to carry feed fluid by-passing said coil section to inject said feed fluid into a zone of the coil carrying fluid of higher temperature, said injection circuit including valve and metering means for controlling flow of feed fluid therein, feed water supply means arranged to normally provide feed water at a rate below the requirements of the steam generator and to intermittently provide an increased flow of feed water when there is a flow of fluid in the injection circuit said increased flow resulting in a total feed water flow in excess of the requirements of the steam generator, a positive displacement motor operated by the exhaust steam from the steam consuming apparatus and arranged to control at least said feed water supply means at a rate substantially proportional to the volume of steam consumed by the consuming apparatus.

The superheater thermostat may be positioned anywhere in the superheater zone of the generator. In another aspect of the invention there is provided according to the present invention a steam generator control system comprising a steam generator, a burner, a once through coil heated by said burner supplying superheated steam to a steam consuming apparatus, a superheater thermostat disposed on the coil at or near the outlet end of the coil in proximity to said burner arranged to sense the temperature of superheated steam, a water injection circuit connected in parallel to at least a section of said coil and arranged to carry fluid from by-passing said coil section to inject said fluid into a zone of the coil carrying fluid of higher temperature, said injection circuit including valve and metering means for controlling flow of fluid therein, feed water supply means arranged to normally provide feed water supply means arranged to normally provide feed water at a rate in the range of 60 percent to 90 percent of requirements of the steam generator and to intermittently provide an increased flow of feed water when there is a flow of fluid in the injection circuit, said increased flow resulting in a total feed water flow in the range of 120 percent to 180 percent of the requirements of the steam generator, the volume of fluid arranged to be injected by the injection circuit being in the range of 30 percent to 90 percent of the increase in feed water flow above that otherwise provided, a positive displacement motor operated by the exhaust steam from the steam consuming apparatus and arranged to control at least said feed water supply means at a rate substantially proportional to the volume of steam consumed by the consuming apparatus.

The feed water supply means may comprise a feed pump and associated metering means for providing feed water at the desired rate. Preferably the supply includes a feed water pump means driven by said positive displacement motor.

The output of the feed water pump means may be increased by increasing pump speed, increasing the stroke of the pump or by providing a stand-by pump.

Conveniently the feed water pump means includes a primary feed water pump arranged to continuously supply feed water to the steam generator whilst in operation and a secondary feed water pump arranged to intermittently supply feed water to the generator under control of said superheater thermostat.

The superheater thermostat is arranged to actuate said injection circuit valve means to allow fluid flow therein and to simultaneously actuate said secondary feed water pump to supply additional feed water to the steam generator coil. The injection circuit is arranged to by-pass a section of the coil, and preferably the inlet of the circuit is connected into the feed water heating zone of the coil and the outlet of the circuit is connected into a fast moving steam zone. The feed pumps are driven by a proportional drive so that good control can be obtained with the injection point located as far back as at a point in the evaporator zone of the steam generator, despite the difficult conditions encountered in an automotive steam power system having widely varying power requirements. It is preferable that the amount of feed water in the injection circuit is limited so as not to deplete the amount of water upstream of the injection outlet, thereby assisting in preventing the production of superheated steam upstream of the injection outlet.

The present invention allows close control over:
i. the amount of fluid injected by the injection circuit, and
ii. the amount of additional feed water administered by the secondary feed water pump thereby giving a rapid response to shortage of water signalled by the outlet thermostat in the steam generator. Furthermore, the additional feed water acts as a follow up to the rapid response provided by the injector.

It has been found that this injector-outlet thermostat system does give a rapid response to shortage of feed water, however fluctuations in the final steam temperature may still occur especially where the coil is composed of lightweight tubing having little heat reserve. To reduce these fluctuations even further, there is also provided by the present invention means for more accurately controlling the proportioning drive motor over its speed range by compensating for the effects of steam leakage and the effects of back pressures in the exhaust steam line to the drive motor at low and high motor speeds respectively. Said means includes a bypass valve or an electric/motor/generator controlling the speed of the motor over the middle or middle and high speed range. Conveniently the drive motor is a simple rotary motor.

The invention will now be described in greater detail having reference to the accompanying drawings.

FIG. 4.

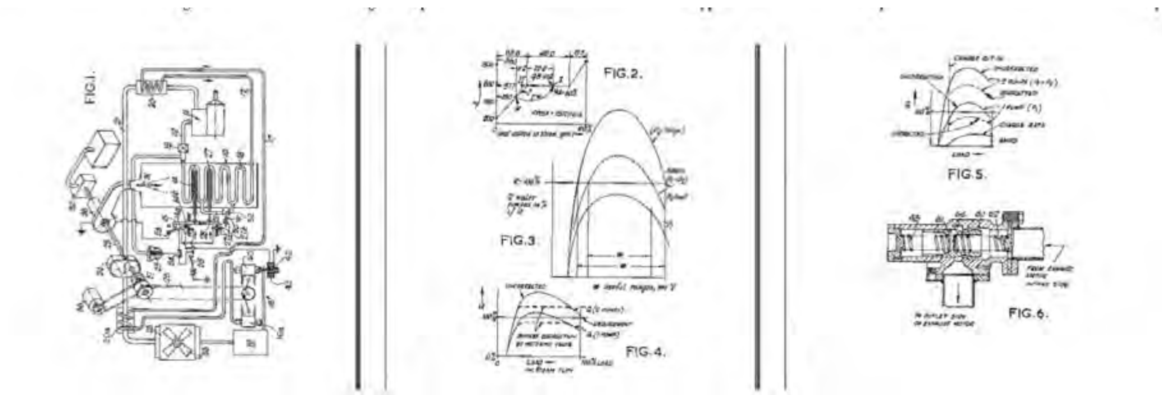


FIG. 1) Semi-schematic view of an overall steam plant showing various auxiliaries arranged in accordance with the present invention.
FIG. 2) Steam generator temperature curve of steam temperature vs. heat added to the steam generator.
FIG. 3) Feed water pumps performance curve of water pumped Q as a percentage of total weight of steam required R against power.
FIG. 4) Curve of water pumped Q as a percentage of total weight of steam required R against power showing the effect of bypass correction by a metering valve of the feed pump drive motor.
FIG. 5) Curve similar to that in FIGS. 3 and 4 in which speed correction in the middle and high speed range of the feed pump drive is obtained by an electrical generator.
FIG. 6) Sectional view of a metering valve calibrated to relieve high back pressures in the exhaust steam line and also bypass some exhaust steam to provide the correction shown in the curve depicted by FIG. 4.

Referring to FIG. 1 a steam generator 10, is adapted to supply steam to an engine 11, by means of pipe 12 and throttle valve 13. A feed water system comprising a tank 19, a positive displacement pump 16, and feed water pipe line 17, is adapted to feed lower tubes 18 of the steam generator through pre-heaters 20 and 20a disposed in the exhaust conduit 21 leading from the engine 11 and engine 24 respectively.

The feed water pump arrangement 16 shown in FIG. 1 includes an auxiliary or secondary feed water pump 40 in parallel with a primary pump 16a, both pumps being preferably driven by the common drive 26. In this arrangement the secondary pump will run free while solenoid 43 is energized. Solenoid 43 is arranged to actuate an armature 42 constituting a valve controlling inflow of water to the pump 40 from tank 19. The current to the solenoid 43 is controlled by superheater thermostat 14. Thermostats 14 and 27 are connected to pivotable arms 15 and 28 respectively arranged to actuate contactors 14b and 27b between two way contact points 14a and 27a. The solenoid 43 is connected to the power supply through contactor 14b and is energised whilst the superheater thermostat 14 is sensing a temperature lower than a preset maximum.

If the preset maximum temperature is exceeded the arm 15 moves a sufficient distance to open the solenoid circuit and practically simultaneously close the injector valve circuit through the other contact point 14a. The injector valve, 52 which is also preferably solenoid actuated as shown at 50, is energized, provided the safety thermostat contactor and contact 27a and b are in the normal position as shown. Safety thermostat 27 is arranged to sense overheating in that part of the steam generator coil which is connected in parallel with the injection line. Alternatively, instead of closing the injector line the water injection point may be temporarily varied to a position upstream of the normal point (not shown). Alternatively the safety thermostat 27 may be arranged to reduce or cut off (not shown) the output of the burner 31. Thus, if the safety thermostat 27 senses a temperature above a predetermined maximum the solenoid circuit 50 is opened by movement of contactor 27b away from contact 27a thereby opening the circuit to the injector solenoid 50 and causing the injector valve 52 to close injector line 51 and thus restore full feed to the by-passed section of the coil.

A manually controlled switch 58 is provided to control operation of the system. An outlet steam pressure switch 53 is provided which is arranged to open and close switch 54 and disconnect and reconnect the burner motor with the power supply, when steam pressure exceeds a predetermined maximum, or falls below a predetermined minimum respectively.

As a precaution the superheater themostat 14 is also arranged to control operation of the burner motor. This control is shown in FIG. 1 comprising a burner switch 55 controlled by arm 15 connected to superheater thermostat 14. The contacts of the burner switch are opened upon the superheater thermostat 14 sensing a steam temperature in excess of (by a predetermined amount) the temperature of the steam which causes the superheater thermostat 14 to open contact 14a. Thus, the opening of the burner switch 55 is a second stage operation which shuts off the burner 31 as a back up to the pressure switch control 53 and the introduction of injector water and additional feed water if (despite the introduction of additional water) the steam temperature continues to rise to an undesirable level.

The exhaust conduit 21 carries exhaust steam from the engine 11 to rotary motor 24 through heat exchanger 20a and thence to a condenser 23. Water from the condenser 23 is returned to feed water tank 19. The rotary motor 24 drives a shaft 25 which in turn drives feed water pump 16 through belt 26. The rotary motor is arranged to drive other auxiliaries such as condenser fan 33, motor generator 56 and the like. The condenser fan drive may come from either side of the one way clutch 57.

The motor generator 56 operates as a motor at starting primarily for driving the feed water pump 16. It may operate as a generator for charging the battery power supply during normal running of the system and also may be used for a further useful purpose in governing the speed of the rotary motor. This latter purpose will be described in greater detail later. The one way clutch 57 is provided to transmit drive from the rotary motor to the motor/generator 56 and feed water pump 16 and condenser fan 33 when the rotary motor 24 is producing power but will not transmit drive from the motor/generator 56 when operating as a motor, as at start thus avoiding unnecessary load on the motor/generator 56. The one way clutch 57a is arranged to free wheel and thus prevent the burner motor 36 from driving the auxilaries on the other side of the clutch 57a.

The present invention has analysed the operation of the various components of the above described system in providing a steam generator control system consisting of:

1. a burner preferably of the ON/OFF type primarily controlled by a device responsive to generator steam pressure, and also an overriding temperature controller responsive to steam temperature in the superheater zone.

2. an exhaust steam rotary motor system preferably driving two feed pumps.

Operation of the feed pump has already been described in which one pump 16a is operable to pump water whenever it is rotated whilst operation of the second, auxiliary, pump 40 is under the control of the superheater thermostat 14 in the generator coil 18. The arrangement is such that the superheater thermostat 14 also controls the flow of injection water through the parallel injector circuit 51 on the generator coil at the same time as the second feed water pump 40 is operating dependant upon normal temperature conditions in the bypassed section of the generator coil.

The analysis of the variable components controlled by the invention is best shown by reference to various equations as hereinafter described in which the following symbols will be used.
P1 = rate of water by weight pumped by first pump.
P2 = rate of water by weight pumped by second pump.
Ew (extra Water) = rate of water by weight injected through injector nozzle when water is flowing through injector circuit.
R (Requirements) = rate of steam by weight passing out of the steam generator.

I. The first consideration to be outlined here is the amount of extra water EW to be injected as compared with the water pumped by the second pump P2. That is the ratio of EW to P2.

It has already been mentioned above that one reason for the long delay in response of the superheater thermostat situated in the superheater zone to the change in feed water quantity into the base of the steam generator is due to "compressibility" of the fluid between these two points.

To illustrate a point, it could be said that the effect of a change in "base" water feed is similar (in that part of the steam generator containing compressible fluid, i.e., steam) to that of a wave front carrying a higher level (high tide) or a lower level (low tide) of the density of the fluid behind the wave front.

The wave can be considered to be traveling at the speed of the actual fluid through the steam generator. In the evaporative steam zone where the dryness fraction of the steam is low, the velocity will also be low.

The response of a thermostat situated in the superheater zone to a change in feed from a water injector located at a point after which the steam is of a dryness fraction of 50 percent or more, or superheated, is rapid. In this case, the steam speed is relatively high and a short time period only is required before mixture is carried from the injector point to the thermostat. With such a rapid response, the thermostat control may turn water injection on and off rapidly enough such that there will be no resultant large fluctuations in the final steam temperature.

It has been found that an additional quantity of water, only up to a rate approximately equal to that fed by the water injector can be fed into the base of the steam generator in step with water injection fed directly from a feed water supply, by dividing the additional water fed into the base. Alternatively all additional water is fed into the base and injection water is obtained from a feed water heating economiser zone as shown in FIGS. 1 and 2. In either case the following discussion generally follows although it particularly applies to the first case in which the additional base water is divided.

The superheater thermostat 14 acts to regulate the quantity of injection water required and could be said to act as an "early warning" regulator on the amount of water entering the base of the steam generator. If, on the other hand, the increase in the amount of water fed into the base of the steam generator is greater than the injection water quantity, there is the likelihood that, when this increased flow "comes throug" to the superheater zone thermostat, it will be too much and it will be too late to turn it off soon enough to prevent an excessive down swing in final steam temperature following.

Thus the water control system operates as follows: P1 is always less than R and, from the above, the additional water feed into the base of the steam generator when the second pump is pumping, -- i.e. (P2 - EW) must be equal or less than EW i.e.: P2 - EW .ltoreq. EW and EW .gtoreq. .50 P2 (1)

ii. of major importance in the control of a steam generator is the ability of the system to control events following a change from the pumping of a smaller quantity of water (such as P1) to a greater quantity of water (such as P1 plus P2). Consider the case where temperature is rising at the superheater outlet thermostat and the latter has caused the second pump and the injection water to be switched on. The flow of steam after the injection point in the steam generator must match "R" without waiting for additional feed from the base of the steam generator. The worst case would be where the flow in the steam generator just before the water injection point may have fallen to "P1 " (low tide).

To satisfy the above, P1 + EW.gtoreq.R. If this requirement is not met, in the above case, temperatures will continue to rise and the thermostat override control will shut off the burner. This will lead to a loss of available power if the steam generator pressure has fallen into the range where burner operation is otherwise required.

In order to allow for such factors as steam generator thermal delay, P1 + EW should have some margin over R, especially if a more rapidly fluctuating injection water control is required in order to assist in smoothing out fluctuations of water feed through the base of the steam generator. With 10 percent margin, P1 + EW.gtoreq.1.10 R.

In addition to the above a further factor must be considered in the case where an ON/OFF burner is used. Consider the case where the system is running at light load, the burner is operating and the second pump and injection circuit have been switched on by rising temperatures in the superheater thermostat 14. In the evaporative zone, a temperature change of from, say, 544 DEGF to 587 DEGF, i.e. 43 DEGF, is required to raise boiling point pressures from 1000 psi. to 1400 psi. at which later pressure it is assumed the burner would be switched off. The above temperature rise may be achieved with a corresponding temperature rise at the superheater thermostat of twice this amount i.e. 86 DEGF. (depending on steam generator tubing layout etc.). Now it is not desirable to have to set the temperature for operation of the burner over-ride control at a large amount above that temperature at which the control operates the second pump and water injector, in order that the burner over-ride will not operate under normal conditions.

Sufficient pressure rise throughout the steam generator can be obtained with a more moderate temperature rise at the superheater thermostat 14, if the quantity of water and steam in the steam generator is increased. Thus, if P1 + EW is increased to be greater than R by an additional margin, (i.e. -- feed will tend somewhat to better match the momentary burner rate rather than the steam output rate) -- satisfactory results may be achieved with closer temperature settings for the pump/injector control and the burner over-ride control.

Thus allowing the further margin for the ON/OFF burner system,

P1 + EW.gtoreq.1.20 R (2)

considering the above case but with a modulating burner which matches the load more closely, temperatures would not be expected to rise significantly with the two pumps and EW feeding with the relation P1 + EW.gtoreq.1.10 R. Thus it would be expected that satisfactory results would be achieved with the quantity P1 + EW less than for the case with an ON/OFF burner system. For an ON/OFF burner system at full load, in which water and burner rates are more closely matched, a relation similar to that applying to the modulating burner system would see applicable.

It should be noted that there are many factors which have some effect in connection with the above relation (2). The applicant has found, however, that experimental results do tend to support the above reasoning.

III. To avoid internal steam generator temperature peaks, control should be exercised over the proportion of injection water provided.

The following method calculates the maximum rate of injection water "EW" injected so that the dryness fraction qB of steam just before the injection circuit outlet is 100 percent i.e. just not superheated.

Having reference to FIG. 2 the full line "I" in the graph indicates water and steam conditions throughout the steam generator heating surface under steady conditions when all feed water is delivered into the bottom of the steam generator, and is equivalent to the burner evaporation capacity at the particular load. Note that a burner controlled on an "ON/OFF" basis can give roughly similar results in matching the load as a modulating burner. The dotted line "II" shows the variation from the above when total feed water pumped equals the burner capacity as before but part of the water "EW" is taken from a feed water heating zone (as is good practice for injection systems) at point "W" and injected into a point "Z" immediately after which the dryness fraction is qA = 60 percent. Steady conditions are again assumed.

The percentage of heat received by water-steam following line I between points W where temp. = 450 DEGF and Z = 11.2 + 28.8 = 40 percent, producing steam at q = 60 percent at Z.

Considering unit weight of water/steam, the percentage of heat to produce steam at q = 100 percent from water at 450 DEGF = 11.2 + 48 = 59.2 percent of total heat added.

It can be seen that, if heat supplied to the steam generator section between W and Z remains constant, and quantity of water passing along this section drops in the ratio of 40 to 59.2 i.e., drops to 40 + 59.2 = 67.6 percent of its former value, steam of qB = 100 percent will be formed just before A i.e., EW = 100 - 67.6 = 32.4 percent of total water pumped. If EW>32.4 percent, steam will superheat just before Z.

It is possible to use an "earlier" injection point to enable EW to be greater. However, greater delay in response to the thermostat would occur. Conversely, with a "later" injection point, EW would have to be less but response delay would be less. It may be desirable to reduce EW to conform with the considerations discussed in paragraph I above. It is considered that the injection point shown is approximately at the optimum position.

It could be argued that a small superheat before Z could be tolerated. Care is needed if this is assumed for the design based on an "ideal" graph. The above examples assumes steady conditions and, in practice conditions are not steady. Variations can occur such as load changes which because of factors such as inertia in flow response to change of load, can lead to effects causing steam before Z to become wetter or drier (superheated) than estimated for steady conditions. A margin of safety is required over the "ideal" graphs shown for steady conditions. Thus, from the above considerations, it appears that the water injector control could control 2 .times. 32.4 = 64.8 percent only of the total feed water. An additional control system is therefore needed.

From the above calculations, it can be seen that, to avoid internal temperature peaks, base water f .gtoreq. .676 R. Since base water feed may, at times, approach P1 (low tide) thus P1 .gtoreq..676 R.

Under some conditions, P1 + EW may be approximately equal to R, then P1 .gtoreq..676 (P1 + EW) from which

EW.ltoreq..48P1 (3)

under conditions such as may occur immediately after start-up, the flow reaching "Z" on the curve shown in FIG. 2 from the base of the steam generator, may temporarily be <P1. The temperature before "Z" would be expected then to rise and the safety thermostat 27 (FIG. 1) would possibly operate.

IV. Considerations involving reductions in steam temperature fluctuations

Some causes of temperature fluctuations in the steam leaving the steam generator are: (a) Response-delay in the superheater thermostat 14 in sensing the correctness of the mixture at "Z," and (b). The magnitude of the "error" in the mixture reaching the superheater thermostat 14.

Assuming a fixed response-delay time, reductions in temperature fluctuations can be achieved by bringing P1 closer to R and minimising EW and P2. Thus there is argument for P2 to be less than P1 i.e. -- Pumps of different capacities, referred to in more detail later.

V. Consideration of the quantities and relationships between P1 P2 and R as effected by Rotary Motor Characteristics

The graph (FIG. 3) shows the effects of leakage and back pressure on the rotary/motor/feed pump/condenser-fan drive system. The effect of leakage is large at the low powers thus leading to low rotary motor speeds. The high back pressure of the fan, rising as the square of the speed, causes a rapid increase in back pressure required to operate the rotary motor at high powers again leading to reduced rotary motor speeds.

It can be seen from the graph, and using the simplified considerations the useful range is that in which P1 <R and P1 + P2 >R, it can be seen that difficulties in obtaining a useful wide range increase as P2 becomes small in proportion to P1. (See later for rotary speed correction devices which assist in overcoming this factor).

The above considerations, I to V are in themselves narrow ones. Account is not taken of such factors as failure of one pump, thermal storage in the steam generator tubes, changes of steam zone positions with changes of load, inertia of the steam generator contents in following load changes. Because of the changes in rotary motor system performance with load, P1 will not bear a fixed relation with R, for example.

The steam generator system described in this specification, however, is protected by the action of a "safety" thermostat and the superheater thermostat as well as a steam pressure switch as previously described. Rapid accommodation to load changes is made with the rapid action of the water injection control system.

Summarising the relations evolved above:

EW.gtoreq..50 P2 (1)

p1 + ew.gtoreq.1.2 r (2)

ew.ltoreq..48 p1 (3)

using a system with the position of the water injection point "Z" as shown in FIG. 2, (i.e. -- so that the dryness fraction after "Z" is 0.60 with feed of water matching output for steady conditions,) and using twin feedpumps so that P1 = P2, with EW = .5 P2, relation (1) will be satisfied and relation "3" will be approximately satisfied. From relation "2" --

1.5 P1 .gtoreq.1.2 R and P1 .gtoreq..80 R

Note that, if EW increased, relation "3" is not satisfied. This means that there is a possibility, under abnormal conditions, of a temperature peak before "Z." The safety thermostat would operate if necessary but this may cause a more serious loss of good control than if EW was not increased. In the latter case, the superheater thermostat may reduce burner output if required under abnormal conditions.

Some more latitude can be allowed for EW in a system using pumps of different sizes. With P1 = 1.15 P2, from relation "3,"
Ew.ltoreq..48 p1
.gtoreq..552 p2
thus EW may be from 0.50 to 0.552 P2.
For EW = 0.50 P2, from relation "2", P1 .gtoreq.0.837 R,
For EW = 0.552 P2, from relation "2," P1 .gtoreq.0.81 R.

EARLIER INJECTION, AND MULTIPLE INJECTION

With water injection earlier than shown, (FIG. 2) EW can be safely increased and a larger margin of operation of P1 as a function of R can be achieved. Response delay can be reduced by injecting through more than one injection point.

EXAMPLE

First Injection Point such that, under steady conditions, with no water injection, dryness fraction of steam = 0.50. Using a method similar to that used for finding relation "3," total EW.ltoreq..66 P1. Half of EW can be injected through a second injection point after which, under steady conditions, dryness fraction of the steam would be, say 0.75.

METERING AND PROPORTIONING OF INJECTION WATER

The injection water line 51 in FIG. 1 incorporates a metering jet which, in the preferred arrangement is the orifice of the solenoid control valve 52 see FIG. 1. This jet is designed to allow the passage of quantities of water equal to approximately 0.50 P2 or as calculated by the use of the above relations.

The method of estimation of the jet size may be as follows:

A percentage load is assumed and the corresponding pressure drop of the water and steam passing through the steam generator proper, between W and Z, FIG. 2. is calculated. The jet size is then calculated so as to pass the correct amount of water at the estimated pressure drop.

EFFECT OF LOAD CHANGE ON EW

The pressure drop from W to Z will vary approximately as the square of the load. The weights of water and steam passing through the steam generator proper between W and Z and also through the water injector will vary but will remain approximately in the same proportions.

EFFECT OF PRESSURE DROP ON EW

At low steam generator pressures, such as may occur immediately after start-up, pressure-drops through the steam generator will be higher (for the same load) due to the lower density of the steam and the higher steam speeds. The proportion of water through the water injector will thus tend to rise. However, the action of the safety thermostat will protect the steam generator if there is any significant upward surge of temperature because of the above.

Referring to FIGS. 4 to 6, FIGS. 4 and 5 show curves indicating the effect of speed correction of the rotary motor 24 (see FIG. 1) in the middle of the range where the speed of the rotary motor tends to be higher than required for proportional control of the feed water pump 16 compared with the steam requirement of the generator. FIG. 4 shows by the dotted line, correction by a bypass or leak valve which has the effect of causing the speed of the rotary motor 24 to remain more closely proportional to the steam requirement, substantially over the useful load range of the power unit.

FIG. 5 shows speed correction by the connection of motor/generator 56 (see FIG. 1) into the rotary motor drive circuit. The motor/generator 56 when operating as a motor is controlled automatically so as to cause feed water to be pumped into the steam generator at a rate approximately equal to 20 percent of the full load rate at such times as the steam generator pressure is substantially below normal and the steam temperatures are above normal. These conditions may occur just after initial start up.

The generator of the motor/generator is operative to impose a torque load on the rotary motor in the middle speed range which is inherently reduced because of the lower torque demand of the generator at higher rotary motor speeds.

The generator may be of the third brush or constant current type and "cut in" of the generator at low speeds may be suitably delayed to reduce torque load on the rotary motor.

FIG. 6 shows a metering valve for positioning in the exhaust steam circuit in parallel to the rotary motor. The valve includes a chamber 60 having a piston 61 therein, the piston 61 is movable between two positions under the controlling influence of biasing springs 62, 63 and steam pressure. The chamber is ported at 64 to allow leakage of steam past the piston 61 at a predetermined pressure in the exhaust steam circuit representing the middle speed range of the rotary motor, thereby bypassing the rotary motor with some of the exhaust steam. The position shown in FIG. 6 is an intermediate position.

With back pressure higher than those normally encountered at full load, such as short term exhaust pressure surges, the piston may take up an extreme position thereby by-passing a considerable amount of steam and relieving the pressure surge.

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IMPROVEMENTS RELATING TO THE CONTROL OF EXPANSION RATIO IN ROTARY MOTORS

A motor driven by a compressible fluid such as steam or air has a rotary structure 4 attached to an output shaft 21 and furnished with sealing segments 4a that engage with blades 3 supported by a fixed shaft 2. A proportion of the fluid in a supply line 6a is diverted through a flow-restricting passage 8 and a passage 9 into one of the interblade chambers 5 between an inlet port 6 and an outlet port 7. When it is necessary to augment the torque at the shaft 21 e.g. on starting, the flow through the passage 9 is increased by a valve 11 opening to connect a passage 10 to a passage 15, this being due to a greater pressure-differential occurring between the line 6a and a passage 13 and consequent deflection of a spring-loaded diaphragm 12. The effect produced by the increased flow through the passage 9 is comparable to that of "late cut-off" in a conventional reciprocating steam-engine. Alternatively, the valve may be such that it opens in response to a rise in the pressure in the line 6a, (For Figures see next page)

This invention relates to rotary motors ob the positive displacement type using steam or compressed air or other expansible gas or vapour as distinct from rotary turbines, in which motors the expansion ratio can be varied without the aid of intake valves such as rotary inlet valves or inlet valves operated by means of link motions or camshafts.

In a rotary motor or reciprocating engine of the positive displacement type which is used over a wide range of speeds as, for example, from zero to the maximum design speed, it is desirable to use a small expansion ratio or "late cut-off" of the high pressure working fluid in order to obtain more positive starting, high overload torque and better smoothness on starting. A smaller expansion ratio or "later cut-off" is also desirable, apart from when starting, in order to run against loads heavier than normal. Under normal loads, it is desirable to run on a higher expansion ratio (early cut-off) so as to obtain more economical use of the working fluids.

In some rotary and reciprocating engines, changes of cut-offs arc obtained, for example, simply by varying the aiTangements of link motions or by changing the positions of cams or, on engines fitted with rotary valves, by changing the position of rotary valve sleeves.

However it is advantageous if intake valves can be eliminated and to rely solely upon porting of the rotary engine thereby reducing initial and ensuing maintenance costs.

This invention has for its principal objective to provide a rotary motor of the type specified in which the expansion ratio can be varied in accordance with load and speed requirements.

With the principal objective in view there is provided according to the present invention a rotary motor of the positive displacement type driven by expansion of a compressible working fluid introduced from an inlet supply line under pressure through an inlet port of the motor into a first expansion stage, said motor having at least one additional expansion stage between said first expansion stage and an outlet port of the motor spaced from said inlet port, the improvements comprising a bleed passage from said inlet supply line leading working fluid to at least one said additional expansion stage in the motor, said bleed passage including means for automatically controlling the amount of working fluid supplied therethrough such that during periods of low speed and/or high load the expansion ratio is reduced by increasing the amount of working fluid admitted to the motor.

Conveniently a pressure sensitive valve is provided in said bleed passage said valve being influenced by the load on the motor.

The bleed passage may be restricted and said restriction may be provided in parallel with said valve to provide a continuous flow of working fluid which is effective at low motor speeds to substantially increase the amount of working fluid admitted to the motor.

Said pressure sensitive valve is convenientLy sensitive to working fluid inlet or expansion stage pressure, or a pressure differential between inlet and expansion stage inlet pressures by which effects of later cut-off are obtained upon increase in load.

It will be understood that according to the invention introduction of the working fluid may take place at several succeeding stages of expansion to a lower pressure in the motor.

A practical embodiment of the invention now to be described is a blade type rotary positive-displacement motor driven by steam or air, however it will be understood that the invention can be applied to various kinds of rotary positive displacement motors in which there is at least two stages of expansion of the working fluid. The embodiment is described having reference to the accompanying diagrammatic drawings.

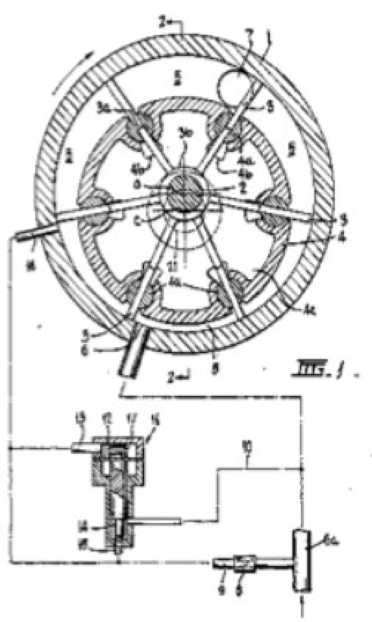


FIG. 1.

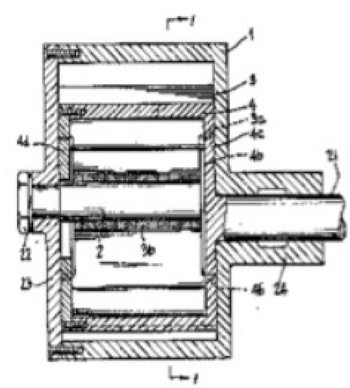


FIG. 2.

There is provided a stationary cylindrical ported chamber 1. In sealing contact with said chamber 1 a plurality of blades 3 are provided which extend radially from bearing bosses 3b mounted on shaft 2 above centre 0 enabling said blades 3 to move about centre 0 independently of each other in the direction of rotation shown. The blades 3 are constructed with their inner portions and bosses 3b forked to fit inside each other along the shaft 2. The blades 3 pass through sealing segments 4a mounted in a rotatable cylindrical structure 4 which is integrally formed with an end flange 4c at the drive end and with a removable flange 4d at the opposite end. The blades 3 are stepped dozen at 3a in overall width (taken along the axis) to clear inner portions 4b of the end flanges of the structure 4.At the driving end of the structure 4 an output shaft 21 on centre C extends from the end flange 4c.

Shaft 2 is held into end wall 23 of chamber 1 by means of a nut 22. Output shaft 21 runs in bearings machined into an extension 24 of the opposite end wall of chamber 1. The ports, inlet 6 and outlet 7 in the chamber 1 are placed approximately opposite one another. It is preferred that a sufficient number of radial blades 3 are provided so that at least two expansion stages are formed between the inlet port 6 and the exhaust port 7. Accordingly smooth running of the motor is obtained despite the lack of intake and exhaust valves as well as providing a greater expansion ratio.

The bleed fluid passes through a restricting passage 8 of a definite predetermined minimum control area in bleed line 9 leading from the main supply line 6a to a later expansion stage. The amount of bleed fluid is increased by opening up of additional passage area controlled by means of a pressure sensitive valve 11 which may be diaphragm controlled and inter-connects passage 10 to passages 9 and 15 through needle valve member 14. The diaphragm 12 may be sensitive to the pressure existing at a datum point such as the fluid intake (not shown) or to a pressure differential such as the difference between the pressures at the intake 6 and at the point of admission.

16 of the working fluid as shown in the embodiment illustrated. In this embodiment the diaphragm 12 is subjected to the pressure in passage 10 on the one side and the pressure in passage 13 on the other side. Since the pressure of working fluid bears a direct relationship to the load on the motor, the valve 11 is in fluenced by the load on the motor. The diaphragm is adapted to move in response to the bias created by the pressure differential whereby the needle valve member 14 is moved to open or close passage 15. If necessary a compression spring 17 may be provided to ensure that the needle valve member 14 is closed at the appropriate time.

A major controlling factor over the maximum expansion ratio on the type of rotary motor illustrated is the number of blades 3. The larger the number of blades, the greater the expansion ratio obtainable.

It will be appreciated that the bleed fluid flowing in the restricted passage S, will have little effect at normal running speed, the volume of flow being of but a small proportion of the total flow of working fluid through the motor. Thus the bleed passage is mainly effective at low speeds as desired.

ATTACHMENT 11

The Keen

Steam Car

This magnificent sports roadster
achieves outstanding performance
in almost complete silence.

THE KEEN STEAM CAR

NO SMOKE — NO DIRT — NO FUMES

Starts at the turn of a switch — No gears — Silent travel.

Here is a magnificent bright red, very sleek sports car of rakish design, losing nothing by comparison with the most expensive and illustrious of that ilk. The exterior has twelve coats of rubbed down lacquer, and has beautiful magnesium wheels. Interior décor is in black and gold, the commodious cockpit having plenty of leg room and clean swept space. The impressive dashboard has a long array of gauges to inform the driver of what is going on, with the reversing lever at the left. If desired a foot pedal could be substituted for this lever.

Careful streamlining and beautiful finish combine to create distinction.

Performance.

A turn of the switch and the burner ignites with a slight puff. No smell and no smoke from oil fuel—lovely combustion. By my watch timing, steam pressure was raised and we moved away in just over one minute with full power available. When the power unit is warm, steam raising is practically instantaneous. We threaded our way through heavy city traffice and then out on

In charge of exciting power, the driver sits amid opulence.

With interior decor in contrasting black and gold surmounted by dove-grey panel which frames the instruments in neat array, the Keen displays excellent craftsmanship. Most of the instruments are of engineering interest only, being merely visual reminders of efficient automatic control.

From left to right are spotlight for instruments, water and fuel gauge, steam temperature gauge, fuel oil pressure, steam pressure, speedometer, steam pressure at engine, engine oil pressure, exhaust steam pressure, ammeter. Below from left to right are signal light for feed water pumps, headlight switch, and windscreen wiper control beside steering column bracket.

Two pedal control is provided by the brake and throttle accelerator pedals.

to the open road. Owner-driver, designer Charles F. Keen let her out and we rolled at sixty and then at seventy, which was all traffic conditions would allow. No fuss and no trouble. The monotube steam generator and automatic controls provide the steam when the engine requires it, all the driver has to do in normal running is use the accelerator pedal and footbrake. To reverse, the engine rotation is reversed. There is no clutch or gearbox. Acceleration is brilliant, being best described by the remark: " . . . . **at the average stop lights I am across the intersection before most cars get started."**

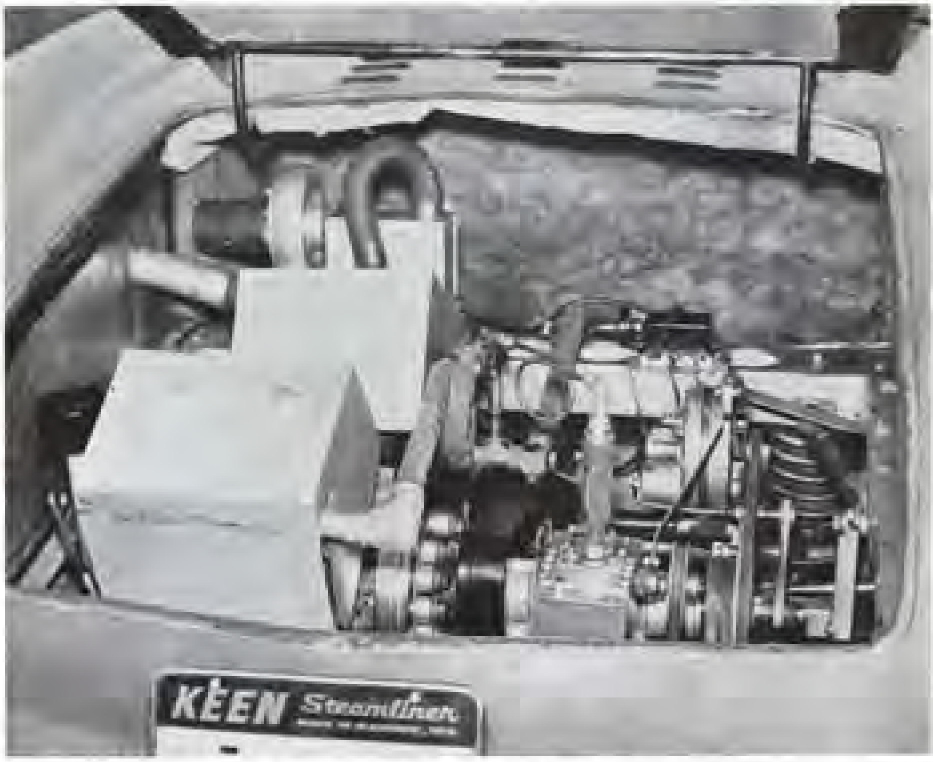
On a spurt, pressure once dropped to 800, but promptly came back, and the rest of the time remained quite steady at 1,000 to 1,200. This type of steam generator, being inherently safe from all fear of explosion is **not** subject to insurance cover or inspection. At 45-50 m.p.h., the burner was frequently automatically switched off due to excess steam pressure, very rarely due to excess steam temperature, which proves the worth of the automatic control system. There are two power settings—a low fire position, which gives about 85 m.p.h. top speed and the high fire with about 100 m.p.h. available.

Economy.

Cheap paraffin (kerosene) or furnace oil gives an economical 12—18 m.p.g. (10-15 m.p.g. American), depending on driving conditions, with improved economy envisaged for the future. Ordinary tap water is used and, with the steam condensed for re-use, the water tank need be only rarely filled.

Silence.

The engine and pumps are extremely quiet, comparing favourably with a perfectly tuned i.c. engine. On a sudden hard pull one is aware of a slight pulsation, but it is not very noticeable unless one is told to watch for it. There are several positions for variation of cut-off (which is the fraction of the piston's stroke during which steam is admitted to the cylinder). Engine drive coupling



The engine compartment under the rear deck.

The 4 cylinder uniflow expansion, single-acting engine is shown at left. Cylinders in this 90 deg. V. design are arranged in two banks of two each. There is direct drive to the rear axle, no clutch or gearbox being required. Freedom from vibration is ensured by a coupling incorporating twenty-four drive pins each surrounded by a rubber bush. With the engine installed transversely aft of the rear axle, the torque in forward direction tends to throw more weight on the rear wheels, thus counteracting wheel spin.

contains 24 drive pins each surrounded by rubber bushes to give smooth, silent transmission. When riding along at 25-30 m.p.h., it is impossible to know whether the burner is on or off.

Engine.

With four cylinders—the equivalent in power impulses of an eight cylinder i.c. engine, and 100 cub. in. (1,639 cc.) capacity, the compact V4 design gives 130 h.p., which can be increased if needed.

Steam distribution in the cylinders is on the uniflow principle, in which steam enters through a valve and exhausts through ports cut in the cylinder walls near the end of the stroke. Very high torque is available at very low r.p.m.,

The steam generator.

Nestling neatly under the bonnet (hood) is the highly efficient, oil-fired, automatically controlled steam producer, quite different from the cumbersome boilers of yesteryear.

so high that there was a danger of excessive wheel slip during acceleration. For this reason the engine is placed transversely **behind** the rear axle so that when power is applied going forward it throws more weight on the rear wheels, thus avoiding wheel spin. Also when the throttle (accelerator) is tromped on, the car hugs the road rather than creating a tendency for the front wheels to lift. That this arrangement is of great practical use is made evident by the ease with which the rear wheels can be made to spin when reversing.

Steam Generator.

Gone are the days of the bucket of coal, belching smoke, and greasy rag. Steam is generated automatically, without noise, smoke or troublesome fumes. Combustion is so good that there is none of the noxious odour associated with the diesel and, to a lesser extent, with the petrol (gas) engine.

Air and oil spray are blown into a totally enclosed combustion chamber at the top of the steam generator, and the hot gases give their heat to closely wound coils of immensely strong tube before being allowed to escape from an exhaust duct beneath the body of the car. Water is pumped into the coils of

The graceful lines give no indication of the smooth, silent steam power, with brilliant acceleration.

tube, turning to steam therein, which is admitted to the engine via a throttle valve operated by the accelerator pedal. Steam pressure is automatically controlled at a maximum of 1,200 lbs. per sq. in. by the action of a pressurestat, which switches the fire on and off to suit the engine's demand for steam, as controlled by the throttle. The normaliser allows a small spray of water to be admitted into the hot or superheater section of the coiled tube, cooling the steam before its exit to the engine and enabling the thermostat to maintain a steady steam temperature. The whole nestles unobtrusively under the bonnet (hood). This is a very light-weight, compact steam producer, not be be confused with a heavy, cumbersome boiler.

Starting is more simple and reliable than an i.c. car. You just turn a switch. There is no need to wait for the engine to fire. Within the minute stored power is available to make the car accelerate right up to maximum speed as fast as the tyres will allow, without a pause for gear changing.

A familiar car in Madison, U.S.A., is the Keen Steamliner, but nevertheless one which rarely fails to merit excited comment. Preliminary arrangements for eventual manufacture on a commercial scale are being made.

Enquiries should be directed to :—

THE KEEN MANUFACTURING COMPANY,

1602 GILSON STREET, MADISON 5, WISCONSIN, U.S.A.

Published by :—

"LIGHT STEAM POWER," KIRK MICHAEL, ISLE OF MAN, U.K.

The Magazine describing steam cars—modern, vintage and veteran—steam boats, etc.
Published every two months.

Subscription, £1 4s. per year ($4.00 for one year, or $7.00 for two years).

Printed by Horne and Son, Ltd., Bridge Street, Whitby, Yorkshire.

Photo courtesy Steam Automobile Club of America.

IN SEARCH OF

The Keen Steamliner

by Jim Benjaminson

At the turn of the century when the automobile industry was in it's infancy there were countless makes of automobiles offered--and it was truly anybodies guess as to which form of motive power would propel the new industry. The gasoline powered internal combustion engines were noisy and smelly but, by and large, reliable. Electric cars were silent but had limited travel ranges before their batteries had to be recharged and that problem literally killed their use. It's a problem that still plagues those that advocate the use of electric power today. And then there was steam. Steam was silent, smooth and reliable but most people shyed away from it as they neither understood the principles of steam power, nor did they want to be bothered with the preparations required to get the boiler fired up to convert water into steam. And water froze in cold weather which limited the use of steam in the northern climates of the country.

Both steam and electricity for automobile power died ignoble deaths. Well--they really didn't DIE--they just more or less faded into oblivion.

F. E. and F. O. Stanley, twin brothers from Newton, Massachusetts, marketed perhaps the most famous steam car in their Stanley Steamer which was built from 1897 to 1927. The man who perhaps advanced steam power the furthest was Abner Doble of San Francisco. Doble's steam car was not nearly so well known as the Stanley's and Doble's cars were super expensive. Doble was also such a perfectionist that few cars were built. After the Stanley's and Doble went out of business there were no commercial offerings made of steam powered cars again, a fact which prompted men like Charles Keen of Madison, Wisconsin, to build his own steam car. And when Keen did build his own steam car at least part of the car was built around a Plymouth!

I first became aware of the Keen Steamliner in January, 1979 when I received a letter from Arthur Phillips of Long Beach, California. Mr. Phillips' letter read, "Perhaps I could be admitted as a member (to the Plymouth Club) by submitting a picture of a Plymouth I own which has been modified to steam power by Mr. Charles Keen of Madison, Wisconsin under the able direction of the famous steam car builder Abner Doble. I don't know the year of the Plymouth body and chassis but I would appreciate it very much if you could positively identify the model year of this unusual one of a kind automobile.

The car is known as the Keen Steamliner. The body is a standard coupe in excellent condition except it needs repainting and most of the trim is rusty but rechromeable. I don't think the top is original--it is a soft top over a noncollapsible frame and it does not have a rumble seat. It has been described as a 1950 Plymouth in our steam automobile club magazine but I am sure this is not correct. One steam magazine states 'the first mention of this car was in a letter by Mr. Keen which was published in October, 1947, referring to the construction of this car which is known as Keen Steamliner No. 1, starting in 1943 and indicating development was nearing completion at that time'. This (letter) may possibly be referring to the steam equipment and not to the complete car but I rather think it was referrina to the complete car. At any rate it seems quite obvious it is not a 1950 Plymouth!"

In subsequent letters Mr. Phillips sent a Xerox copy of a "brochure" photo of the Keen Steamliner which was taken from the book "Smogless Days" written by Stanley Ellis, published by Howell North Books, 1050 Parker Street, Berkley, California. Mr. Phillips again wrote about the car: "It has a Stanley Steamer engine connected directly to the differential by spur gears. The car has a monotube coiled boiler and top fired burner that raises steam in one minute. Of course the engine is incased and runs in oil. The steam pressure and temperature are automatically controlled."

Mr. Phillips claimed that Stanley Ellis, when he owned the car, drove the Steamliner "every day for ten years". After acquiring the car himself Mr. Phillips worked on it for some time and "had the car running after about a years work but the automatic heat control was not set properly, which was adjusted, but then a pin hole blew in the steam generator (boiler)."

Referring to Mr. Ellis' book "Smogless Days", Ellis wrote that he visited Mr. Keen and took a ride in another Keen Steamliner which made him "yearn for a 'modern' steamer". Ellis states in the book "Mr. Keen had built an earlier model about 1950 and it was still in existence in other hands. I contacted the owner and it (Steamliner No. 1) was shipped to me from Lincoln, Nebraska, in 1960."

Ellis made further references to the car, stating that the car had a Stanley 20 horse power engine although the rest of the car was "pure Keen--beautifully made." Ellis stated that in talking to Charles Keen he made reference to the fact that Abner Doble had helped him with some features of the car before Doble's death.

Stanley Ellis drove the Keen Steamliner No. 1 on a regular basis through the first winter he owned the car. Although the steam apparatus worked faily well he was not at all satisfied with the body of the car. Quoting from his book Elis wrote: "The only undesireable feature was the body and chassis which came from a Plymouth coupe of 1950 This meant room for only three passengers including driver and there was insufficient ventilation from the smallish windows. In hot weather this became intolerable. Fifty to sixty miles per hour was about its nicest cruising speed . . but the limiting factor was not the powerplant at all, but the old Plymouth chassis. It was stiff and bouncy and far from comfortable at high speed."

Following some minor problems with the car, in the automatic steam controls and not in the steam engine itself, Mr. Ellis sold the car back to its builder, Charles Keen, and Keen towed the car from Ellis' Cape Cod home back to Wisconsin. How the Steamliner made its way into Mr. Phillips' hands following the death of Mr. Keen is unknown.

The question now arises--just how much of the Keen Steamliner is a Plymouth? And what year Plymouth? There is no doubt that the front sheetmetal of the Steamliner is from a pre-war Plymouth--in all probability a 1942 model. It would only stand to reason that if Keen were working on the car as early as 1943 that he would have to be using parts from earlier model cars. However, several items in the overall picture of the Steamliner just do not fit into place.

Bill Leonhardt of Lincoln, Nebraska located a copy of Stanley Ellis' book "Smogless Days" which provided better photographs of the car but unfortunately they could not be reproduced with this article because of copyright infringments. The photos did reveal several items which simply are "not kosher" with a Plymouth body.

The first apparent change in the car was that if it were indeed built on a Plymouth chassis that the wheelbase had been shortened considerably. (Plymouth's had a 117" wb from 1940 through 1948). That in itself would explain the harsh, bouncy ride, Mr. Ellis had referred to in his book. Early Plymouth's had anything BUT a harsh ride!

Even more puzzling was the front door of the coupe, which had a VERTICAL rear door post, while all Plymouth coupes since 1936 had a forward SLANTING rear post. And the door handle was located BENEATH the chrome belt line mouldings rather than mounted flush ON the moulding as was Plymouth's practice for many years. What really stood out, however, was the exposed lower door hinge as well as the pedestal mounted windshield wipers. At rest the wipers pointed outward rather than pointing inward.

In reseraching the Steamliner further I contacted the Steam Automobile Club of America at their Pleasant Garden, North Carolina address. In talking with Sharon Yow, secretary to club president R. A. Gibbs, she offered to send me a copy of their club magazine which contained a photograph of several Keen Steamliners. The photo with this article is reprodced from that issue. In talking with Ms. Yow she stated she was under the impression that the Steamliner was based on a Chevrolet body--and not that of a Plymouth!

This lead to researching George Dammen's book "Sixty Years of Chevrolet" which soon revelaed that the '39 Chevrolet had the door handles mounted beneath the belt line mouldings, pedestal mounted windshield wipers and, as the clincher, the lower door hinge was exposed, just as were those items on the Keen car.

Following these revelations attempts are now being made to contact the current owner of the Steamliner in hope that perhaps he can shed further light on the car. Is the chassis that of a 1942 Plymouth or is it that of a 1939 Chevrolet? Is the body Chevrolet or were pieces of a Chevrolet mated to a Plymouth body?

There is no doubt in this writers mind that the body is at least partially that of a '39 Chevrolet but there is also no doubt that at least the front fenders and hood are from a 1942 Plymouth. The front grill bars have been modified somewhat to hide the cars identity but the "blackout" style short front fender trim and the stamping crease beneath the headlamps are pure 1942 Plymouth. The hood is also that of a '42 Plymouth although it has been modified to open "Buick style" from the sides rather than "alligator" style from the rear as did the original. Close examination also reveals that the hood trim mouldings do not have the same contours of the belt line mouldings on the car. The hubcaps are definately Plymouth and the wheels also appear to be, hinting that the front suspension may be Plymouth as well, as Plymouth wheels used a 5 bolt lug pattern which would not fit a Chevrolet as they used a 6 bolt lug pattern during that time. It is indeed unfortunate that Charles Keen passed away some years ago and cannot answer any of our questions about the car.

Bill Leonhardt, the club's resident '42 Plymouth detective and himself a native of Lincoln, Nebraska, where the Steamliner spent several years, contacted several people in the Lincoln area seeking further information about the car. Of three local steam enthusaists two remembered the Steamliner and one had ridden in the car on various occassions. This fellow gave Bill a lead as to where to find the widow of the car's Lincoln owner. In talking with her briefly she thought she may still have some photographs of the car. Hopefully her photo albums will reveal more information about the Steamliner in the future.

In talking with the man in Lincoln who was familiar with the Steamliner, Leonhardt was told it was this mans understanding that "the fellow that originally built the car was good at metal forming and had done an excellent job of the body modifications."

Without a doubt Charles Keen created a unique motor car. Where else on the face of this earth are you going to find a car that is part Stanley Steamer, part Chevrolet and part Plymouth?

(Editor's Note: These photographs and a brief note arrived shortly before press time from the Keen Steamliner's current owner, Loren Burch of Cantil, California.)

Side view of Steamliner shows short chassis, obvious mating of various bodies. Is the hood missing or just not pictured?

Sorry for the delay in getting the pictures but the roll of film got misplaced for awhile. These are probably too late for your article but I think you will find this car is not as interesting as you thought as I believe the body is mounted on a Willys Chassis! The chassis is not Plymouth. The front and rear body I believe is Plymouth but from two different cars. There is no name or I.D. plate anywhere on the car that I can find relating to Plymouth or any other car except Wiilly's hub caps and the "Keen Steamliner" name plate.

The pictures don't show it but the splice is concealed by the top, which is constructed of fabricated steel tubing.

Front view shows its Plymouth heritage. Note Keen Steamliner name badge on right fender.

Deck lid license holder and trunk lid handle look like '40 Plymoutn items. Is rear half of car another Plymouth?

Steam generator (boiler) appears to have seen better days. Rust spots may indicate hood is missing entirely.

Instrument panel is highly modified but still shows its '39 Chevrolet heritage.

SPECIFICATIONS FOR KEEN STEAMLINER - MODEL S

For many years we have done considerable development work on steam automobiles and will attempt to give you a general idea on what is practical. The first boilers we built were the water level type, and with these boilers we tried out first vaporizing burners which were much superior to the old burners used on the steam cars in the past. However, we were not satisfied with the vaporizing type burner. From practical experience, we decided the atomizing burner with electrical ignition would be more suitable for motor vehicle use. Then we built and installed the atomizing type burner under the water level boiler and in some respects this gave us better performance than the former burners. We then decided an entirely different type of boiler would have to be designed. We decided the next thing to do was to try a mono-tube boiler with enough steaming capacity and also with some reserve capacity. After considerable preliminary lay out and design, we started to build this new boiler. After the boiler was completed we installed it in a 1920 Stanley Steamer with a regular 4 x 5 engine together with a new condenser which replaced the old Stanley condenser. In addition to this we used a tubular condenser made of 1/2" O.D. steel tubing in the place of the old exhaust pipe which was placed under the running board. This boiler which would produce at least twice as much steam as the large Stanley boiler certainly gave this car good performance and with the improved condensing arrangement the car would make over 100 miles on a tank of water in summer weather, which was unusually good for a Stanley. Despite many of the critics of the Stanley engine we agree that it is not the most economical engine on steam, but with the modern boiler it still will give a good showing. The reason we show a Stanley engine is that this is about the only engine that can be had at this time. There is no question that a more modern engine would give better performance but the high cost of labor and materials would be beyond the reach of the average steam car builder.

BOILER FEED PUMPS

The feed pumps shown on the drawing are the easiest to construct. The only objection to them is that they are not as quiet a pump as a multi-cylinder pump. These are driven with a spiral bevel gear off the rear axle through a drive shaft with universal joints. However this is quite a costly arrangement. The feed pumps are controlled by a solenoid valve and this solenoid is operated by a thermostat and a switch in the control box. When the boiler does not demand water, it is by-passed back to the water tank. We do not have any boiler prints for sale. We have built a few of these boilers and burners and they run around $1200.00 and up. However, at the present time we are not building any boilers.

BOILER

This boiler steams up from all cold in 35 seconds to 1 minute. Maximum steam pressure is 1500 pounds. Steam temperature can be adjusted to suit individual engine 600 degrees to 800 degrees farenheit. Boiler diameter is 24" and height approximately 28". Burner will burn gasoline, kerosene or furnace oil without any change or adjustments.

NOT NOW AVAILABLE - SORRY

ATTACHMENT 12

Goldsmith

The Pyrenees Heritage Preservation Magazine No133 August 2015

Lake Goldsmith Steam Preservation Association Inc

Registration No:- A0032895

Rally Grounds:-1234 Lake Goldsmith-Carngham Road Lake Goldsmith Vic.

GOLDSMITH SPRING RALLY No 106

Plus

Friday October 30 2015

Great Southern Steam Trek
Ballarat -Beaufort & Lake Goldsmith
See page 3

Sat Oct 31 & Sun Nov 1 2015

International Truck Tractor & Farm Trek & Rally
See page 5

Mission Statement

To foster, nurture, encourage and demonstrate technical, agricultural and life skills associated with the Industrial Era.

To provide a quality environment where these skills may be used to educate and entertain members and visitors.

To run two weekend rallies each year, and be available at convenient time for other interested groups or individuals.

To conserve and develop a heritage collection.

A French Connection

From Heather Taylor,

Pyrenees Shire Tourism and events

An unusual coincidence for this Rally, is the arrival of visitors from France and Luxembourg where there are 13 of the more than 20 towns of Beaufort around the world. They are here for the 2015 Rassemblement de(*gathering of*) Beaufort, which this year is hosted by Beaufort in Western Victoria.

41 guests are expected to be here from the 29th of October to the 5th of November. The visitors are all billeted out to stay with local residents and they have tours arranged to local attractions, one of which is the Steam Rally at Lake Goldsmith on Saturday 31st of October.

We hope that they enjoy week in Beaufort.

Find us on the net at:- www.lakegoldsmithsteamrally.org.au

Or contact us by email info@lakegoldsmithsteamrally.org.au

Or write to: **The Secretary:- P.O. Box 21 Beaufort 3373**

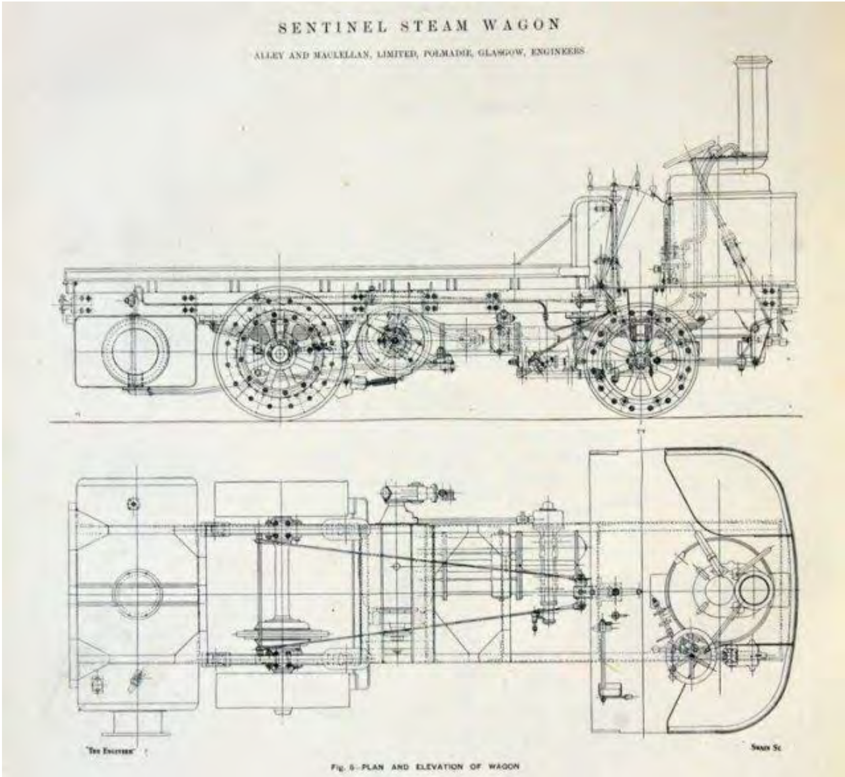
Or contact the editor:- goldsmitgazet@optusnet.com.au

To register for this "cost & obligation free" bi-monthly e-magazine "Goldsmith" email:-

goldsmitgazet@optusnet.com.au **or ph 0425 744 052**

The Sentinel Steam Wagon

The Sentinel Steam wagon started out with some designs and patents taken out by the firm of Simpson and Bibby who were based at Shropshire in England. The interests of this firm were acquired by the Sentinel Works of Alley & MacLellan, based at Glasgow in Scotland



The Sentinel Works was an established business (founded in 1875) manufacturing valves and steam equipment including steam engines, railway equipment and powered boats.

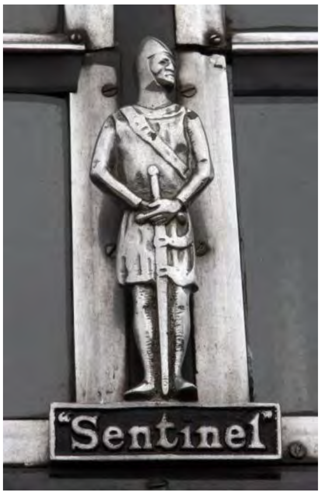
Designer, Daniel Simpson transferred to Sentinel and the first Standard Sentinel was produced in 1905. The Standard was simple and reliable and it's efficient vertical forward mounted superheated boiler, and the centrally mounted underfloor twin cylinder double acting engine, made a large tray area possible and made life acceptable for the driver. When used with a trailer 10 Ton loads were practical.

The Sentinel was well accepted by the market and soon more factory space was required. A new factory was designed and fabricated in Glasgow, and erected at Shrewsbury in Shropshire.

Production of the Sentinel Wagon shifted to Shrewsbury and commenced there in 1915. The Glasgow works continued with its core production which included high speed steam generating plants, such as this compound in Northern N.S.W., which was later used to power a timber mill.

Daniel Simpson was General Manager of the new plant. The Glasgow plant was sold to the engineering and shipbuilding firm William Beardmore & Co Ltd.

Stephen Alley acquired the complete works at Shrewsbury and named the new business "Sentinel Wagon Works Ltd" with himself as Chairman and Managing Director. The company was renamed the Sentinel Wagon works (1920) Ltd



The Glasgow nameplate, the factory guard & the wagon nameplate.

The Standard model continued in production until 1923 by which time about 3700 had been produced. The Lighter Super Sentinel was introduced in the same year. The single chain drive to the back axle was replaced by a separate chain driving each rear wheel from a differential mounted within the crankshaft of the motor unit. Over 1500 Super Sentinels were built and they continued in production until 1933.

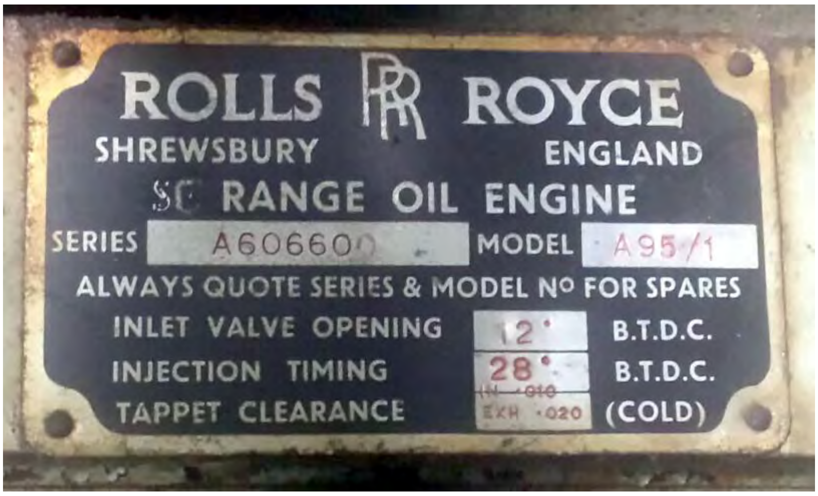
The DG4 was introduced in 1928. This model used an improved engine and added a second driving speed, Double Gearing hence the DG prefix. Over 850 DG's were built by 1937 when production ceased.

In 1933 the last Super Sentinel was produced and the S4 model was introduced. The S4 used shaft drive and a 4 cyiinder single acting engine and 2 speed gearbox. The cabin was redesigned and the boiler was located behind the driver. Over 400 S4's were produced.

The last large order of Sentinel S6 bogie tippers was placed by the Argentine Government for 100 trucks to cart coal from the coal mine to the Rail head in Patagonia. Steam Wagon production ceased in 1951

A separate company was formed in 1923 for the manufacture of railway Steam Locomotives and a variety of wheeled and tracked tractors were produced during the 1920's. There is a lot of information available on the internet about the history of Sentinel. Searches on Sentinel or Shropshire history will yield a lot of detail, some of which has been included here With nearly 8000 wagons produced, this company has played an interesting part in transport history, particularly when petrol and diesel lorries were in their infancy.

With the demise of the steam lorry market, Sentinel acquired Garner Motors for a short period, and after WW2, during which they had been engaged on war work, they introduced their own range of Diesel lorries which continued until 1956 when the factory was acquired by Rolls Royce for Diesel Engine production, which continued until 1983 when Perkins took over. Later Sentinel Training and Sentinel Manufacturing were formed. Perkins Engines and CAT remanufacturing are still in operation today.



Try www.sentinelmanufacturing.co.uk/our-history for more back ground.

William Adams were the agents for Sentinel, in Australia, and the Super Sentinels that are expected to form the core of the Wagons in the

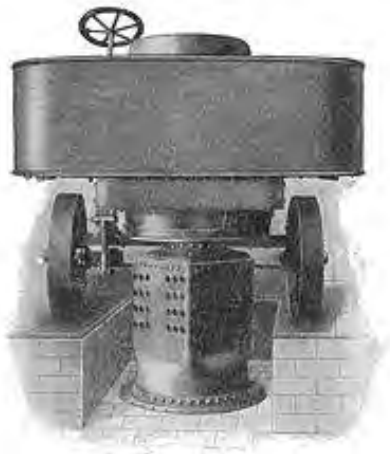
Great Southern Steam Trek

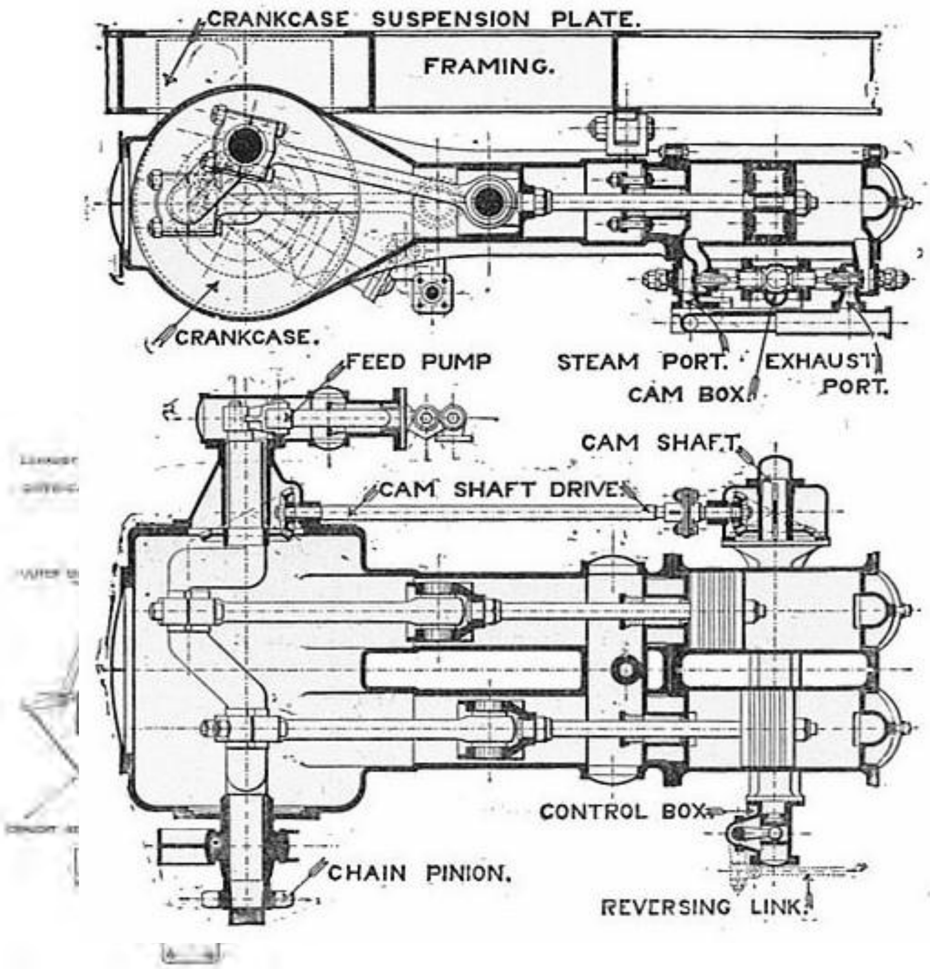
These wagons arrived here via the companies Melbourne and Sydney offices. William Adams advertised the S4 but none are thought to have arrived here through them. Some have arrived since, imported by privately collectors.

The last new Sentinel Steam Wagon arrived in Australia in 1927.

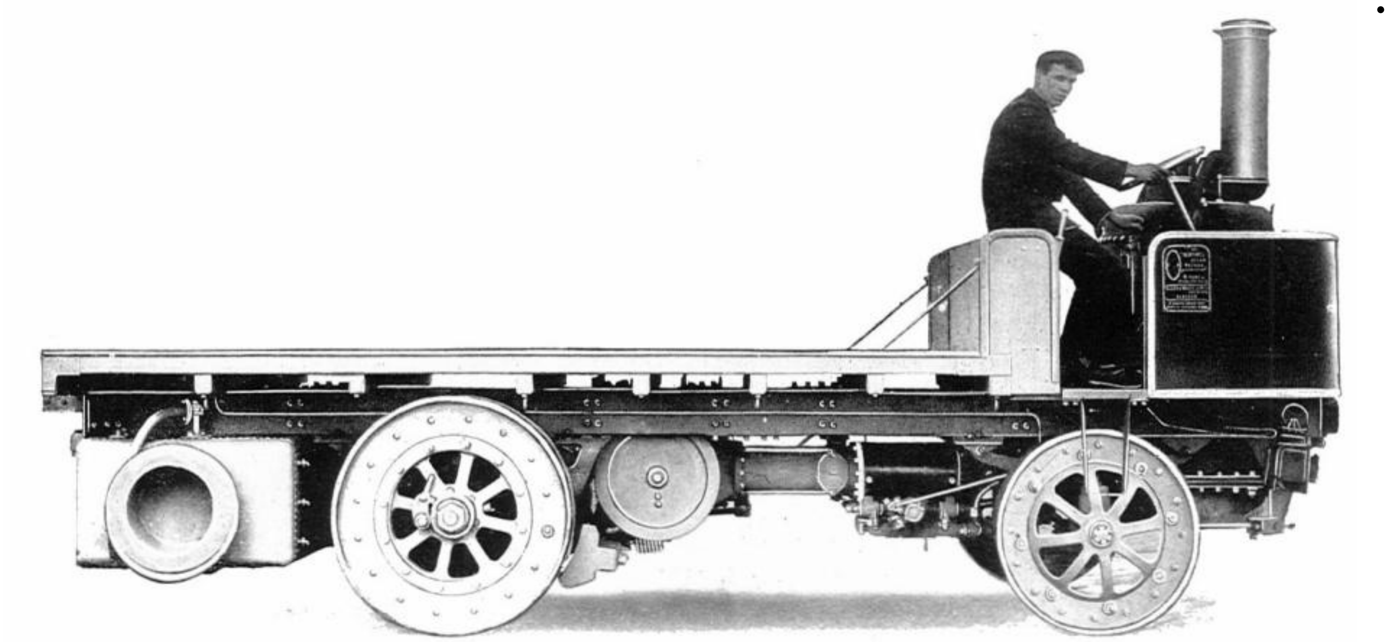
The Standard Model Sentinel 1905 to 1923

A vertical boiler was a feature common to all models. The standards and later models after 1932 used a vertical boiler with a removable square firebox which was fitted with inclined water tubes. A superheater was used and the boiler pressure was typically about 230 psi. and could raise steam in an hour. The firebox could be lowered to the ground for cleaning, as shown below, without having to remove the boiler from the Wagon. This was recommended at 2 to 12 month intervals, depending on water quality.

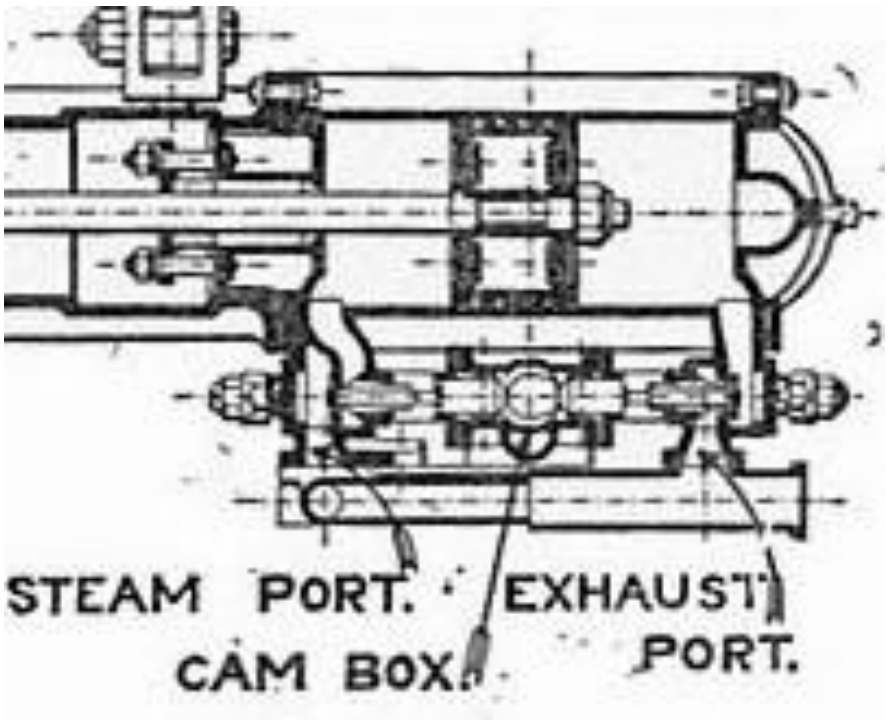




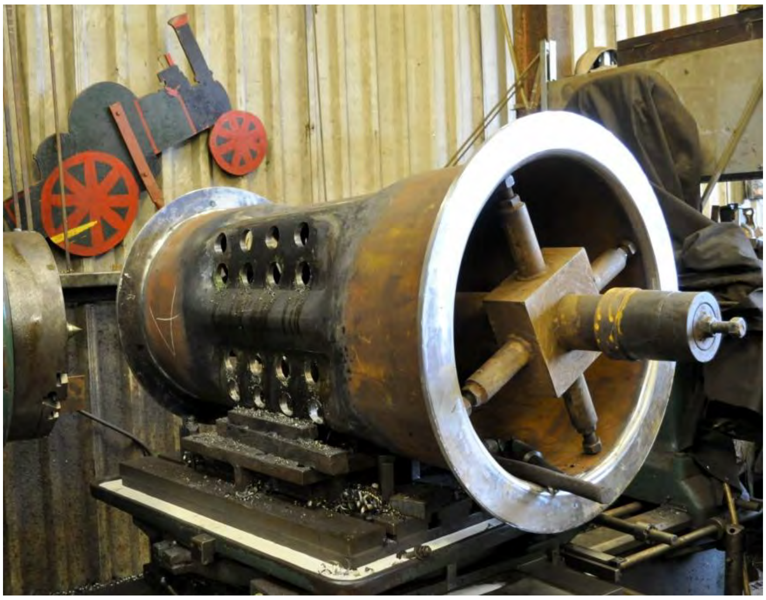
On the left, an early Standard Model is show with the square fire box dropped into a floor pit for cleaning. The drawing on the left shows a section through the square firebox boiler. The water tubes double as stays. The superheater coil sits above the water tubes, and both leave a clear central opening for coal or other solid fuel to be dropped in from the central top firebox door. An ash pan below the grate can be filled with water. The drawing on the right shows the arrangement of the standard model engine. The single speed chain sprocket is mounted on one end of the crankshaft, and the water pump is mounted on the other. The camshaft is mounted below the cylinders and is driven by a side shaft and 2 sets of bevel gears.



The picture above shows the arrangement of the Standard Sentinel, and shows the easy access to the valve assembly and warm up drain cock.



The valves are similar in operation to the poppet valves used in the internal combustion engine, but totally different in construction. The valves are opened by a pressure sealed pushrod. These pushrods push the bottom of a bucket or thimble which sits inside the cylinder space,(exhaust port) or steam manifold(inlet port) and is held against the 45 Degree valve seat by a spring inside the bucket. The spring is held in place by a sealed cap and bridge piece on the cylinder head. This arrangement makes the thimble valves very easy to remove without affecting the seal on the pushrod, which functions as the valve stem. If the engine is to be out of use for a long time, or the engine has been shut down wet, it is necessary to remove these valves to avoid damage. The valves have 2 selectable shutoff positions, at about 80 degrees for heavy work and 30deg for running.



The above Standard Sentinel Wagon is owned by Bob Butrims and Bruce Roberts from South Australia. This Wagon was built near the end of Standard production. The water pump can be seen clearly, and the single chain driven differential can be seen on the rear axle.

The photo on the upper right shows the new square fire box being machined to fit the new water tubes. Hopefully this rare wagon will make it to the rally, and if all goes well it may be in the Steam Trek

The Super Sentinel   1923 to 1933

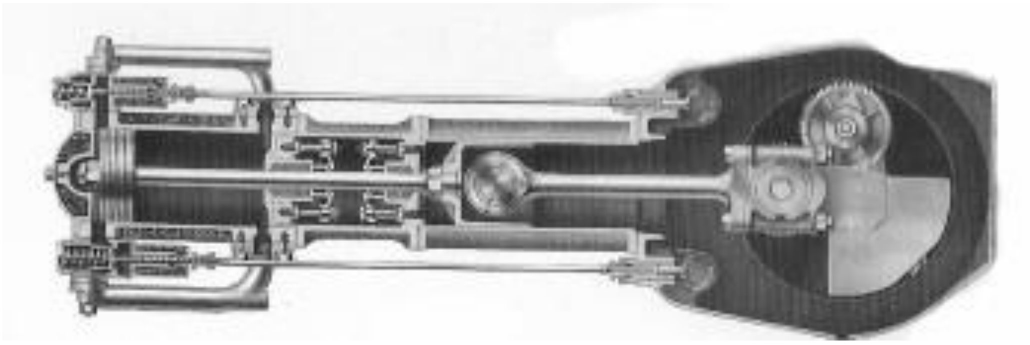
The Super Sentinel was lighter and cheaper to produce than the Standard. It used a similar vertical boiler. The main difference was the use of a circular firebox with a spiral water tube array manufactured by Galloway. The firebox could be dropped in the same way for cleaning

The firebox on the right (below) was manufactured by Galloway until their demise in 1932. The "spiral" water tubes can be seen in the corrugations pressed into the firebox wall. This arrangement is typical of the vehicles that will be seen on the Great Southern Steam Trek. This boiler owned by Paul Dove, has been fitted with new water tubes, as can be seen in the photo below.

The photo on the left gives a good idea of what the boiler and accessories look like when assembled for inspection. The picture below shows the boiler fitted to the wagon frame with the pipework installed. The waste heat recovery feedwater heater can be seen beside the boiler

This Sentinel has been restored recently in Sydney by Paul Dove with help from Karen and daughter Emily,(seated) all of whom have had a longstanding involvement with Lake Goldsmith Rallies.

Paul has also been a prime mover in organising the "The Great Southern Steam Trek"

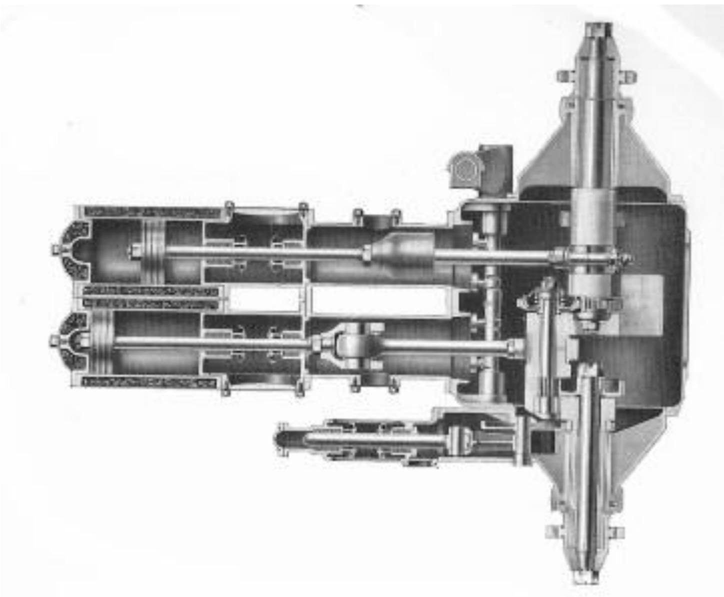


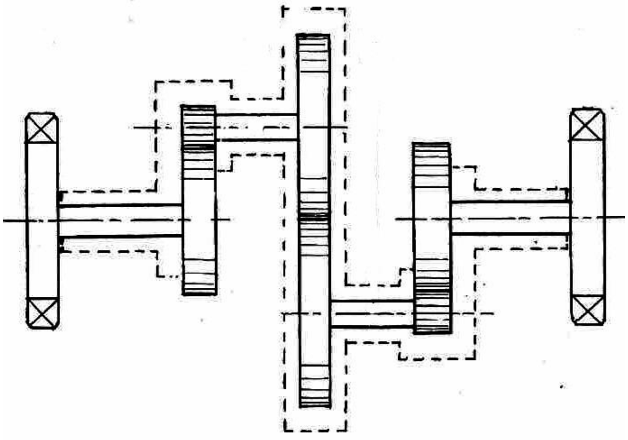
The engine is similar to the Standard that it is a twin cylinder double acting. The extended piston rod has a steam gland at the cylinder end and an oil gland to keep moisture out of the sump.

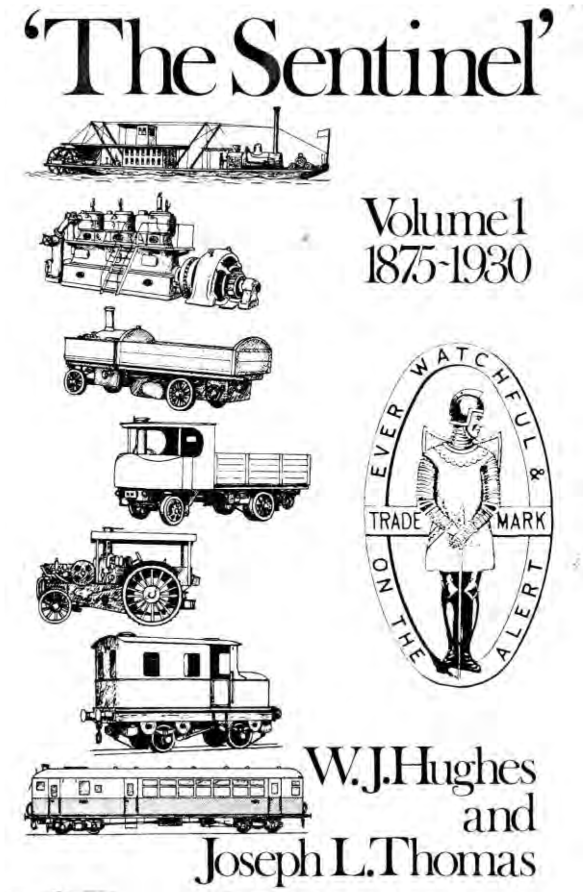
The single, gear driven camshaft has been replaced by 2 camshafts and long pushrods. The top camshaft operates the inlet and the lower camshaft operates the exhaust valves. The under piston side is fed from long transfer ports. The valve thimbles, pushrods and glands are similar to the Standard model, and the inlet thimbles can open to relieve any hydraulic pressure which may occur if water accumulates in the cylinders.

The Super Sentinel is fitted with a balanced crankshaft which incorporates the limited slip differential. The drawing on the right shows the

arrangement of the differential gears and shafts within the dashed crankshaft outline. The Sprockets are shown on the outer ends of the shafts.







The cutaway on the left shows the General Arrangement. A cone clutch can be seen in the gear at the top end of the lower bigend journal. This clutch is set to resist differential movement until there is a large difference in traction between each driving wheel. This allows the clutch to slip when cornering, but resists wheel spin when either wheel loses traction. For 1923 this was a novel innovation that must have helped when working in slippery construction sites.

The actuator that controls steam cutoff and rotation reversal can be seen at the top end of the inlet camshaft.

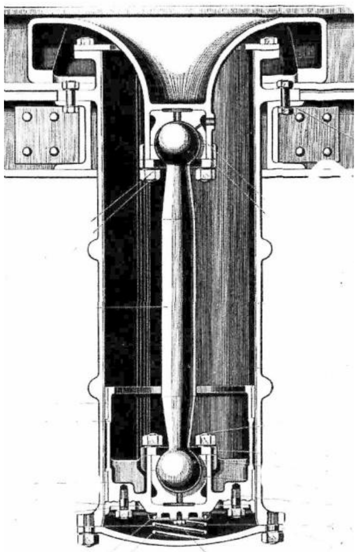
For anyone interested in more information on the Sentinel the books by W Hughes & Joseph Thomas are a must, and some samples from this work are included here.

Later DG models and railway engines used an improved version of this engine. The Under piston cylinder valves were relocated to eliminate the dead volume of the long transfer ports, and a 3rd cutoff settings were added to improve efficiency and the thimble valves were replaced by more conventional poppets.

The Super Sentinel:-

Produced 70 HP and had a torque of 3086 lb ft.
It normally operated at 25mph but has hit 40
Boiler pressure is 230psi, & superheat temp to 340C
Engine/ Transmission unit weighed 22cwt (1100KG)
The bore is 6 ¾" Ø with a stroke of 9" .
Boiler capacity 50 Imp Gallons produced 1200lb/hr of steam.

The above 3 photo's show the valve access ports and the thimble valve assy.



The above picture shows the twin chain drive on the rear of Sam Newman's Sentinel. This wagon was a 3 way tip tipper, but following the theft of the injector that raises the tilt cylinder, it is being assembled as a tray. The water tank that is normally under the rear of the chassis is located behind

the cab on the tippers. A section view of the tilt cylinder is shown on the right.

Science works have a restored tipper that can be seen at:-

http://museumvictoria.com.au/collections/items/407359/steam-wagon-works-ltd-super-sentinel-circa-1924

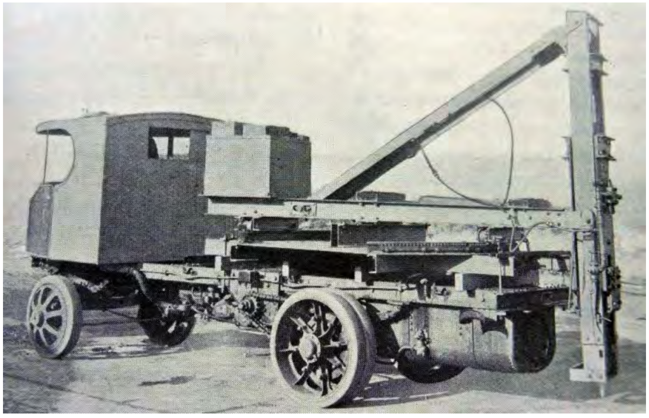
Scienceworks Sentinal Tipper, (Ben Klaster pictures.) The restororarion of this Wagon was started by Peter Adams and completed by Ben Klaster, who also restored Peter Jackman's Super Sentinel on page 12.

The Super Sentinel below is owned by Andrew Johnson, and it is a familiar

sight in the Ballarat area and at Lake Goldsmith. The Wagon has already driven to a Lake Goldsmith Rally, where this picture was taken. The signwriting is a giveaway to Des Langs past involvement in the restoration of this Super Sentinel.

Andrew is the co-organiser of the Steam Trek with Paul Dove.

This Wagon started life with a building foundation company and a steam hammer pile driver was attached to the rear. This required a lot of steam and the wagon was fitted with a heavy duty boiler by the manufacturer. This vehicle still has its William Adams agents plate attached. The pile driver has vanished into the mists of time, but fortunately some pictures have survived.

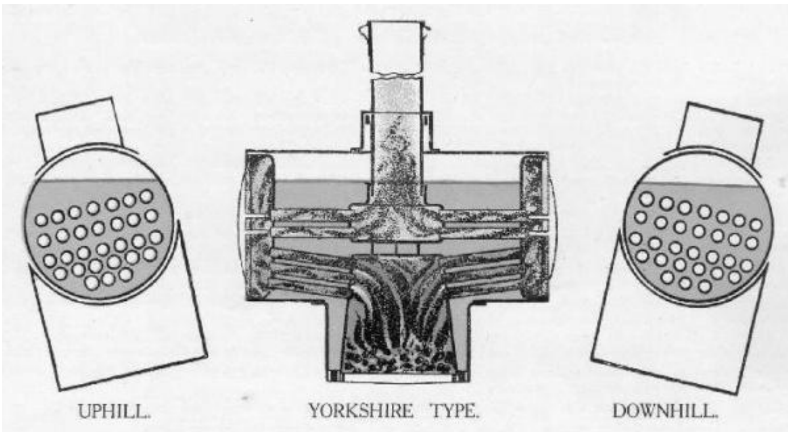


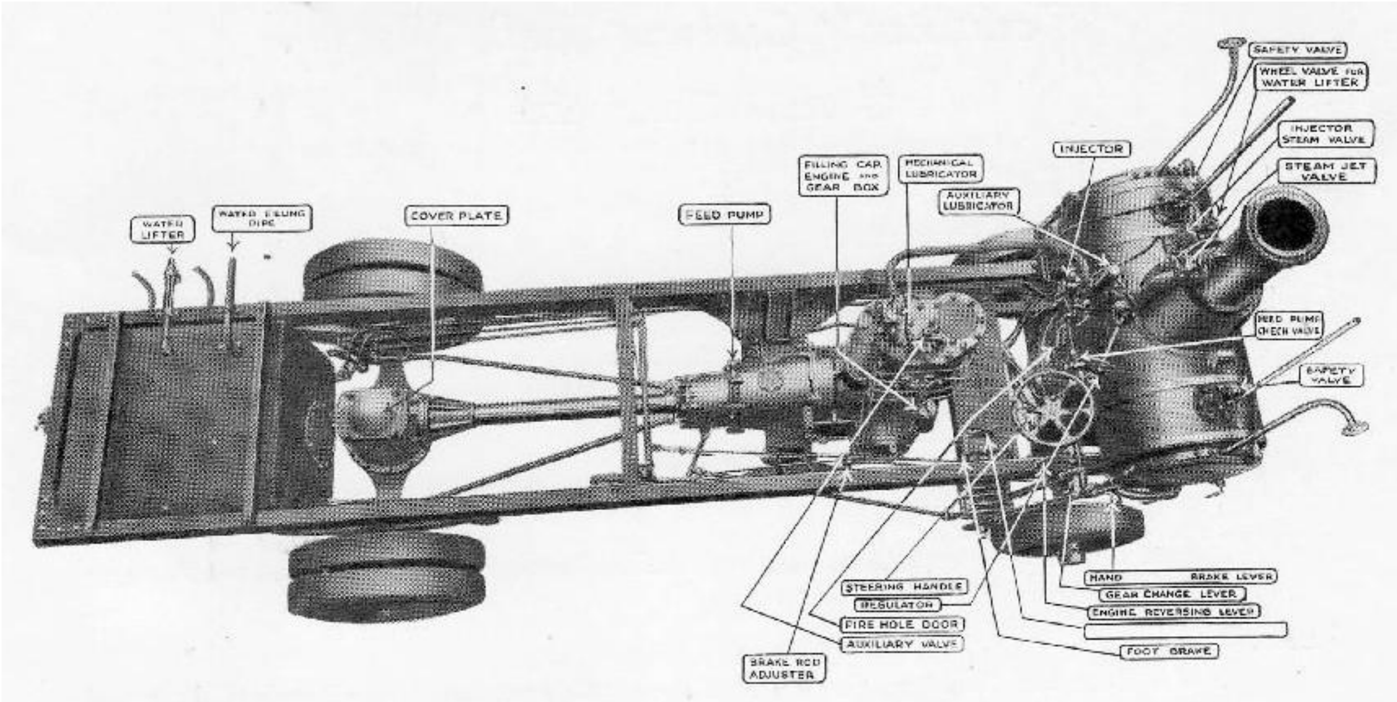
Whilst the Sentinel Steam Wagon owners have organised the Steam Trek other Steam wagons are expected to be on the Trek, and there are others that will be at the Rally but will not be on the Trek .

THE YORKSHIRE PATENT STEAM WAGON CO.

Hunslet, Leeds England

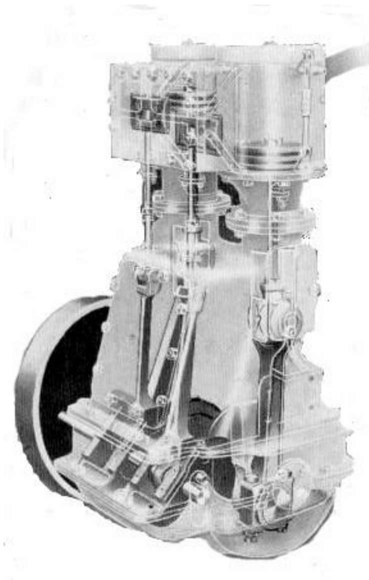
This UK company produced Steam Wagons from 1901 to 1937 during which time 1356 wagons were produced These wagons used an East-West double ended boiler with a central firebox. Early models used chain drive and later models had 2 road speeds and shaft drive.

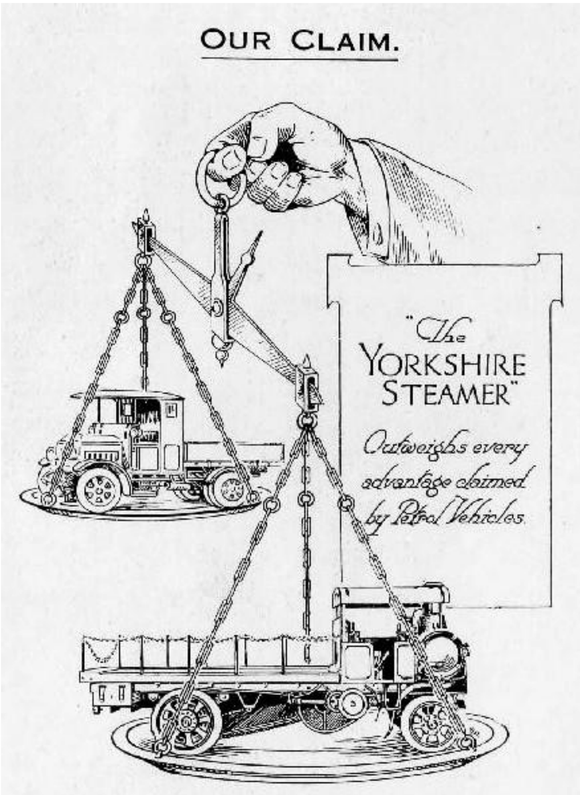




Plan View of Shaft Drive "Yorkshire" Steam Wagon.
Note Simplicity with Stability of Construction.

The above drawing shows the typical wagon layout for shaft drive models. The engine sits vertically behind the driver and fireman and the boiler is in front. Brakes are fitted to the rear axle, and the transmission (2 or 3 speed) and engine are all sealed.





The engines use reversible slide or piston valve gear, and a "simpling" valve can be used to run the compound engine as a high pressure twin, for extra power or easy starts.

The boiler is fed from a pump which is continuously driven from the transmission and an injector mounted in the cab,

On the left is the promotional claim:-

The Yorkshire Steamer

Outweighs every advantage claimed by petrol vehicles

If all goes to plan. There will be 2 "YORKIES" on the great Southern Steam Trek.

The green 6 ton Yorkshire wagon on the left is owned by Robin Gibb, as is the Super Sentinel on the right. It is a chain drive WE model and was built in 1922.

The wagon on the right belongs to Dave Mickle. This picture was taken at the Melbourne Steam Centre at their 2015 Steamfest. It is a WG model built in 1924 and has a shaft drive with 3 speed transmission and the engine is fitted with piston valves.

Fodens Ltd

Sandbach Cheshire England

Fodens produced a range of steam powered vehicles, in particular from our perspective are their traction engines and road Wagons. The Wagons were produced from 1901 to 1932, during which time 6500 were produced. The 1923 C type wagon pictured below is a regular sight at Lake Goldsmith Rallies, and it is a familiar sight on the Road between Snake Valley and the Rally Grounds where the photo on the lower left was taken. The photo on the right was taken at the Ballarat Heritage Festival.

A background story of the Wagon and the Navy Steam Club can be found in:- Goldsmith No 125 (which can be downloaded from:-

www.lakegoldsmithsteamrally.org.au under the magazine tab

The article outlines the history of the Navy Steam Club and some history of this Foden Wagon which they have had since 1969. The Steam club members all Navy personnel and are stationed at HMAS CERBERUS which is a training base at Crib Point near Hastings in Victoria. Steam is now a nostalgic memory for ships and stationary plant at Naval bases, but the Steam Club use it to advantage and present inadvertently as a high profile Public Relations team in places where a ship could never be. The Navy Steam Club can be seen at many rallies and other public events where they are a popular and well turned out team.

The photo on the left was taken when the wagon was recovered from a quarry at Emu Plains in New South Wales in 1969.

Ransomes Simms & Jefferies

Ipswich Suffolk England

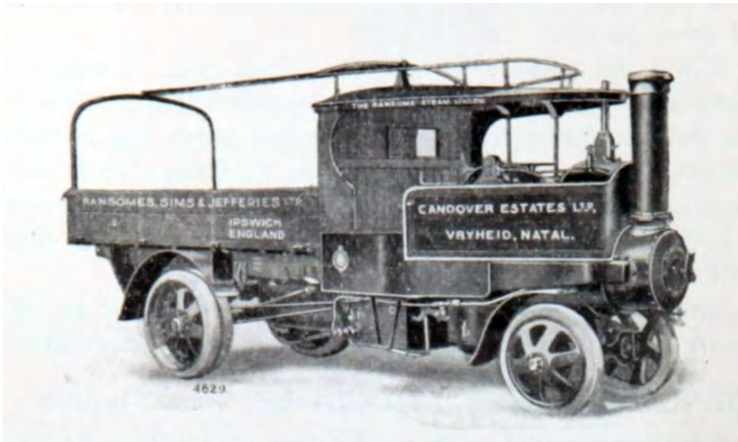


Fig. 41. Five-ton Overtype Steam Wagon by Ransomes, Sims & Jefferies Ltd.

The 1923 ex CRB Ransomes Wagon above is currently being repaired, and it is hoped that it will be ready for the Rally, and with some luck the road run. The scan on the right is from an earlier day and comes from Graces Guide where some history on Ransomes, and pictures of their early products can be found.

These wagons had an unusual "Pistol Boiler". The conventional fire tube arrangement is fitted into a boiler which I understand, is formed from 4 plates, one of which is the pressed firebox. The other plates are the smokebox tubplate, and 2 plates that are riveted together to form the outer shell. The boiler shell had a distinct curve at the bend, reminiscent of an early muzzle loading pistol.

An interesting bit of trivia is that Ransomes produced the first powered commercially available lawn mower, many of which still survive today.

Clayton & Shuttleworth
Lincoln England

This very rare 1916 5 Ton Clayton and Shuttleworth Steam Wagon is a resident of Lake Goldsmith.

It was restored by John Norris and friends over a long period and exhibited by Eric Wolverson at Lake Goldsmith Rallies.

Unfortunately the Clayton will not be in the Steam Trek. It is still fitted with its original steel wheels which keep it off the asphalt, but it will be at the Rally.

This wagon has had extensive restoration works carried out. The boiler was fitted with a new shell in 1975, and later the firebox crown sheet and tube plate were replaced. Neil Bandenoch made new drive gears, and a new body was fitted.

The wagon spent its working life near Canowndia, north of Cowra in New South Wales. The Engine is a double Crank Compound with a piston valve on the high pressure cylinder and a slide valve on the low. The transmission has 2 speeds and a chain drive to the rear axle. Only 5 are known to survive.

Again Graces Guide can help with Clayton & Shuttleworth background.

Tom Lord -Replicar

Geelong Victoria

Tom Lord has recombined a selection of vintage truck, wagon, train and tank parts to create this 21st century Steam Wagon. The boiler is from a Super Sentinel and is oil fired, the chain drive rear axle assembly is from a 1915 3 Ton Albion. The front Axle and constant mesh gearbox (3F*1R) are from a French SOMUA truck. The front wheels were track idlers from a centurion tank and the engine was from the Stoking engine on an R Class
Steam Locomotive with modifications to provide valve gearing.

Other steam vehicles are expected on the trek. The New Zealand owned Lincoln and Vasey Lady's are typical of what might be seen on the trek

'Los Chufi'

The Argentine Sentinels

Built by Sentinel in 1949-51, 100 'S6' waggons were commisioned by the Argentine Coal Board. These advanced designed waggons were to be the last ever steam road haulage from Sentinel.

Background

It was the war-time shortage of coal that prompted the new excavations. Argentina had relied heavily on Welsh coal that rapidly became unavailable as the U-boat war developed. The country experienced a serious fuel crisis, despite increased oil production and the use of wood and other 'biomass' fuels for locomotives.

Coal from Río Turbio

Located in the province of Santa Cruz, Southern Argentina. Due to its remote location, a means of transporting the coal was needed from the mines to the port on the Atlantic Coast 160 miles away. For the first few years petrol lorries were used, consuming incidentally more energy than they actually carried and often being abandoned on the road for lack of parts to repair them.

Arrival of the 'S' Type

1950 they received a fleet of 'S' type under-type (i.e. with cylinders below the frame) steam lorries from Sentinel of Shrewsbury, England. They were known colloquially as *'los chufi'*. These were the last steam lorries to be built for commercial use anywhere in the world, and one commentator suggests that the Argentine state never completed the payments for them! [1]
Under the technical supervision of a Mr.

McKay from the Falklands, they operated in convoys of 10-15 taking 12 hours for the journey to Río Gallegos[2]. They were relatively modern in design but still used a substantial proportion of their load during the 320 mile round trip and it became obvious that only a railway would do the job properly.

End of an era

The formal opening was on 25th November 1951. The railway was initially known as the Ramal Ferro Industrial Eva Perón (RFIEP or Eva Perón industrial railway line) However, after the military coup in 1955, renamed the RFIRT, or Río Turbio industrial railway line.

In preservation

One of the Sentinels is preserved at Río Turbio (now a preserved railway) and another lies at Lujan zoo near Buenos Aires. Recent reports suggest that some of them remained in use until 1959.

1. A Report by Héctor Peréz Morando in el diario Río Negro 10 April 2004.
2. Con corazón de carbón, by Sergio Garcia, a comprehensive study of the RFIRT in Todo Trenes magazine no 68, June 2009.

www.martynbane.co.uk/modernsteam/ldp/rfirt/santafes.htm
www.railwaysofthefarsouth.co.uk/09dbuildingrfirt.html
hwww.railwaysofthefarsouth.co.uk/09dbuildingrfirt.html

Picture Credits:
One of only two known photographs showing a Sentinel S6 steam waggon in action. © W.Roil - Río Gallegos (pioneer commercial photographer and historical archive).
The only remaining Río Turbio Chuffie looking somewhat battered on display at the mines museum. January 23 2004

S-Type Key Statistics

S-Type
The ‘Sentinel Waggon Works’ launched in 1933 the new shaft drive waggon known as the S-Type

265 Manufactured
From 1933 - 1938
265 S-Types were produced.

Models
S4 Payload 7 Tons (4 wheels)
S6 Payload 11 Tons (6 wheels)
S8 Payload 13 Tons (8 wheels)
3WT (Three way Tipper)

Water
Feed water tanks hold 165 gallons
will run for 40 - 60 miles

Coal
Coal bunkers hold 330 kg
will run for 150 - 180 miles
Coal consumption per mile 3 lb

Speed
On road 30 - 40mph

Boiler
Working pressure of 255psi

Engine
Four cylinder, single acting engine.
120bhp revolution
457 KG in weight
14 lb bhp per hour in steam consumption

Two Speed Gear Box
Top gear was direct.
Low gear ratio 2.72:1

Shaft
Cardan shaft 3ft drive from engine to rear axle

Brakes
Rear wheel brakes applied by hand rachet lever
or by steam controlled foot pedal
Front wheel brakes were a optional extra at the factory.

Cab
Light weight frame.
Windows fitted with ‘Safety glass’.
Throttle foot operated.
Brake Lever, Gear Change & Cam Shaft Control
Blower & Injector

ATTACHMENT 13

730218

Reviewing the California Steam Bus Project*

Roy A. Renner
California Steam Bus Project, International Research and Technology Corp.

THE PURPOSE of the California Steam Bus Project* was to demonstrate the feasibility of the external combustion engine (ECE) as a low-emission, quiet propulsion system for a city bus. Emphasis was on the early demonstration of potential, rather than extensive development or technical perfection. The inquiry was an outgrowth of hearings held by the California State Assembly in early 1968, dealing with possibilities of steam automobiles. An initial grant of research funds to the Assembly was approved in February 1969 by the Urban Mass Transportation Administration of the U.S. Dept. of Transportation. Design and development work was begun in June 1970 by three engineering contractors, each in cooperation with a California fleet operator: William M. Brobeck and Assoc., Berkeley, Calif., with the Alameda-Contra Costa Transit District (A-C) based in Oakland; Lear Motors Corp., Reno, Nev., with the San Francisco Municipal Railway (MUNI); Steam Power Systems, San Diego, Calif., with the Southern California Rapid Transit District (SCRTD) of Los Angeles.

All three contractors completed installations of power systems into standard 40 ft urban coaches (Fig. 1), and provided maintenance support during the period of engineering tests and public service demonstrations. While many other forms of ECE have been suggested (such as Stirling cycle engines) the contractors all chose Rankine cycle systems for early exploration. The program evaluation covered engineering, operational, and nontechnical aspects of the use of steam power for city buses.

Exhaust emissions were evaluated by the California Air Resources Board. Sound level measurements were conducted by the California Highway Patrol. Supporting services were also provided by the Assembly Office of Research, the State Dept. of Public Health, and the Division of Highways.

Overall project management was by the Scientific Analysis Corp. of San Francisco. The International Research and Technology Corp., Washington, D.C. provided technical management and evaluation services through a California field office. Another California firm, Instrumentation Associates of Castro Valley, assisted with instrumentation and services in road testing.

The project was completed in September 1972. It was found that the ECE can compete with diesel power for city bus propulsion in terms of road performance and system weight. Exhaust emissions are low, and are well below the levels permitted by the 1975 California Heavy Duty Vehicle

*A project sponsored by the California State Assembly with a grant of funds from the Urban Mass Transportation Administration of the U.S. Department of Transportation.

ABSTRACT

The California Steam Bus Project demonstrated the potential of low-emission, quiet external combustion engines in public transit service. Three contractors supplied and installed steam powerplants in urban buses, replacing the original diesel engines. Exhaust emissions were found to be considerably lower than the 1975 California requirements for heavy-duty vehicles. Substantial reductions in sound levels were measured in one of the buses. Powerplant weights can be lower than present diesel engines. Road performance was similar to that with diesel engines, but very high fuel consumption was experienced with these nonoptimized demonstration vehicles. Prospects for future improvements are given in this paper, including the outlook for large reductions in fuel consumption and exhaust emissions.

Fig. 1 - A 40 ft urban coach converted to steam power. (Southern California Rapid Transit District, with powerplant by Steam Power Systems, Inc. Illustration courtesy SPS, Inc.)

Standards in terms of carbon monoxide (CO), hydrocarbon (HC), and oxides of nitrogen (NO_x). The NO_x, in particular, are sharply reduced below current diesel levels. The potential for considerably quieter operation was shown, but interior noise levels proved more difficult to reduce than was the noise emitted to the outside environment. Fuel consumption at best (at the present level of development) was considerably higher than that of diesel units. Substantial improvement in fuel economy is a foreseen probability, but will require basic redesign of the power systems. Not surprisingly, many breakdowns were experienced with these early and rudimentary powerplants, but there seems no reason to believe that an acceptable level of system reliability would not be reached with future evolution. While freezing was not a problem in the California test environment, one of the contractors (Lear) exhibited a small heater that could keep a bus engine compartment warm.

The project staff has endeavored to evaluate the steam buses with an eye to the untapped potential remaining in the future. While the state-of-the-art in steam-propelled vehicles is not advanced enough to warrant immediate introduction into fleet service, the ECE has now been identified as one of the more promising candidates for the "clean engine of the future." Accordingly, guidelines were prepared for the Urban Mass Transportation Administration for possible future development.

HISTORY OF STEAM BUSES

Steam-propelled road vehicles have existed for over 200 years. The French engineer Cugnot demonstrated a 3-wheeled artillery tractor during the 1760s. Steam-powered stage coaches (the first steam buses) were operated commercially in England in the first half of the nineteenth century, although they were rapidly superceded by faster and more efficient rail conveyances.

The birth of the true automobile occurred during the 1890s. Until around 1910, many observers regarded steam power as superior for road transport. Lightweight, high-torque, and silent steam engines were invented and manufactured by the thousands. Steam cars were displaced by the gasoline-fueled internal combustion engines (ICE) when the latter evolved into forms that were cheaper, simpler, and more convenient to use.

Fig. 2 - Historical photograph of a Henschel-Doble bus operated by Suburban Railway of Bremen, Germany during late 1930s

Interest in the latent possibilities of steam was not totally forgotten, however. The work of Doble, Besler, Williams, and others (1)* in the interim years may yet prove to be forecasts rather than of historical interest only.

Returning to bus applications, the London public transit system operated some hundreds of Clarkson steam buses until 1919 (2). These vehicles were fueled by kerosene, and employed condensers for the recycling of the water.

The Doble technology (3) found its way into city buses, presaging the present California experiment. During the early 1920s, the Detroit Motor Bus Co. operated two Doble-powered buses for over 30,000 miles. These vehicles had an acceleration rate which was greater than that of contemporary gasoline buses, and with a fuel consumption which was competitive (4). In 1929, the Doble Co. installed a steam system in a General Motors Yellow Coach.

During the mid-1930s, high-grade motor fuels were in short supply in the German Third Reich. Warren Doble worked closely with the Henschel works at Kassel to introduce "Dampfomnibusse," which could burn fuel oils derived from coal. One such bus prototype is shown in Fig. 2. The direct-drive and reversible steam engine developed a rear-wheel torque which was greater at all road speeds than the competing ICE with 4-speed transmission (5).

Much more could be said about the background of steam-powered motor vehicles, but those interested may review additional referenced literature (6-9). It may suffice to state that some of the works past embodied considerable merit, and we are still relearning many of the pertinent lessons. Much engineering remains to be done before the full potential will be shown.

DESCRIPTION OF THREE POWER SYSTEMS

During this exploratory work, the three contractors were encouraged to develop their own individual design approaches.

*Numbers in parentheses designate References at end of paper.

Each contractor seriously considered or implemented more than one design, and so the project benefited from the evaluation of a rather broad set of choices. Reciprocating, rotary, and turbine expanders all reached the preliminary bench test stage. A number of working fluids other than water were examined and some were used in bench-test powerplants. Several variations of control systems, auxiliary drives, feed pumps, and burners, went on to the expensive junk pile.

The present systems have some features in common. All use water as the working fluid. All generate the steam in forced-circulation, continuous-coil tubular steam generators. Final control of the steam temperature is by the "normalizer" principle, in which supplemental feed water is injected into the superheater as required. Condensing is by fan-cooled, finned tubular radiators. As an expedient in this short-term endeavor, all three buses use commercially available multi-ratio automatic torque converter transmissions. In each case, the main expander (engine or turbine) drives auxiliaries and accessories at idle. While a variety of liquid fuels may be used, most testing was conducted with No. 1 diesel. Specific features of each system follow.

WILLIAM M. BROBECK & ASSOC. - The Brobeck system is an outgrowth of the automatic monotube steam generators and compound-expansion piston engines developed earlier by Doble and Besler (10). The steam generator and its automatic controls are mounted in the original engine compartment at the rear of the bus. As shown in Fig. 3, the other systems elements are located amidships under the floor. All accessory and auxiliary units are belt driven from pulleys on the forward end of the engine crankshaft. Condenser fans are remotely driven by hydraulic motors. The transmission is a Dana-Spicer model 184 2-speed torque converter unit, locking up into direct drive at 29 mph.

Approximately one-quarter mile of tubing is used in the steam generator, varying from 0.50 in OD in the economizer section, to 1.0 in OD in the superheater. In order to reduce pressure drop through the generator, two parallel tube paths are used in the economizer and most of the evaporation zone. These are merged into a single monotube coil in the final evaporation and superheating regions. Both tangential and axial burner firing were tried, with the former yielding better results in this generator configuration. The burner uses a single air-atomizing nozzle, with automatic switching among four steady-states: off, idle, low fire, and high fire.

The engine (expander) has three double-acting cylinders (Fig. 4). Compound expansion is utilized, with one high-pressure cylinder exhausting into two low-pressure cylinders. As an expedient for this early demonstration, a nonreversible fixed cutoff valve gear is used.

By locating the system components in existing spaces, the original seating capacity (51 passengers) was retained.

LEAR MOTORS CORP. - The Lear power system differs strikingly from the other two, in the use of a turbine as an expander. All major components are placed in the original rear compartment. It was necessary, however, to enlarge this compartment because of the shape of the steam generator and to accommodate regenerators.

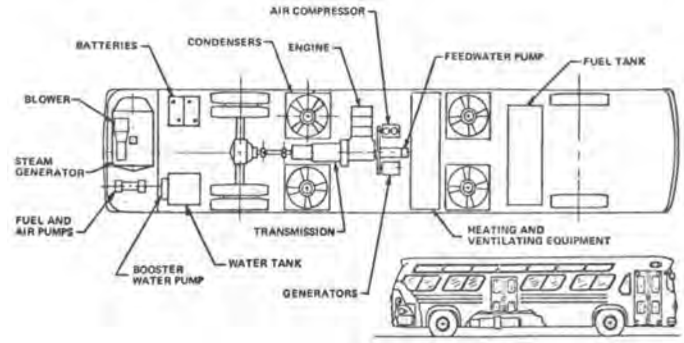


Fig. 3 - Location of powerplant components in vehicle (courtesy William M. Brobeck and Assoc.)

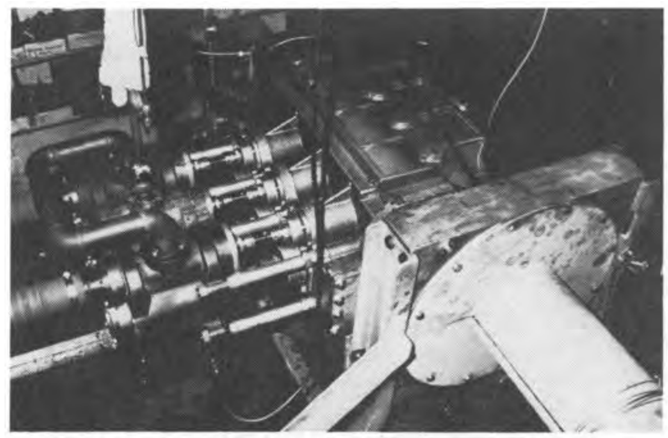


Fig. 4 - Brobeck steam engine on test stand (courtesy William M. Brobeck and Assoc.)

Lear's steam generator features a radial outflow of the hot gases through the tube bundle. During the development period, several types of burner were tried, including vaporizing mechanical atomizing, and air atomizing. An air-atomizing burner was finally adopted.

So far as is known, this vehicle is the first in history to be successfully propelled by a steam turbine. Originally, this turbine was designed to operate on an alternate working fluid having antifreeze characteristics and a molecular weight greater than that of water. During bench testing, however, it was found that this fluid deteriorated chemically at the required operating temperatures. Steam was then substituted, with redesigned turbine nozzles. The single-stage impulse turbine is very small in size (wheel diameter 5.6 in) and rotates at high speeds (to 65,000 rpm). Reduction gearing of 24:1 ratio connects the turbine, via an Allison HT-740 D 4-speed automatic transmission, to the rear axle. Most of the auxiliaries are also driven from the speed-reducing gearbox, including the feed water pump, two condenser fans, and the burner blower. The general arrangement of the powerplant is shown in Figs. 5 and 6.

STEAM POWER SYSTEMS, INC. - The SPS powerplant (11) features a 6-cyl double-acting compound-expansion engine. The steam is reheated between the two expansion stages. Steam generation is by a series-parallel tubular boiler, with an additional section for the interstage resuperheating. The

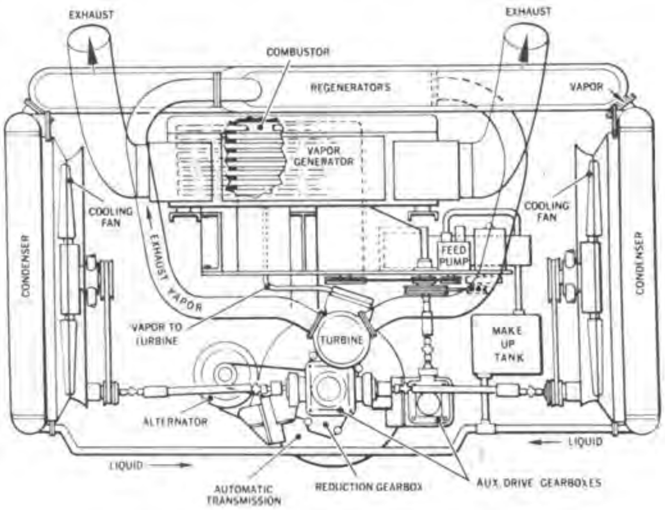


Fig. 5 - Lear component arrangement and flow diagram, as viewed from rear of bus (courtesy Lear Motors Corp.)

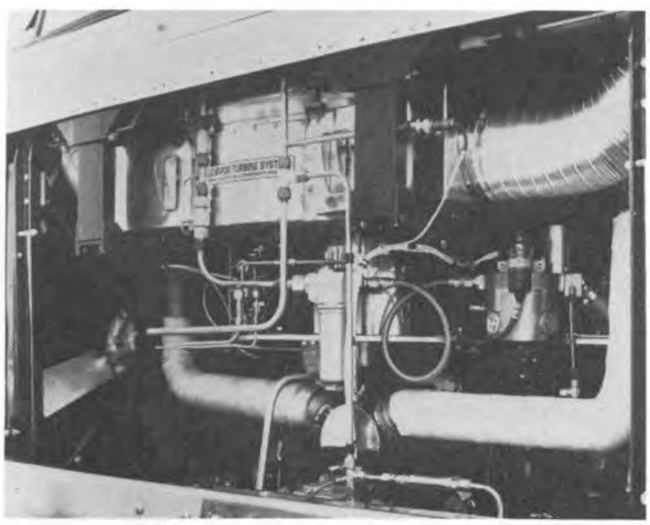


Fig. 6 - Lear vapor turbine system installed in bus (courtesy Lear Motors Corp.)

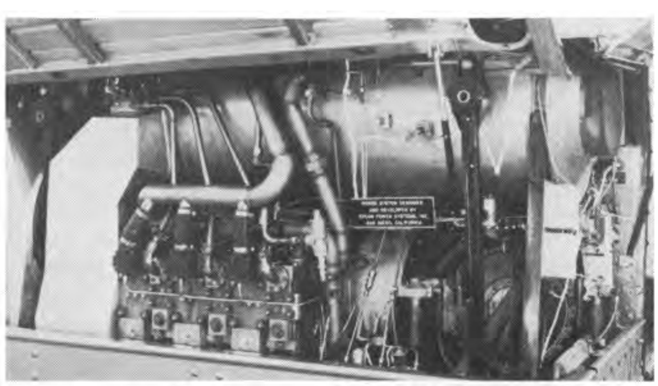


Fig. 7 - Powerplant installation by Steam Power Systems, Inc. (courtesy SPS, Inc.)

steam generator, expander, auxiliaries, and one of the condensers, are located in an enlarged rear-engine compartment. Three additional condenser cores are located under the bus, just behind the front axle. Fig. 7 shows the system installation.

Table 1 - Powerplant Specifications

	Brobeck	Lear	SPS
Expander type	Reciprocating	Turbine	Reciprocating
Max expander gross bhp	240	250*	275
Max auxiliary load, hp	40	40	50
Rated net system bhp	200	180	225
Max expander rpm	2,100	65,000	1,850
Max steam rate, lb/h	2,500	2,340	3,600*
Max fuel rate, gal/h	30	30	47*
Boiler heating surface, ft^2	180.2	275	356**
Combustion intensity, Btu/h ft^3	0.5×10^6	1.25×10^6	1.1×10^6
Condenser frontal area, ft^2	34.5	19.4	32.2
Steam pressure, psi	1,000	1,000	1,000†
Steam temperature, F	850	1,000	750†
Lowest bsfc, lb/net bhp·h	0.985	1.13	1.18
Approx. wt, lb:			
Boiler with burner	920	890	850
Expander	965	110††	1,250
Condensers with fans	750	420	800
Transmission	625	700	600
Auxiliaries	491	392	800
Other	1,026	590	400
Total system dry weight (a)	4,777	3,102	4,700

*Derated from figures shown for actual use in bus system.
**Including reheater section.
†In the SPS system, the steam leaving the reheater is 240 psi at 650-750 F.
††With gearbox.
(a)Present 6-cyl diesel powerplants weigh approximately 3800 lb, including transmission and auxiliary items.

Of the three buses, this is the only one to retain the original transmission (GM-Allison Super V) and angledrive rear axle. It is also the only bus equipped with air conditioning.

Two significant innovations were carried to the bench test phase, but were laid aside temporarily when time did not permit sufficient development to allow installation into the bus. One of these was the use of infinitely variable cutoff valve gear, and the other was the elimination of oil lubricants in the steam cylinder. The first of these allowed engine speed control without a throttling valve and would be conducive to high-thermal efficiency. The second would avoid the old problem of oil carry-over into the condenser and boiler.

TABULATION OF SPECIFICATIONS - The specifications of the three powerplants are compared in Table 1. Because configurations changed many times during the project's history, values given may differ from those reported in earlier publications.

EVALUATION OF RESULTS

The technical results of this program are interesting because they represent an early point of departure, upon which future improvements may be based.

Table 2 - Urban Bus Road Performance

	Diesel, GM 6V-71*	Diesel, GM 8V-71**	Diesel, Cummins 903 V8†	Steam, Brobeck	Steam, Lear	Steam, SPS††
Gvw as tested, lb	25,320	26,860	28,000	30,580	28,470	30,900
Top speed, mph	52	65(a)	70+(a)	56	54	58(a)
Acceleration, s:						
0-10 mph	4.0	3.0	3.7	3.0	5.0	5.0
0-30 mph	18	12	19	20	22	25
0-50 mph	57	33	46	62	74	71
Gradeability	16% at 3 mph	19% at 7 mph (b)	16% at 8 mph	18% at 2 mph	20% at 2 mph	N.A.

*N-55 injectors.
**N-60 injectors.
†Derated engine.
††Steam temperatures were too low for best power output.
(a)Overdrive transmission used.
(b)35,000 lb gvw overload test.

CUMULATIVE EXPERIENCE - Many hours of bench testing of the systems served a primary purpose of "debugging," rework, and adjustments prior to installation. Another valuable contribution was the practical education of a cadre of engineers and technicians in relating theory to design.

Approximately 8372 miles of road testing and public service were accumulated under steam power during this program. The longest single trip was by the Lear bus, 235 miles from San Francisco to Reno.

ROAD PERFORMANCE - The road performance of the steam-powered buses was similar to buses powered by 6-cyl diesel engines. Obviously, the performance of such systems could be scaled upward or downward if desired. In actual passenger-carrying service, the steam buses could usually duplicate, to the minute, the time schedules achieved by diesel power.

Because torque-converter transmissions were used, not much advantage could be taken of the very favorable torque rise, and high-stall torques, and potential retarding effort inherent in steam engines.

Road performance data of steam versus diesel buses are summarized in Table 2.

EMISSIONS - Several tests were made of the exhaust emissions of diesel versus steam buses by the California Air Resources Board. Table 3 is a summary of the results which confirm that the external combustion engine (ECE) can produce very low exhaust emissions even under the handicap of significantly higher fuel rates. All steam buses easily met the 1975 California Heavy Duty Vehicle Standards. These standards limit CO emissions to 25 g/engine bhp·h and combined HCs and NO_x to 5 g/bhp·h. Of special interest is the fact that the cleanest steam system emitted only 6% NO_x as the cleanest diesel tested. It should be emphasized that the diesel emission test results are based on a random sampling from well-maintained fleets, and may or may not be "typical" of diesel engines generally.

The Air Resources Board used test procedures which will accompany the 1973 and 1975 California standards for heavy-duty vehicles (12, 13). Testing was done with a chassis dynamometer, with emissions sampled during 13 separate steady-state modes of speed and load, including idle. While road-load transients are not included during sampling in this procedure, any transients due to boiler and burner response to hold the given road loads are integrated into the results.

All emissions tests, as well as most of the experimental bus operation, were made with No. 1 diesel fuel. With proper

Table 3 - Exhaust Emissions of Steam and Diesel Buses*, Figures in Grams per Engine bhp·h

	CO	HC	NO_2**	HC + NO_2
Steam buses				
Brobeck (test 10-71)	2.0	1.2	1.2	2.4
Brobeck (5-72)	1.6	0.8	0.5	1.3
Lear (9-72)	7.9	1.1	1.6	2.7
Lear (9-72)†	5.6	0.2	1.6	1.8
SPS (5-72)	2.7	1.6	1.5	3.1
SPS (8-72)	4.4	0.6	4.2	4.8
Avg. steam	4.0	0.9	1.8	2.7
Diesel buses††				
A-C #678 (GM 6V-71)	4.4	2.5	9.0	11.5
STA #408 (GM 6V-71)	2.6	1.5	13.9	15.4
MUNI #3141 (GM8V-71)	7.9	0.9	8.4	9.3
SCRTD #7185 (CUM. 903)	2.3	0.5	10.2	10.7
Avg. diesel	4.3	1.4	10.4	11.8
California Heavy Duty Standards				
1973	40	–	–	16
1975	25	–	–	5

*All tests were performed by the California Air Resources Board.
**NO_x was measured as nitric oxide (NO) and expressed as equivalent NO_2.
†The second Lear test was a composite of two tests, with an improved (but not optimized) idle setting between tests.
††Diesel results are from a very limited sampling of well-maintained vehicles, and may not be representative or typical of diesel engines in general service. Bus designated "STA" was loaned by Sacramento Transit Authority.

Table 4 - Exterior Sound Levels of Steam and Diesel Buses

	Steam Buses			Diesel Buses			
	Brobeck	Lear	SPS	A-C #678, GM6V-71	STA #408, GM6V-71	MUNI #3309, GM8V-71	SCRTD #7185, Cum. 903
Full-throttle drive-by, microphone at 50 ft	76	85	80.5	78.5	84	86	82
Full-throttle standing start, microphone at 15 ft	74	88	86	88	89	90	94.5
Idle, microphone at 15 ft	68.5	78	78	75.5	78	74.5	75.5

NOTE:
All figures are maximum sound-pressure levels in dB re 0.0002 microbar, "A" weighted scale.
All measurements by California Highway Patrol.
Microphone was placed alongside the roadway, with distances measured from the centerline of path of travel.

Table 5 - Interior Sound Levels of Steam and Diesel Buses

	Steam Buses			Diesel Buses			
	Brobeck	Lear	SPS	A-C #678, GM6V-71	STA #408, GM6V-71	MUNI #3309, GM8V-71	SCRTD #7185, Cum. 903
Full throttle acceleration, just prior to up-shift							
Front	75	74.5	76	75	75	79	73.5
Center	81	81	79	78	79	84	79
Rear	78	84	83	85	84	87.5	82
At idle							
Front	62	63	60	62	63	64	60
Center	67	65	66	68	67	66	65
Rear	66	71	72	72	68	72	69

NOTE:
All figures are maximum sound-pressure levels in dB re 0.0002 microbar, "A" weighted scale.
All measurements by California Highway Patrol.
Microphone positions were along the centerline of the aisle, midway between the floor and ceiling of coach.

adjustment, combustion is virtually smokeless. However, with improper control settings, puffs of exhaust smoke were sometimes observed during load changes. Light odors reminiscent of gas turbine or jet engine exhaust were sometimes noted.

NOISE - The California Highway Patrol made surveys of the sound levels both inside the buses and in the near-field outside environment. The following tests were made:

1. Drive-by, full-throttle tests. A microphone was placed 50 ft from the center of the roadway lane, in accordance with SAE Recommended Practice J366a. As the bus approached the microphone position, it was accelerated at full throttle within a speed range 20-35 mph. Sound levels were measured in both directions of travel.

2. Standing starts. With a microphone placed 15 ft from the center of the lane, sound levels were taken first at engine idle and then under full-throttle acceleration from a standing start. This procedure approximates the perception of a bystander near a bus stop.

3. Interior noise. Sound levels were taken along the centerline of the aisle, at the front, center, and rear of the bus.

Test results are summarized in Tables 4 and 5.

The quietest steam bus was 2.5-10 dB quieter than diesel buses during the 50 ft drive-by tests. Moreover, the quietest steam bus in the 15 ft tests (simulating curb side) was 6-14 dB quieter than the quietest diesel tested. On the other hand, interior sound levels were similar or higher than diesel in several cases. It appears that interior sound levels may be influenced as much by the construction of the bus as by the character of the powerplant.

The Lear system emitted a high-frequency sound characteristic of turbines. It is believed that the transmitted and radiated sound levels of this vehicle, now higher than diesel, can be reduced by techniques that have proved successful in gas turbine practice.

FUEL CONSUMPTION

The demonstration buses, in the present state of limited development, have a very high fuel consumption. The highest cruise fuel mileage of the Brobeck steam bus was 3.5 mpg at 40 mph. Under the same test conditions, a diesel bus can do at least 8-10 mpg. Under actual stop-and-go route conditions,

Table 6 - Fuel Consumption of Steam and Diesel Buses, gvw 25,000-30,000 lb

	Brobeck	Lear	SPS	GM 6V-71	GM 8V-71	Cummins 903 V8
Cruise fuel mileage, mpg						
20 mph	2.4	1.8	2.2	–	4.7	7.7
30 mph	3.5	2.2	2.3	10.2	7.1	11.8
40 mph	3.0	2.3	2.9	–	8.1	10.3
45 mph	–	–	–	8.9	–	–
50 mph	2.5	2.1	2.5	–	7.1	8.8
60 mph	–	–	–	–	–	7.5
Idle fuel consumption, gal/h	4.5	3.2	4.7	0.5	0.65	0.62
Examples of route fuel mileages, mpg						
A-C #58, local	1.1	–	–	3.58	–	–
MUNI #32, local	–	0.7	–	–	3.68	–
SCRTD #83, local	–	–	0.6	–	–	3.02

steam at 0.5-1 mpg was noted against the diesel at 2.3-3.7 mpg. (More characteristics of such routes will be discussed later.) The idle fuel consumption was 3.2-4.7 gal/h for steam, versus 0.5-0.7 gal/h diesel.

Table 6 gives some of the comparative statistics on fuel consumption.

These three steam systems did not achieve specific fuel consumption (sfc) as low as demonstrated possible during the Doble-Besler era. In the present project, bench tests yielded sfc exceeding 1.0 lb/net bhp·h. Ref. 1 cites a bsfc of 0.81 attained by a Doble engine in 1936, presumably based on gross expander output (0.93 possible, if on the basis of net system output). The many reasons for the present excessive fuel rates, and the hope for considerable future improvement, will be given in a later section.

OPERATING CHARACTERISTICS

Driver controls on all buses were arranged to be similar or identical to the original diesel buses. These included foot throttle, air brake treadle, and forward-neutral-reverse selector lever. In addition to the original panel of instruments, a tachometer and a steam-pressure gage were included, together with indicator lights signifying powerplant conditions or incipient problems.

All fire-up procedures were controlled from the driver's seat. Sufficient steam to start the expander can be raised within a minute from a cold switch-on. Careful warmup of the expander is then needed in the case of the reciprocating designs, and this can require an additional 2-5 min. The Lear turbine may be started just as soon as steam is available. All three systems must be driven a few blocks before the entire system is up to temperature and maximum power becomes available. Once the powerplant is hot, it may be restarted within a matter of seconds, even after a lapse of up to 1/2 h.

While all three power systems employed condensers for the recovery of water, none were completely sealed systems. By means of relief valves, excess steam exhaust could be relieved under overload conditions on a hot day. The buses have adequately sized condensers and sufficient fan horsepower, which should have provided a touring range at least equal to a normal day's operation. In practice, however, all the steam buses sometimes fell short of this goal. Earlier in the program, the Brobeck system suffered insufficient water recovery, due to the confined space in which the condensers were mounted. Later, however, the mounting configuration was changed and another condenser core was added, appreciably adding to the water mileage.

The waste heat release from a Rankine-cycle powerplant is appreciably greater than that of ICE. Therefore, much consideration had to be given to directing the heat flow away from the passenger compartment and from bystanders. In the future, much thought will no doubt be given to placing condensers on the rooftop of the vehicle, with both comfort and unimpeded airflow in mind.

SAFETY

Complete operational safety was a firm requirement in this demonstration project. Careful surveillance and control were exercised during all phases, and included design reviews, laboratory proof-testing, and frequent in-service inspections. The following areas of concern and criteria applied:

1. Working fluids which were toxic, flammable, or explosive were not permitted in this program.
2. The steam generators were required to be of inherently nonexplosive designs.
3. Several safety limiting devices were used, such as pressure and temperature limit switches in the automatic steam generator control circuits. Safety valves were also used.
4. Limiting governors were applied to prevent accidental expander overspeed.
5. Flame sensors were installed to stop fuel flow in the event of ignition failure.
6. Driver's controls were simplified and made as similar as possible to those of a standard diesel bus.

Concern is sometimes expressed regarding the possibility of "boiler explosions." In this project, large, pressurized vessels were not permitted as steam-generating apparatus. Hence, a sudden explosive release of the boiler's energy content is not possible with the designs adopted for these buses. A relatively small amount of steam and water is confined to a long, coiled length of tubing (Fig. 8). On a number of occasions, tube failures did occur on the experimental steam generators. These occurrences proved to be inconveniences, rather than presenting a hazard. Because of the large exhaust duct, steam from a tube failure would vent harmlessly to the atmosphere.

Overall, with good design practice and careful workmanship, the potential hazard level of these systems was judged to be similar to that of gas turbines, in which large quantities of fuel are burned in combustors outside of the "engine block."

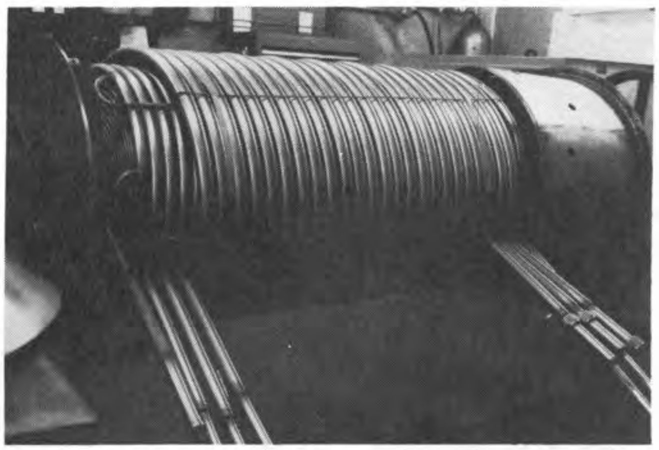


Fig. 8 - Interior view of a steam generator built by Steam Power Systems, Inc. Hot gases, produced in combustion chamber on right, pass through tube bundle. Tubing extensions shown are temporary, for hydrostatic proof testing (courtesy SPS, Inc.)

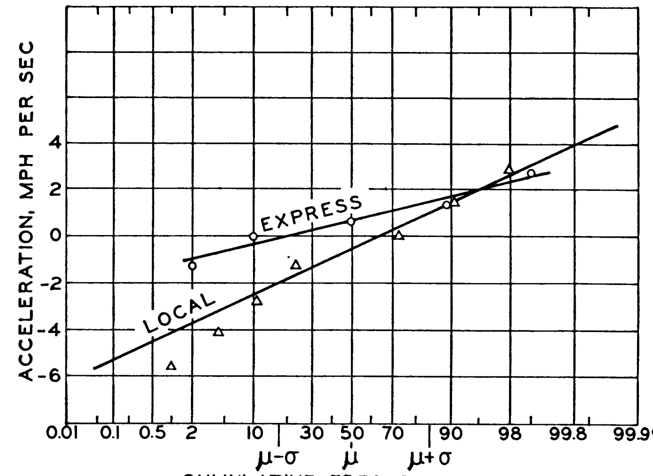


Fig. 9 - Statistical distribution of vehicular acceleration. Routes for Figs. 9-12 were A-C Transit No. 58 (local) and No. R-F (express)

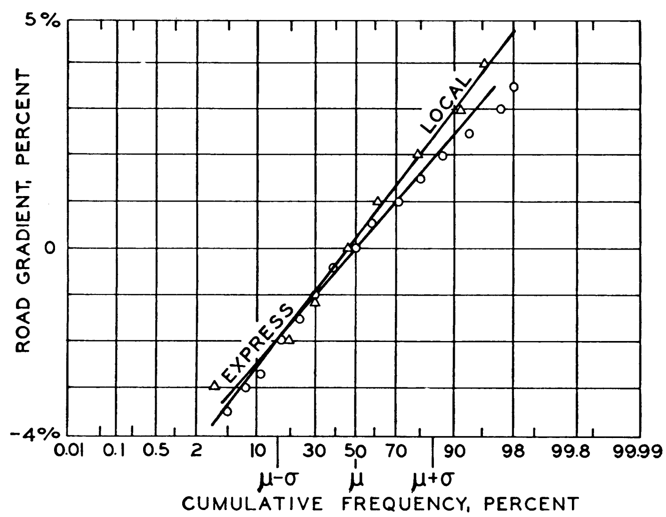


Fig. 10 - Statistical distribution of road gradient

CONTEXT: URBAN DRIVING CYCLES

When a designer contemplates an unorthodox powerplant for a vehicle, some rather fundamental questions need to be answered. What are the average, maximum, and instantaneous values of power required over a driving cycle? How much time is spent at idle and at low power levels? What are the route profiles in terms of road gradients, speed, and accelerations? These and other characteristics must be understood in order to compile a reasonable set of objectives and specifications. Specifications for a new diesel bus can become almost a routine extrapolation based on recent experience; however, more study and analysis is desirable when the proposed powerplant is relatively unfamiliar. This is particularly true when the visualized power system has a substantial overload capacity, or if it can draw from a reserve of energy storage. A possible consideration with some future powerplants would be the conservation of some of the energy normally dissipated by the brakes.

During the course of this project, diesel- and steam-powered buses were fitted with portable instrumentation for measuring and recording a number of vehicular and route characteristics. Actual bus routes (or segments of routes) were experimentally driven with a constant ballast payload of 4500 lb (representing a partial load of 30 passengers). Simulated passenger stops were made at locations and for the durations observed during previous surveys of passenger-carrying runs. The driver made other stops as dictated by traffic conditions. After each driving cycle test, the portable recording instrument was removed from the bus, and data were fed into a computer. A detailed sequential record, in the form of a computer printout, described characteristics of the route and what the bus did in coping with conditions along the route.*

Information on the printouts included these measured or computed values for each route tested: distance traveled, velocity, acceleration, road gradient, road horsepower, engine rpm, totalized propulsive energy, totalized braking energy, fuel consumption, interior sound level, and powerplant variables, such as pressure, temperatures, etc.

The data were also analyzed by statistical methods, for convenient assessment. Sample results are summarized in Figs. 9-12, for two contrasting types of route. The scale of such graphs has been contrived such that a straight-line fit to the data represents a Gaussian normal distribution. The assumption that such statistics as acceleration, road gradient, and horsepower requirements may be approximated by a Gaussian distribution appears well founded. Velocity, too, can be characterized as a Gaussian normal distribution, but only after transformation to log-squared velocity.

An overview of some of the characteristics of several of the routes tested is given in Table 7. It is interesting to observe, for local routes, the low average speeds, the rather low average power requirement (but with a capacity for high peak power being needed occasionally), and the high fraction of propelling energy that is ultimately dissipated in braking

*Two papers (14, 15) give the rationale and procedures used in determining the properties of vehicular driving cycles.

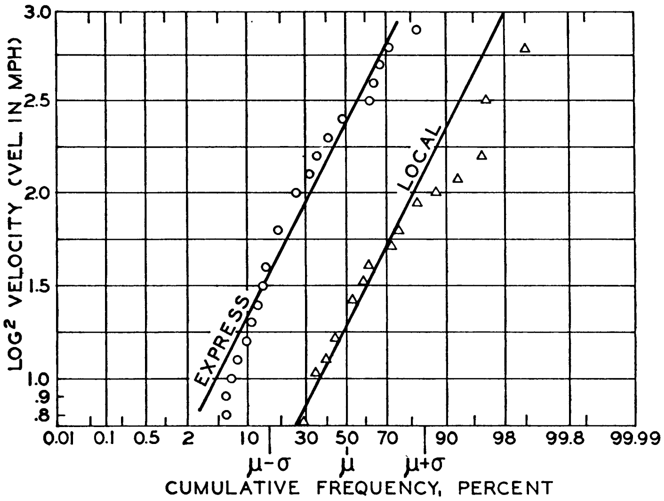


Fig. 11 - Statistical distribution of vehicular velocity, plotted as $\log^2 V$

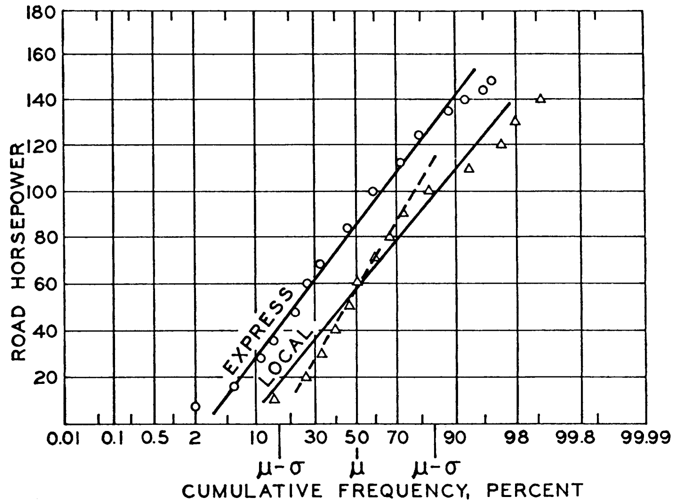


Fig. 12 - Statistical distribution of road horsepower. Dashed line is an optional fit over mid-range of local route data

Table 7 - Characteristics of Urban and Suburban Bus Driving Cycles

	Local, A-C 58	Express, A-C R-F	Local, MUNI 32	Local, MUNI 55	Local, SCRTD 83	Express, SCRTD 60-E
Average speed, mph	10.3	31.2	11.7	9.7	8.5	38.0
Stops per mile	7.1	0.64	4.6	10.2	9.1	0.6
Percent of time at idle	32	7	28	34	42	11
Max upgrade, %	6.1	8.8	8.4	19.3	6.9	8.7
Max downgrade, %	5.3	5.9	11.1	16.2	4.7	5.6
Max hp to rear wheels	138	169	181	210	166	213
Avg hp to rear wheels	24.3	58.7	22.4	42.4	25.9	78.8
Total energy delivered to wheels, hp·h	30.6	55.8	14.2	38.1	29.8	65.7
Energy dissipated by brakes and retarding, hp·h	15.7	11.1	4.1	20.9	13.7	7.8
Fuel mileage with diesel, mpg	3.58	6.15	3.68	2.28	3.02	6.50
Fuel mileage with steam, mpg	1.11	2.05	0.7	0.52	0.6	–

NOTE:
Figures are as tested with diesel coaches, except for comparative steam mpg.
Engines were: A-C, GM 6V-71; MUNI, GM 8V-71; SCRTD, Cummins 903 V8.

(up to 55%). The substantial fraction of the time spent at idle is also worth noting.

Realistic driving cycle data can be extremely useful in many ways:

1. As an aid to writing future powerplant specifications.
2. As background information in powerplant design.
3. Bus duty cycles may now be reproduced in the engine test laboratory. Moreover, power system properties may be simulated by computer for optimization studies.
4. Emissions under road conditions may be calculated, for instance, on the basis of grams per vehicle mission or grams per passenger mile.
5. The benefits of recovery of braking energy may be assessed.

SUMMARY OF PRESENT STATUS

Vehicles developed under this project matched expectations for road performance. It has been demonstrated that steam-powered buses can meet local route schedules to the minute. Acceleration, top speed, and hill climbing have been shown to approximate that of 6-cyl diesel buses. Powerplant output could be scaled to equal 8-cyl diesels, if desired. Exhaust emissions are very low, and comfortably meet the 1975 California Heavy Duty Vehicle Standards. Reductions in NO_X are particularly remarkable, with a sixteenfold reduction over the tested diesels having been observed in the cleanest steam bus. Some of the tests indicated that the ECE can provide greater quietness and smoothness under all operating conditions when compared to diesel power, although interior sound levels are difficult to reduce.

Two out of the three power systems were heavier than conventional diesel systems, and one (Lear) was lighter. All three occupied more space than the ICE. Because the several elements could be separately located, however, it was shown that passenger space need not be diminished (Brobeck).

Familiar and conventional driver's controls were used, so the need for special driver instruction was minimized. Special knowledge was required, however, for the powerplant maintenance. All three buses were used in revenue passenger service, and were demonstrated to be satisfactory in terms of operational safety and passenger comfort. The SPS bus includes air conditioning, effectively driven by shaft power taken from the main expander.

It should be remembered, however, that these converted buses were only intended for use in early demonstrations of potential. They are not preproduction prototypes, for much engineering development would be required before such power systems could measure up to the standards of the transit industry in terms of packaging, reliability, and operating economy.

The fuel economy of the present steam buses is poor when compared to the diesel power, though the discrepancy is not as great if compared with other fledgling systems such as the gas turbine and the spark-ignition engine fueled with natural gas (16, 17). Much can be done to improve fuel economy in the ECE, and this subject will be touched upon in the next section of this paper.

As with any new experimental devices, a great deal of inspection, rework, and maintenance was necessary in the field demonstrations of these vehicles. This led some observers to believe that steam engines would always require a great deal of maintenance, but such a conclusion is certainly not warranted at this early date.

At the present time, all three buses have been retired from active passenger-carrying service, and are being used as experimental test beds by the contractors.

FUTURE POSSIBILITIES

GENERAL OUTLOOK - With the ECE, the problem of air pollution control can be attacked at its roots, namely the physics and chemistry of the combustion process. It may not be an exaggeration to state that a well-perfected ECE would have the potential of being as clean as a fuel-burning engine ever can be. The Rankine-cycle ECE, with its possibilities for a smooth, quiet application of high-torque propelling energy, seems an excellent candidate for the urban vehicle operating under stop-and-go conditions.

Some years of progressive, persistent, and coherent engineering work will be required, however, before the ECE is ready for general application and acceptance. Obvious areas for improvement include those of fuel economy, operating reliability, packaging, combustor technology, automatic controls, and improved transmissions. Winterizing mobile steam powerplants is another important subject, though this would not be as difficult a problem in fleet operations as it would be with privately owned automobiles.

At the same time, much research needs to be carried forward if the appropriate lubricants, metallurgy, working fluids, and control components are to be ready for the ECE of the future.

AN IMPORTANT VIEWPOINT - While reducing fuel consumption may be singled out as a goal of high priority, the subject is important for reasons beyond its impact upon operation costs*. A great many characteristics would be improved if the ECE system thermal efficiency were raised. Some examples are:

1. Specific emissions (grams of pollutant per hp·h) would be decreased even further.
2. Lower steam consumption would reduce the size and weight of the boiler and condenser.
3. When the condenser load is reduced, condenser fan power requirements go down. The resultant parasitic power requirement then reflects back as a further improvement in overall system thermal efficiency.
4. Reduced fan power also means an even quieter powerplant.
5. Environmental heat pollution would be diminished.

Because of these and other crucial interactions, it would seem imperative to examine the ways in which fuel consumption can be reduced. If one can be convinced that fuel consumption can be brought into line, then there is an even greater justification in continuing development work on Rankine-cycle systems.

RANKINE-CYCLE THERMAL EFFICIENCY - Questions regarding the fuel economy of any power system may be analyzed in terms of the system's thermal efficiency. If a power system were placed on a bench test, the overall thermal efficiency could be determined using the following relationship:

$$E_{th} = \frac{\text{Actual net output power}}{\text{Rate of fuel energy input}} \qquad (1)$$

E_{th} is obviously always lower in value than the efficiency of the ideal thermodynamic cycle, E_i, since the ideal cycle does not take into account friction, parasitic accessory loads, miscellaneous heat losses, and the like. Values of E_i for an arbitrary example of a Rankine cycle have been calculated and plotted on the upper curve of Fig. 13. These values are seen to increase when temperature of the feed steam is increased. (The calculations were based upon steam at an initial pressure of 1000 psi, expanded to 20 times initial volume in an ideal expander, and then returned to the boiler as condensed water at 200 F.)

Thermal efficiencies that can be realized in practice are shown in the shaded region of Fig. 13. For example, if steam at 800 F were used, the ideal cycle efficiency would be

*Fuel costs are only about 3% of the total annual costs of urban transportation systems. Maintenance costs are around 15%.

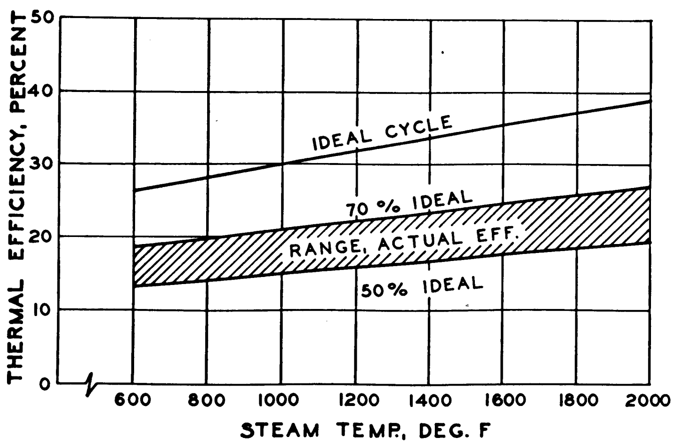


Fig. 13 - Range of ideal and actual Rankine cycle thermal efficiencies, as influenced by steam temperature

around 28%, but E_{th} of an actual system would be in the range of 14-20%.

Bench tests of the three nonoptimized bus systems showed full-load sfc of 0.985-1.18 lb fuel/net bhp·h, which corresponds to E_{th} = 11.7 - 14%. These values fall somewhat below the E_{th} range given in Fig. 13. This is partly because the ideal cycle efficiencies were less than those shown in the figure, but mostly because of incomplete expansion and very high parasitic loads.

When installed in the vehicles, E_{th} suffered even further. At high loads in the buses, exhaust (condenser) pressures rose, while at lower loads, parasitic effects took a proportionately higher toll. As installed, the systems could be characterized as E_i = 25%, and E_{th} = 10%, approximately. As presently will be discussed, many potential opportunities exist to greatly improve upon this state of affairs.

VEHICULAR EFFICIENCY AND FUEL ECONOMY - What really matters is the overall vehicular thermal efficiency, E_v, in terms of power actually delivered to the rear wheels. Fuel economy, in mpg, is determined primarily by the powerplant efficiency, E_{th}, multiplied by the power transmission efficiency, E_t. Values for E_t can vary from zero (a hydraulic torque converter at stall) to numbers approaching 90% (losses would be in gears, bearings, universal joints, etc.) If (as an estimate) the mean transmission efficiency in stop-and-go service were 60%, and the powerplant E_{th} were 10%, the overall E_v would only be 6%.

Another factor influencing route fuel economy is the idle fuel rate of the powerplant. We have seen from the route-cycle testing that up to one-third to one-half of the route time may be at idle.

OPPORTUNITIES TO IMPROVE FUEL ECONOMY - Having identified the causes of low efficiencies in the present steam vehicles, it should be possible to make substantial improvements in fuel economy in the near future. Fruitful areas for engineering development include:

1. Raising the ideal cycle efficiency (E_i). Obvious improvements can be made by increasing the temperatures of the steam or other working fluid. This route has been followed in gas turbines, with working fluid temperatures raised from 1500 to 2000 F in 15-20 years development (18, 19). Alternatives to simple Rankine cycles can also help, such as the use of reheat, regeneration, and binary vapor concepts. As-installed values of E_i can be increased from the present 25% to 30% in the near term, and 32-35% or more eventually.

2. Approaching the ideal more closely. Present actual thermal efficiencies are as low as 40% of the ideal. Sixty percent of E_i may be attainable in the near term, maybe 70% eventually. Major gains can be made in reducing parasitic auxiliary loads and by increasing expansion efficiencies. Smaller, but worthwhile, advances can be made in reducing boiler heat losses and mechanical friction. One example, for the reduction of powerplant auxiliary load, is the possible improvement in condenser fans. Over 30 hp is presently used to drive such fans in some of the installations. By the use of more efficient fans and fan drives, this can be reduced to 10-15 hp. It would also be possible, as in later Doble developments, to use exhaust blow-down turbines to drive condenser fans (3). This would not only reduce the consumption of premium shaft power even further, but would convert additional heat to productive work.

3. Reducing transmission losses. Heavy losses were suffered with the transmissions used in the present program, because available units were a poor match to expander characteristics. In the case of reciprocating steam engines, a direct drive (or at least to eliminate the hydraulic torque converter) would increase vehicular thermal efficiency appreciably. Transmission improvements are also possible for turbine expanders, which would allow the turbine to operate more of the time at peak efficiency.

4. Reducing idling fuel consumption. The use of a small auxiliary expander could reduce the idling fuel consumption to one third the present idle fuel rate.

5. Integrating energy services. Functions such as air conditioning and vehicular retarding could be integrated into the power system in ways conducive to energy conservation.

Some of the possibilities for improving the fuel economy of ECE-powered vehicles are given in Table 8.

POSSIBLE TRENDS IN REDUCING EMISSIONS - Even though the emissions demonstrated in this program were acceptably low, further reductions can be obtained by:

1. Reducing the amount of pollutants generated per pound of fuel burned (cleaner combustion).

2. Reducing, in turn, the amount of fuel burned per hp·h of work produced.

The burners produced in this early program were designed and built without the benefit of extensive combustion research. Meanwhile, a new body of pertinent research information is becoming available through contracts sponsored by the Advanced Automotive Power Systems (AAPS) program of the Environmental Protection Agency (20). One of the contractors has, in steady-state burner tests, demonstrated

Table 8 - Growth Potential for Efficiency and Fuel Economy of Steam Propulsion Systems for Buses, Compared with Present Diesel

	Steam, Present	Steam, Near Future	Steam, Eventual	Diesel, Present
Ideal cycle efficiency	0.25	0.30	0.35	–
System net thermal efficiency	0.10	0.15*	0.21*	0.30
System bsfc, lb/bhp·h**	1.38	0.92	0.66	0.46
Transmission efficiency, example	0.60†	0.85††	0.85††	0.60†
Vehicular thermal efficiency	0.06	0.13	0.18	0.18
Idle fuel rate, gal/h	4.5	1.5(a)	1.0(a)	0.5
Calculated fuel mileage, mpg, hypothetical local bus route (b)	1.0	2.3	3.3	3.5

*Sixty-seventy percent of ideal cycle efficiency may be attainable under test conditions in the near-term and eventual configurations, respectively. However, in vehicular applications, off-peak conditions will occur during some fraction of the operating time for either variable cutoff or turbine expanders. Therefore, the values of these modifiers have been reduced to an assumed mean of 50% and 60%, respectively.

**As-installed operating conditions.

†Assumed mean E_t with torque converter operating at high slip a substantial fraction of the time.

††Direct-geared drive assumed, or high-efficiency transmission developed for turbine.

(a)Separate small expander maintains only essential idle load.

(b)One local route tested required 2.4 hp·h of propulsive energy per mile, and had 2 min of idle time per mile.

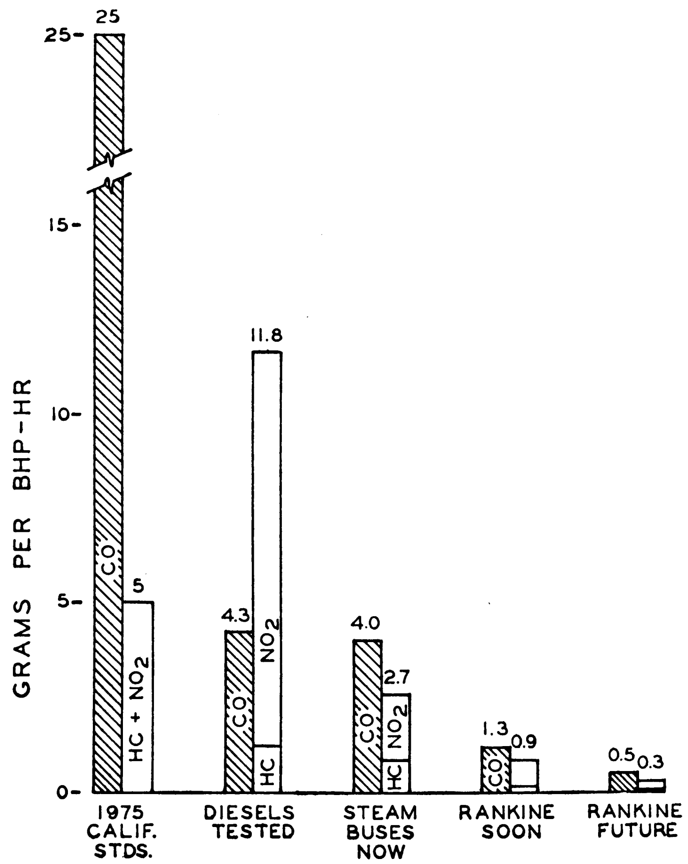


Fig. 14 - Exhaust emissions compared, together with future projections

less than one-fourth of the CO, one-tenth the HC, and one-third the NO_x found in some of the better steam bus test runs (on the basis of grams pollutant per unit mass of fuel burned). To be conservative in extrapolation, it might be expected that at least half of these indicated reductions could be obtained in the form of a system developed in the near future. The full reductions certainly ought to be feasible eventually in heavy-duty vehicle engines employing the Rankine cycle.

From Table 8, the projected bsfc can probably be reduced to 67% of present levels with near-term development, and to 48% eventually. Combining the effects of cleaner combustion and reduced fuel consumption, then, we may expect future reductions, as depicted in Fig. 14.

PROGRESS IN PACKAGING - Much was learned from the recent installations in regard to packaging, even though the work was conducted on the basis of ad hoc retrofit. It was found, for example, that the Rankine system offers considerable flexibility in the placement of the major elements in the chassis. While the total volume occupied by the ECE will probably always be greater than the space occupied by the present diesels, it has been shown that seating capacity need not be reduced. Powerplant weight can be less than diesel systems. Both volume and weight will diminish as the thermal efficiency is increased in the future.

Because of the large heat release from the condensers, consideration should be given to mounting these units on the roof in future designs. Under-floor mountings proved unsatisfactory from many points of view, including problems with cooling air circulation, the gathering of dirt, and heat release. The Lear side-mount condensers were much better, with outside air drawn inward by the fans. This led to engine compartment temperatures that were higher than desired, however.

Fig. 15 shows progress that is being made in the increase of specific output of Rankine power systems. Such trends, coupled with the visualized future increases in thermal efficiency, are indeed encouraging to those concerned with packaging.

COST PROJECTIONS - More engineering and testing must be done before such factors as first cost of powerplants can be accurately forecast. For the present, a fairly reliable guide is the cost per pound of manufactured products, with allowances made for any premium or nonstandard materials or fabrication techniques required (21). Steam systems are likely to cost somewhat more per pound than diesels, but may be lighter in weight. Even if the ECE remains higher in first cost, it is almost a certainty that future ICE systems will become more expensive as the demand for cleanliness and quietness increases. Unit costs are, of course, sensitive to the production quantities involved. Clearly, since the urban bus market represents less than 5000 units per year in the foreseeable future, commonality with other segments of

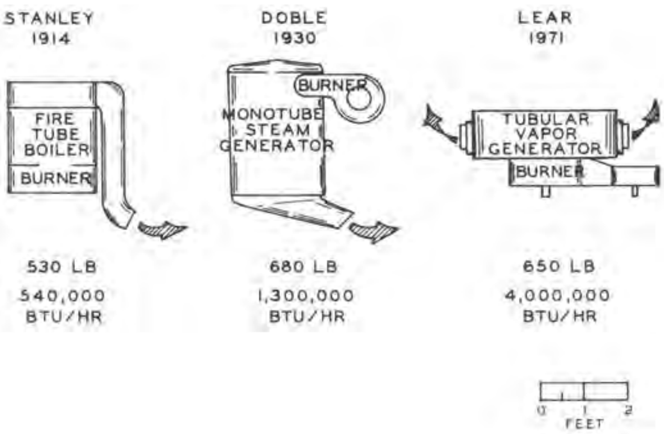


Fig. 15 - Trends in steam generator specific power outputs. Lear vapor generator shown is a research unit; vapor generator installed in bus was similar in size but somewhat heavier in construction

the heavy-duty engine market will be needed for the costs to become reasonable.

Eventual maintenance costs also remain a matter of speculation. A whole-vehicle comparison must be made, since a possible outcome might be reduced costs to service brakes and transmissions, but with new attention demanded by steam generators and controls. Expander maintenance (if a turbine) would be less than with the present basic engine block, but would be similar with reciprocating expanders.

Fuel costs can approach the economy of a diesel if the ECE becomes sufficiently well developed, but only for stop-and-go service where the present diesel and its transmission operate at a disadvantage. It does not seem likely that diesel fuel economy under steady cruise conditions (long-haul) will be exceeded for a long time to come.

It is not obvious that any cost advantage would result from the use of the ECE compared to the present diesel equipment. Costs over the vehicle's life would, with sufficient development, be similar. However, the benefits of cleanliness and quietness can greatly exceed those available with the diesel, while the diesel would almost certainly become considerably more costly, complex, and bulky in attempts to meet tighter standards.

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CURRENT STATUS OF PROJECT

From Automotive Engineering, August 1973

WHAT HAPPENED TO THE CALIFORNIA STEAM BUS PROJECT? - The California legislature has released its final report on the state's steam bus project. And, although the vehicle is still considered an excellent candidate for stop-and-go urban vehicles, it's obvious that substantial problems still remain. High fuel consumption continues to be the largest obstacle. Economy may be improved in steam engine buses in several ways, such as increasing the temperatures of steam or other working fluids. Values of ideal Rankine cycle efficiency could be raised from the present 25% to about 30% in a two year period, and eventually to 32-35%.

Present thermal efficiencies are as low as 40% of ideal cycle efficiency. This could increase to 60% in the short term, and to 70% eventually. Major gains could be obtained by reducing parasitic auxiliary loads and by increasing expansion efficiencies. For example, by using a more efficient fan, its horsepower consumed could be cut to 10-15 hp from the present 30 hp.

Another way to cut fuel consumption would be to minimize the present method of sustaining the whole steam powerplant at idle. Use of a small auxiliary expander for essential idle loads could reduce idle fuel consumption by two-thirds. Transmission improvements also are possible for turbine expanders which would allow the turbine to operate more of the time at peak efficiency.

All in all, the best steam bus is only obtaining 1 mpg vs 3.5 mpg for today's diesel buses under local conditions. However, the California Legislature's Assembly Office of Research predicts that it should be possible to raise steam bus mileage to about 2.3 mpg with two more years of development, and 3.3 mpg looks possible within a decade.

REPLY FROM R. WILLIAM HAUCK, DIRECTOR, CALIFORNIA LEGISLATURE, ASSEMBLY OFFICE OF RESEARCH

We have noted your very appropriate question under "News Briefs," in the August 1973 issue of Automotive Engineering. The question was, "What Happened to the California Steam Bus Project?" On behalf of the Assembly, California Legislature, I would like to offer an answer.

Given our limited objectives, level of funding, and the extremely short time period of the work, we consider that the Steam Bus Project was highly valuable and successful in testing and validating low exhaust emissions from steam engines. But as you implied in your review, a substantial amount of work remains to be done.

The Steam Bus Project was concluded September 30, 1972 when the U. S. Department of Transportation decided not to renew the grant of funds to the Assembly for further steam bus work. While we believe DOT was pleased with the early yield of data and the experience gained from the project, our report reached them coincidentally with DOT's reappraisal of its role in engine development.

Meanwhile, the California Assembly decided that the critical nature of the automotive emissions problem demanded that it continue work in steam engine development. This time, however, the test vehicles are sub-compact automobiles suitable for urban use. The project is funded jointly by the State and private industry. Two contractors, Steam Power Systems, Inc. of San Diego, and the Aerojet Liquid Rocket Company of Sacramento are expected to deliver two steam cars for the Legislature's evaluation in May of 1974. One of our goals is to reduce emissions to less than one-half the levels required in the original 1976 Federal standards.

It should be pointed out that California does not advocate a particular engine. We have used the steam engine merely as one example of accessible technology in alternative clean engines. Because the Rankine Cycle has a significant growth potential in areas other than emissions, we find every reason to encourage its development.

We will periodically report progress to you on this work.

ATTACHMENT 14

Institution of Mechanical Engineers

Railway Division

I MECH E

The Sir Seymour Biscoe Tritton Lecture

MODERN STEAM - AN ECONOMIC AND ENVIRONMENTAL ALTERNATIVE TO DIESEL TRACTION

ROGER WALLER, Dipl.-Eng.ETH

Lecture presented at the
Sir Seymour Biscoe Tritton Lecture
on Monday 3 February 2003 and Tuesday 4 February 2003

Printed in Great Britain by Moreton Hall Press Limited, Bury St Edmunds, Suffolk

MODERN STEAM - AN ECONOMIC AND ENVIRONMENTAL ALTERNATIVE TO DIESEL TRACTION

ROGER WALLER, Dipl.-Eng.ETH

1. INTRODUCTION

More than 30 years have elapsed since a paper on steam locomotive development was presented to the Institution of Locomotive Engineers. Whilst that paper [1] given by Mr. L. D. Porta in 1969 was directed to the traction requirements of the under-developed countries, this paper suggests a fresh look at *modern steam* as a potential alternative to diesel traction mainly in the first world. This strong statement is based on practical experiences gained over the last 11 years whereby *modern steam* traction has compared favourably with diesel traction.

Since 1969, steam traction has seen ups and downs, but the general tendency has been that of decline. However, during the oil crisis in the 1980's, steam power was reconsidered by many railways, recognising its inherent advantage in its ability to burn most types of fuel. Even in the USA, steam traction was seriously looked at, resulting in several ambitious projects including ACE 3000 [2]. When the oil price dropped again, these projects were terminated at an early stage of development. Nevertheless, several other projects have been realised in countries with abundant, cheap coal, amongst which was the rebuilding of 89 Garratt locomotives in Zimbabwe [3]. It incorporated the conversion of all axles to roller bearings, but otherwise the design was left unchanged. The rebuilt Garratts replaced diesel locomotives, saving oil and money.

In South Africa, steam locomotives were developed under the direction of David Wardale, who employed Porta's technology to rebuild 19D class light 4-8-2 No.2644 and 25NC class heavy 4-8-4 No.3450 [4]. The author has been involved in testing the latter. However this decision to leave the Swiss Locomotive and Machine Works to work on steam locomotive development was based on interest rather than intentions. Like most people I thought that steam locomotives were fascinating, but inefficient, polluting and old-fashioned. This attitude changed with the insight of an economic traction study done by the South African Railways in 1981 for the mainline from Kimberley to De Aar [5], whereby the 30 year old 25NC class steam locomotives proved to be more economical than both the newer 34 class diesel locomotives and the 7E electrics. The rebuilt No.25NC 3450 was the most economic of all. This unexpected result proved that steam locomotives were not a priori uneconomical, but it did not change the long-term traction policy of SAR. The drive to be "modern" was stronger than the aim to optimise the economics. Realising this meant that steam locomotive development has to be done in the first world, if it is to be seriously considered by normal commercial railways. Switzerland, with 99 % of its railway lines electrified, was certainly the most unlikely place for steam locomotive development and therefore ideal for the desired effect. With one steam railway only, the choice of where to propose modern steam locomotives was not too difficult!

At that time the only steam operated railway in Switzerland, the Brienz-Rothorn Railway, was about to purchase yet another diesel locomotive. Diesel traction had been introduced in 1973, when a solution had to be found to improve the economics and increase the traffic capacity. The old steam locomotives could no longer cope with the demand and were expensive to operate. In 1970 a traction committee therefore investigated alternatives, carefully looking at all traction modes. The recommendation was for diesel-hydrostatic locomotives and lightweight coaches. The first diesel locomotive No. 8 was not quite up to the expectations, but provided a basis for a much better version built in 1975. Locomotives No. 9 and 10 are capable of handling 112 passengers with a driver and a guard, whilst the old steam locomotives transport 48 to 80 passengers only and require a fireman.

Rolling Stock of the Brienz-Rothorn Railway from 1975 to 1986						
Engine No.	Type	Built	Coaches	Seats	Train Crew	"Productivity"
1...5	Steam	1891/92	1	48	3	100 %
6, 7	Steam	1933/36	2	80	3	167 %
8	Diesel	1973	1	48	2	150 %
9, 10	Diesel	1975	2	112	2	350 %

Table 1: Rolling Stock of the Brienz-Rothorn Railway from 1975 to 1986. "Productivity" relates to the number of passengers per train crew member in relation to the oldest steam train.

This situation left the railway with a dilemma - most passengers wanted to ride in steam trains, but capacity and economics forced the railway to prefer diesel traction. The result was a continuous decline in the number of passengers that were actually transported by steam traction. Many passengers were dissatisfied and complained. The author thought it was time to present a better alternative and proposed modern steam locomotives that would be as economical as the diesels and as attractive in interest as the old steam locomotives. Fortunately the director of the Brienz-Rothorn Railway was interested, but it turned out to be more difficult to convince the management of the Swiss Locomotive and Machine Works to take up the production of steam locomotives again, which had been terminated in 1952. Indeed the first design proposal as well as the first meeting with the director of the Brienz-Rothorn Railway were done in spare time, with kind permission of SLM. Many internal discussions followed, but in the end the SLM management proposed to leave the decision to the results of market research. Six or more new rack steam locomotives would mean the go ahead. If the call was for less, the file on new steam locomotives would be closed for good.

The market research revealed a demand for no less than 15 new steam locomotives, more than anyone had expected. The Brienz-Rothorn Railway opted for two, the electrified (!) Montreux-Glion-Rochers-de-Naye Railway for one and the Austrian Federal Railway for 12, six each for the rack lines on the Schafberg and the Schneeberg.

2. SHORTCOMINGS OF OLD STEAM POWER

Most comparisons between steam, diesel and electric traction ignored a considerable age difference and were therefore neither balanced nor fair although it cannot be denied that old steam locomotives did indeed have shortcomings. These are still well known and therefore only briefly mentioned:

- High footplate staff costs due to the fireman
- High maintenance costs (on account of the old age or obsolete constructional practice)
- Low thermal efficiency resulting in high fuel consumption
- Smoke and air pollution due to incomplete combustion
- Risk of line side fires due to spark emission
- High stand-by losses due to lack of insulation of boiler, steam pipes and cylinders.
- Extensive servicing necessary for taking coal and water, preparing and cleaning the fire, emptying ashpan and smokebox, washing out the boiler
- No interchangeable parts

To overcome these shortcomings in order to compete against diesel and electric traction, a thorough analysis was done. It was found that the majority of deficiencies were dictated by the use of outdated technology and constructional practice. The conclusion was that employing modern technology would allow economical and clean steam traction.

3. ADVANTAGES OF MODERN STEAM POWER

New steam locomotives that are economically and ecologically competitive need to have the following advantages:

- One man operation
- Light oil firing with excellent combustion
- Higher thermal efficiency
- Full insulation of boiler, cylinder and steam pipes
- Quick start-up
- Minimum servicing requirements
- High mechanical efficiency
- No leakage of lubricating oil
- Interchangeable parts

It was soon clear that an entirely new design was needed to achieve all these technical improvements. Rebuilding of existing old rack steam locomotives would not be appropriate and was not even discussed. It was also clear that the entire train operation had to be looked at. The aim was to match the latest diesel locomotives of the Brienz-Rothorn Railway and to outperform the diesel railcars of the Schafberg Railway. This was by no means an easy task, as the last two diesel locomotives of the Brienz-Rothorn Railway performed exceptionally well and the railcars of the Schafberg Railway had given quite good service.

To improve the economics, more passengers must be carried with fewer personnel. This called for a new concept.

4. ECONOMICAL OPERATING CONCEPTS

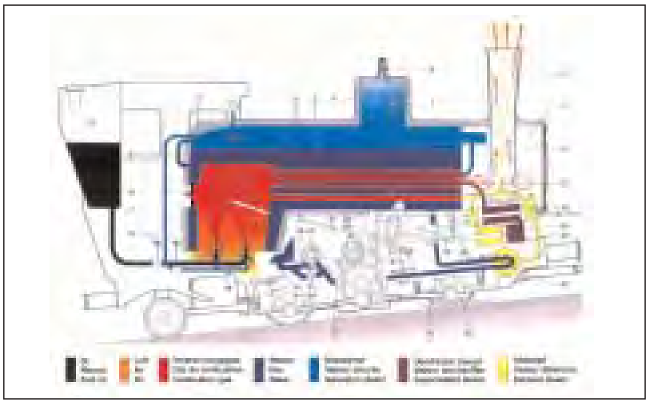
The century-old track of the Brienz-Rothorn Railway restricts the train weight to 32 tons, which meant that an increase in the number of passengers required minimal weights of the locomotive and the coaches. The existing coaches were already of excellent lightweight construction, weighing 3.1 tons for 56 seats and 4.0 tons for 60 seats respectively. According to the Swiss norms, average passengers weigh 75 kg. The aim was to take the two heavier coaches with 120 passengers up the 1 in 4 inclines of the Brienz-Rothorn to outperform the diesel trains seating 112 passengers meant a service weight of a mere 15 tons for the engine. Compared to the latest steam locomotives of the Brienz-Rothorn Railway built in 1933 and in 1936, the weight of the new engines had to be reduced by 5 tons, whilst the power had to be increased considerably to attain the higher speed envisaged. This consequently required application of the principles of lightweight design and the use of new materials previously unknown in steam locomotive construction. Of course, lightweight design requires careful engineering and additional calculations. Table 2 shows a comparison of the weight per seat and proves the excellent relative position of the new rack steam trains. Only the last series of diesel locomotives of the Brienz-Rothorn Railway are slightly better in this respect. Railcars, either diesel or electric, have a much higher weight per seat, a fact that is not commonly realised. Less weight per seat also means reduced energy consumption, especially on mountain railways. The actual energy consumption per passenger round trip is much more important than a maximum efficiency achieved at a specific load on a test bed.

Comparison of the Weights per Seat on Rack Railways			
Railway, max. Gradient	Train	Seats	
Train	Weight	No.	Weight
Brienz-Rothorn Railway, 250 ‰ (1 in 4)			(per seat)
Diesel locomotive No. 9 - 11 + 2 SIG - Coaches	19'400	112	173
Steam locomotive No. 12, 14, 15 + 2 SIG - Coaches	21'200	112	189
ÖBB Schafberg Railway, 250 ‰ (1 in 4)			
Steam locomotive 999.201 – 204 + 2 ÖBB - Coaches	24'800	105	236
Diesel railcar 5099.001, 002	25'700	77	334
NÖSBB Schneeberg Railway, 200 ‰ (1 in 5)			
Steam locomotive 999.201 + 2 Bombardier - Coaches	23'800	110	216
Diesel No. 11 – 13 + 2 Coaches No. 21,22; 31, 32	32'150	120	268
Snowdon Mountain Railway, 200 ‰ (1 in 5)			
Diesel railcar No. 21 - 23	15'250	41	372
Diesel locomotive No. 11 – 13 + 1 Coach No. 2 – 8, 10	25'200	56	450

Table 2: Comparison of the train weights per seat on rack railways. All weights are in kg. The number of seats on the diesel railcars 5099.001 and 002 have been reduced from 77 to 70 in 2001 for fire safety reasons.

5. TECHNICAL DESCRIPTION

As can be seen from figure 1, the basic layout of the new steam rack locomotives has remained classical, albeit with many design improvements.



The following is not a full technical description and is limited to the innovative features of the new rack steam locomotives:

5.1 One-Man Operation

The new steam locomotives are operated without a fireman, reducing footplate staff costs to the level of diesel and electric traction. One-man operation is facilitated by the fact that the trains are pushed. Consequently line observation when climbing is assured by the guard riding up front, leaving the driver to concentrate on his engine. When running downhill the driver has to observe the track ahead; on the other hand the boiler requires no attention then. Nevertheless various improvements ensure that the driver is not overtaxed with his dual responsibility of driving and firing:

- **Oil firing:** Compared with hand firing of coal, oil firing saves a lot of work. Moreover a newly developed compound governor enables the firing rate to be controlled with one hand.
- **Boiler feed pump:** There is a mechanically driven feed pump for feeding the boiler while in motion. The feed rate is controlled by means of a throttle valve.
- **Mechanical lubrication:** The driver does not have to worry about lubrication while running. Lubrication is carried out in the shed at intervals.
- **Vigilance systems:** Vigilance pedals are provided for safety protection.

The task of driving the new steam locomotive is nevertheless more challenging (and interesting) than driving a diesel locomotive. Eleven years of experience show, however, that the one-man operation is safe and works very well.

5.2 Oil firing

Oil fired steam locomotives are not new, but most of them burned heavy fuel oil. For the new rack locomotives this was ruled out. Heavy fuel oil has to be preheated for filling-up and firing, necessitating heating coils. This means more weight and extra energy consumption. The high sulphur content (>1%) is detrimental to the environment and to boiler life (corrosion). Since heavy fuel oil is used by major industries it is difficult to obtain in tourist resorts, whereas light oil, also used in domestic heating, is easy to get.

The decision to go for light oil meant that a new firing system had to be developed, as there were no suitable models on the market. The main problem was to achieve complete combustion in the small firebox. The advantages of designing anew were exploited by enlarging the firebox volume significantly. On account of the overall dimensions and the weight limit, however, there was no room for a combustion chamber. Therefore the quantity of fuel delivered had to be divided to shorten the length of the flame. In view of the almost square firebox shape, four main burners were provided to achieve a uniform firebox loading. To ignite the main burners there is a pilot burner located in the middle. The pilot burner is also used for stand-by and shunting. All burners fire vertically upwards. The flames do not touch the firebox. This is essential for optimal emission values.

In view of the new concept it was decided to test the oil firing while the locomotives were being built. The first boiler was given a specially designed superheated steam collector from which steam was discharged to atmosphere after passing through a stable throttle valve. The amount of exhaust steam could thus be adjusted, maintaining conditions with the regulator wide open. Draught was produced with a blower, enabling the lowest amount of excess air to be established.

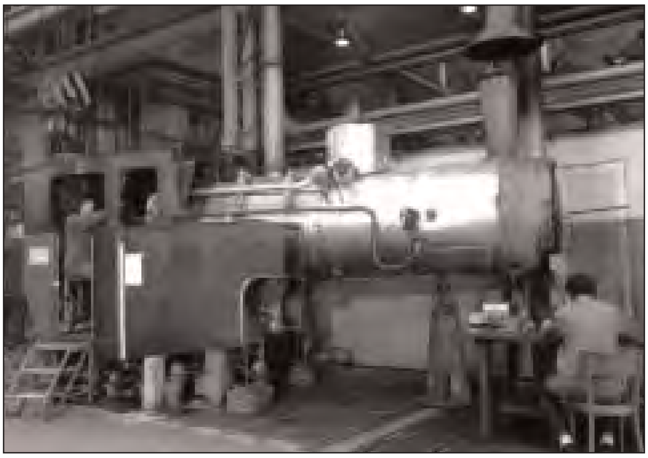


Fig. 2: Test stand for the new light oil firing. The boiler is provisionally insulated. The cab is a mock-up.

Development work in its truest sense was necessary to tune up the oil firing system to the required standard. With the first attempt (figure 3), the combustion was awful, producing a lot of smoke. The air flow around the burners had to be changed radically (figure 4). With these and other modifications, very clean combustion was then achieved.

Fig. 3: Oil firing system as delivered.

Fig. 4: Oil firing system after the tests.

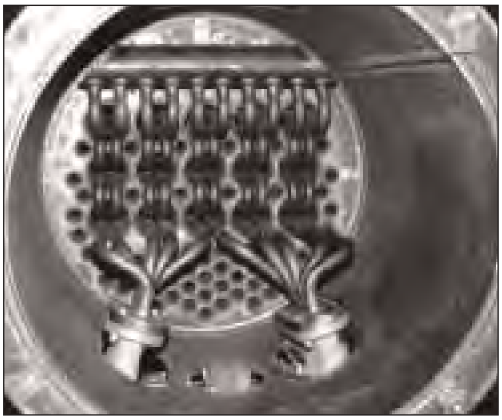


Fig. 6: All-welded light weight superheater.

5.3 Boiler and Superheater

Oil firing and the weight limitations dictated an all-welded boiler with a steel firebox (figure 5). The inner and outer fireboxes are joined by the U-shaped foundation ring and thread-less hollow stay bolts. The boiler is bolted to the cylinder block at the smoke box and rests on two swing plates at the foundation ring to allow for thermal expansion.

Special care was necessary to secure an adequate water level over the firebox crown at all inclinations over which the locomotives are worked, from level up to gradients of 250 ‰ (1 in 4). As a safeguard, an electronic low water alarm system shutting off the oil flow by means of an electromagnetic valve is provided. It replaces the fusible plug usual with coal firing.

For feeding the boiler, the century-old system of the mechanical feed pumps was "re-invented" in a modern form. The feed pump is belt driven from a toothed wheel on the crankshaft. The feed pump delivers the feedwater taken from the side tanks via an exhaust steam feedwater heater to the check valve. The water supply is controlled by means of a bypass valve easily operated by the driver. When not in motion, the non-lifting injector is used. The boiler has no steam manifold. Auxiliary steam is extracted directly at the dome. The regulator fitted in the dome is a commercial valve which allows finely graduated operation thanks to its special geometry. After the regulator the wet steam passes through the regulator pipe, before being delivered to the superheater.

Initial thermodynamic boiler calculations showed that superheating with elements in six series stages is necessary to achieve the desired steam temperature of 420°C. This called for the special arrangement of the superheater elements (figure 6). The superheated steam is led directly to the cylinders.

Fig. 5: Construction of the boilers.

5.4 Efficient Boiler Insulation

Even in heavy traffic conditions the locomotives operate only 8 to 10 hours per day, the rest of the time they stand in the shed. To save energy and staff costs, the boiler has very efficient insulation and stays in steam overnight, the oil firing being shut off. With a boiler pressure of 6 to 9 bar on the following morning, the pilot burner is lit and the locomotive is ready for service immediately. The electric preheating device is needed only after a boiler wash-out or a long period out of service.

In the past energy losses by radiation were grossly underestimated by most railway engineers. Admittedly 3 to 5 % of the maximum evaporation does not seem a lot, but in terms of energy, 20 kW for small, 50 kW for medium size and more than 100 kW for large European locomotives used to be constantly radiated from traditional boilers and fittings all the time the engine is in steam. If a main line locomotive is in steam for say 300 days a year, the energy losses by radiation amount to 300 x 24 h x 100 kW = 720,000 kWh per year, not really negligible. Considerable amounts of energy can thus be saved by proper insulation. The state of the art can be derived from standards applied to industrial boilers, where the importance of optimum insulation was recognised much earlier. Whilst on coal fired locomotives, some of the energy saved by proper insulation will be lost by increased blowing off at the safety valves for lack of fine modulation of the coal fire on the grate, the insulation of oil fired boilers cannot be too good.

5.5 Steam Engine and Valve Gear

The steam engine is a classical two-cylinder simple expansion engine with Walschaerts valve gear. Numerous improvements have been realised compared with earlier designs:

- enlarged steam chest volume
- straight steam ports
- minimal clearance volumes
- reducing power absorbed in exhaust back pressure
- optimised blast pipe
- generous valve travel

The welded double cylinder unit has cast-iron liners. The piston valves are guided on both sides, with the front guide inside. They have 7 narrow rings per valve head, ensuring good steam tightness. The piston with piston rod is of all-welded lightweight design. To connect the piston rod with the crosshead, a design based on American practice was chosen.

The rods and valve gear have been kept as bright as possible and matt chromed to inhibit corrosion. Reversing is done by hand wheel from the cab.

To enable the steam engine to operate within its economical speed range, the locomotive has an intermediate gear in the final drive with a reduction ratio of about 2.3 : 1.

5.6 Frame, Springs and Drive
The all-welded frame had been designed following the principles of lightweight construction, necessitating FE-calculations. Leaf springs are used for the locomotive suspension.

The crank pins on the large gear wheels drive the two road axles through the front and rear coupling rods. The driving axles to the rack are supported in their bearings and in the supporting road wheels. The tractive force is transmitted solely via the driving pinions which engage in the rack. These are sprung in the direction of rotation to compensate for pitch errors in the rack. On account of weight the driving axles have hollow shafts.

The hind truck is of the classical bissel or pony type. The support is via leaf spring through a carrying roller, which turns on a slightly V-shaped plate. This arrangement allows perfect centering while travelling on the straight and good curve negotiation thanks to the moderate centering effect. To minimise rolling the hind truck is equipped with a stabiliser.

5.7 Adaptability to Gauge and Rack Systems
Rack railways employ a variety of gauges, rack types and electric power systems, so that standardised motive power to get an economy of scale in production is difficult to achieve. The steam locomotive has inherent advantages, which have been exploited. Gauges from 800 mm (Brienz-Rothorn, Montreux – Glion – Rochers-de-Naye) to metre gauge (Schafberg, Schneeberg) are accommodated by merely altering the disks of the wheels (figure 7). The height of the rack above the rail is accommodated by the varying diameter of the road wheels.

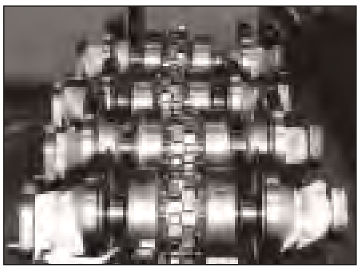


Fig. 7: Driving axles for 800 mm and metre gauge. Note the wheels, the centres of which are simply turned to accommodate the difference in the gauges. All the other parts are identical.

5.8 Brakes
The locomotives are equipped with three independent brakes:

- A Riggenbach counter-pressure brake serves as a wear-free service brake. The steam engine then acts as a compressor, the valve gear being set against the direction of travel. In the braking process heat is generated, which is converted into steam by injecting cooling water. The braking action can be controlled by means of a throttle valve. To reduce the hissing noise a silencer, integrated in the rear buffer, is provided.
- Mechanical brake system I is a spring-operated brake actuated by compressed air. Locomotive and coaches each brake their own masses proportionally. Brake system I is normally operated by the driver. All emergency brake applications act on brake system I via electro-pneumatic valves.
- Mechanical brake system II is concentrated on the locomotive and is able to stop the entire train without the assistance of the coach brakes.

5.9 Exhaust System
Initially three exhaust systems, all of proven efficiency, have been evaluated: Kylchap, Giesl and Lempor. For reasons of simplicity, weight, availability of the calculation method and optical appearance, a single Lempor draught apparatus was chosen. The original design with four nozzles was simplified to one nozzle only. All parts are made of stainless steel thereby eliminating corrosion.

When some of the Austrian drivers complained about the noise in the cab at full power, an analysis showed that sound absorbtion in the cab would not be sufficient and a silencer on top of the chimney would spoil the looks and foul the loading gauge. By slightly increasing the angle of the diffuser part of the Lempor exhaust, the height of the chimney could be reduced without reducing the draught, a silencer in the shape of a "Kobel" spark arrester could be fitted. Such spark arresters were quite common in Austria on coal and wood fired steam locomotives. The "stack talk" is thus reduced by 6 dB(A) and not all passengers like the whispering sound, but the drivers are happy.

5.10 Electrical Equipment
The locomotive is equipped with a modern electronic safety and emergency brake control system. Batteries are provided for the locomotive's current supply. These are charged via a mechanically driven alternator while running and in the shed through an external battery charger as necessary. Apart from the alternator and batteries, all electrical equipment is in the rear of the cab, separating the electrics from steam equipment.

5.11 Safety provisions
One-man operation of the locomotive and the strict regulations for rack railways dictate comprehensive safety provisions:

- Vigilance systems pedals with quick and slow action
- over-speed trip
- roll-back protection

All monitoring functions, speed and distance displays and recording are provided by the electronic TELOC 2000 S unit.

5.12 Electric Feedwater Preheating Device
To improve the operational readiness of the new steam locomotives and to save man-hours for preparation, an electric preheating device was developed. A 'cold' locomotive can thus be put in steam or a 'warm' locomotive can be kept in steam without supervision.

The principle of operation is quite simple (figures 8 and 9): Water from the boiler flows by gravity to the circulation pump, which forces the water through the electrical heater back into the boiler. The forced circulation causes extremely uniform heating, because the entire boiler is heated from the water side and therefore has the same temperature everywhere - unlike conventional warming-up, which heats the firebox and the tubes first while the outer firebox and boiler barrel are still cold. The electric preheating device warms up the water slowly to the temperature set on the control thermostat.

Fig. 8: The electric preheating device can also be used for coal-fired steam locomotives, considerably reducing the amount of smoke produced during lighting up. Neighbours are delighted.

Fig. 9: Two flexible hoses connect the boiler to the preheating device. Note that the hoses can only be disconnected if both ball valves are shut. This ensures that the preheating device cannot be disconnected under pressure.

The preheating device for the new rack steam locomotives, which have fully insulated boilers, is rated at 25 kW only. When starting with cold boiler water, it takes 12-16 hours to reach a pressure of 10 bar. The intention is to preheat a cold locomotive overnight, so that the locomotive is in steam the next morning. Before moving the locomotive, the preheating device must be detached. Switching it off and disconnecting the two flexible hoses takes five to ten minutes.

If the preheating device is used to keep a locomotive in steam or just warm, the desired temperature can be selected with the control thermostat, which maintains the set temperature within +/- 5°C by switching the heating on and off. A safety valve and a second thermostat prevent the maximum pressure or temperature being exceeded in case the control thermostat should fail.

6. WORK LOAD TRIALS

The fact that the “last” steam locomotives had been built by SLM in 1952, and the abundance of technical innovations made works trials advisable. The concept of employing a second steam locomotive as brake locomotive made it possible to build an attractive, low-cost test stand. The two locomotives were set up on inclined ramps and coupled by means of a Cardan shaft (figure 10). Whilst one locomotive was driving, the other one was retarded by means of the counter-pressure brake.

First the locomotive No. 12 of the Brienz-Rothorn-Railway was put on the test stand and instrumented with the measuring equipment. Five days later, the first revolutions under steam took place. Everything went right from the start. When the second locomotive, No. 999.201 of the Austrian Federal Railways was ready, the tests began. Even under load there were few problems. The main tasks were to tune the draughting to the oil firing for optimum combustion and to take electronic indicator diagrams to check the valve events and determine the power. The measured results were better than calculated.

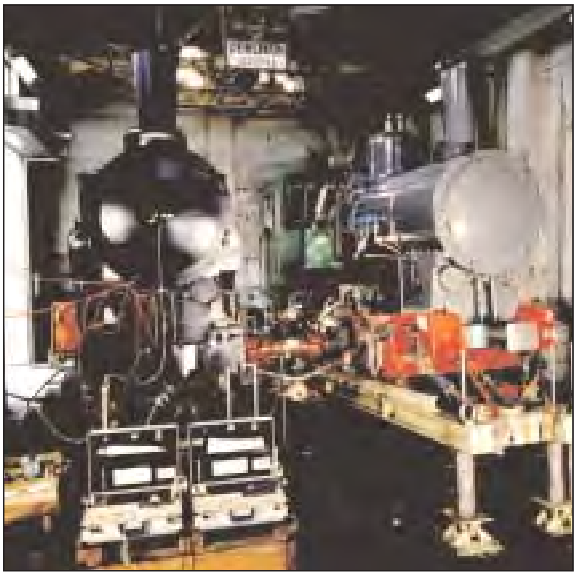


Fig. 10: Work load trials at SLM with locomotive No.12 of the Brienz -Rothorn Railway on the left side and 999.201 of the Austrian Federal Railway. The two bright cases in the foreground contain the emission analysers.

7. EMISSIONS

Traditional steam locomotives cannot claim to be particularly environment-friendly. Our intention was to change this with the new light oil firing system and to achieve clean combustion, but no more than that. We measured the emissions mainly to determine the quantity of excess air. Only when we realised how good the values actually were did we get more ambitious and attempted to find the optimum. We then thought it worthwhile to compare the measured emissions with the ones of the latest diesel of the Brienz-Rothorn Railway. Because diesel locomotive No. 11 was five years older than steam locomotive No. 12, the manufacturer of the diesel engine was asked to provide the cleanest actual emission data. For the sake of a truly fair comparison, No. 11 was thus “equipped” with data from the latest diesel engine. The measured emission values were then calculated in relation to the power at the rack driving pinions. A mountain railway cycle, consisting of 10 % stand-by, 45 % uphill and 45 % downhill working was used for comparison of the total emissions per round trip. The diesel locomotive benefits from its higher thermal efficiency, which is partly offset by the ability of the new steam locomotive to go downhill with the oil firing shut off. The result of the comparison can be seen in figure 11.

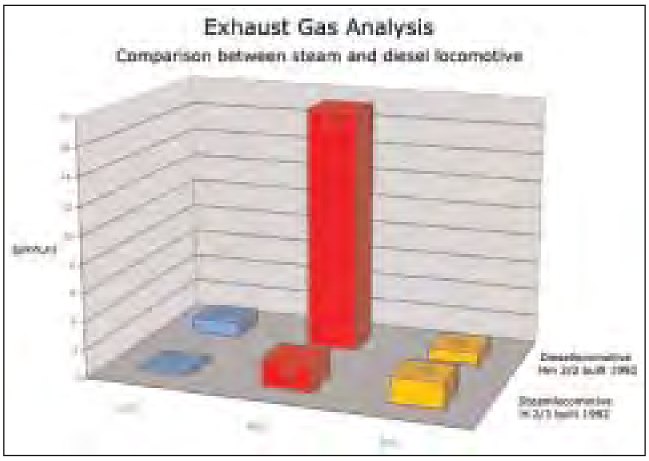


Fig. 11: CO-, NOx- and SO2-Emissions for diesel and steam locomotives on a mountain railway cycle.

If steam locomotives had always been treated with the same fairness in former comparisons as we have treated the diesel locomotives here, steam traction might have lasted longer.

8. OPERATING EXPERIENCES

Thanks to the good basic concept, an abundance of calculations, the preliminary testing of new components on other locomotives, the development of the oil firing on the test stand and the extensive testing and instrumentation in the works, the new steam locomotives worked straight away and went in to revenue service soon after delivery. Of course there were teething troubles too, but these did not interfere with the daily operation. Modifications were made when the engines were out of service due to boiler wash-outs or in the winter, when the railways do not normally operate.

Fig. 12: Locomotive No. 12 of the Brienz Rothorn with 120 passengers just outside Brienz. White exhaust steam can be seen thanks to the cold outside temperature.

Fig. 13: Locomotive No. 1 of the Montreux – Glion – Rochers-de-Naye at Caux on its separate, non-electrified track. The rest of the line is electrified. Note the American style water tower with integrated fuel station.

Fig. 14: Locomotive No. 999.201 of the Schafberg Railway with a full load of passengers on 1 in 4 grade. Note the clean combustion at full load.

The good technical and economic results led to an order for a further lot of five modern rack steam locomotives. In 1996, two locomotives were delivered to the Brienz- Rothorn Railway and three to the Schafberg Railway. These locomotives are almost identical to the prototypes, the main modification being a lighter crosshead. With hindsight this modification was not really necessary.

Fig. 15: Environment-friendly transport of environment-friendly products. Two brand new rack steam locomotives built in 1996 for the Schafberg Railway, ready to be sent by rail transport

9. STEAM – DIESEL – STEAM

Diesel traction had been introduced to the previously all steam operated railways on the Brienzer-Rothorn and the Schafberg to increase traffic capacity and to reduce operating costs. The old steam locomotives remained in service, but less and less passengers were transported by steam trains. Figures 16 and 18 illustrate that the introduction of modern, economic steam locomotives led to a reversal of this trend:

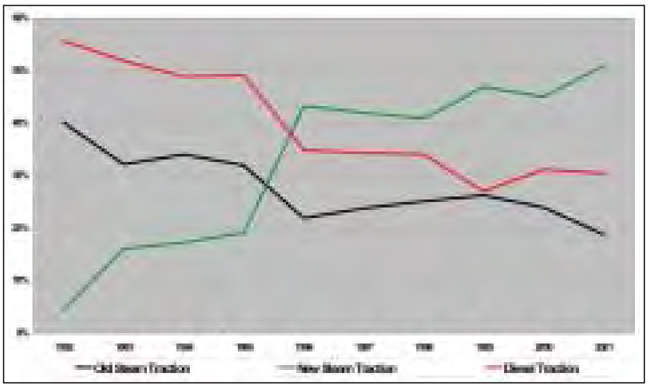


Fig. 16: Brienz-Rothorn Railway: Modal split between old steam traction, diesel traction and modern steam traction from 1992 to 2001. The percentages relate to actual mileage multiplied by seat capacity.

On the Brienz-Rothorn Railway the percentage of passengers hauled by diesel traction has been reduced from 70 % before the new steam locomotives were introduced to now only 30 %.

In 1996 the prototype diesel locomotive No. 8 was sold. Diesel locomotive No. 9 is relegated to works trains whereas No. 10 is on stand-by and helps out in peak traffic. Only the latest diesel locomotive No. 11 is still used regularly. The rolling stock now consists of:

Rolling Stock of the Brienz Rothorn Railway as from 1996						
Engine No.	Type	Built	Coaches	Seats	Train Crew	Productivity
1…5	Steam	1891/92	1	48	3	100 %
6, 7	Steam	1933/36	2	80	3	167 %
9, 10	Diesel	1975	2	112	2	350 %
11	Diesel	1987	2	112	2	350 %
12	Steam	1992	2	112	2	350 %
14, 15	Steam	1996	2	112	2	350 %

Table 3: Rolling Stock of the Brienz-Rothorn Railway as from 1996. Productivity relates to the number of passengers per train crew member in relation to the oldest steam train. The locomotives No. 11, 12, 14 and 15 are also capable to haul two heavier coaches seating 120 passengers. There is no No. 13!

Thanks to the new steam locomotives, the total number of passengers has increased considerably. In the ten years before the introduction of the new steam locomotives, the Brienz-Rothorn Railway carried 1,585,645, in the ten years with the new steam locomotives, 1,869,290 passengers, an increase of 18 %. This required only 3% more train journeys, a result of the higher capacity of the modern steam trains.

Railways are usually reluctant to release figures of their operating costs. Several attempts to get these from electric rack railways remained unsuccessful. We are therefore very grateful to the Brienz-Rothorn Railway to have released their figures, which allow one to compare the respective operating costs of old steam, diesel and modern steam traction on the same line and the same staff.

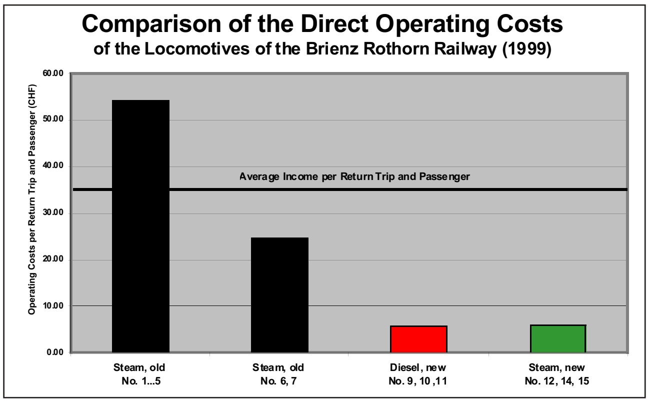


Fig. 17: Comparison of operating costs per passenger of old steam locomotives, diesel locomotives and modern steam locomotives in relation to the average income per passenger. The operating costs include all costs for staff, maintenance, fuel, water and lubricants.

Figure 17 shows clearly why the Brienz-Rothorn Railway preferred to use diesel locomotives before new steam locomotives were introduced. In Switzerland there is not only competition amongst the many rack railways, but also an overabundance of cable railways and aerial ropeways. This limits the ticket prices. With the price level more or less fixed and considering the fact that tourist railways are not subsidised, the operating costs have to be competitive, or else the railway will close. If the oldest steam locomotives are used, the income doesn't even cover the operating costs, so that the railway loses money on each passenger. By using either new steam or diesel locomotives, most of the income remains to cover capital costs, track maintenance, overheads and all other costs. Figure 18 proves what had been claimed when the new steam locomotives were introduced: the shortcomings of the traditional steam locomotives are a matter of old age and design concept and can be overcome by employing modern technology.

On the Schafberg Railway traffic is now almost entirely in the hands of the modern steam locomotives:

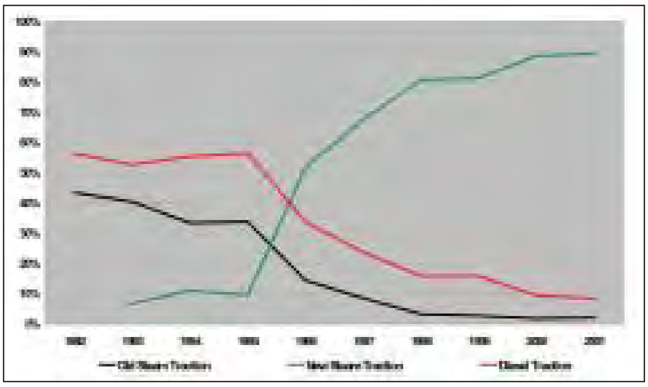


Fig. 18: Schafberg Railway: Modal split between old steam traction, diesel traction and modern steam traction from 1992 to 2001. The percentages relate to actual mileages times the seat capacity.

The diesel railcars are still there, but are being used less and less. Before the new steam locomotives arrived, the diesel railcars carried some 55 % of the passengers, but this was down to about 8 % in 2001. The old coal-fired steam locomotives transported some 3 % only. This may be explained by the much longer journey time and the "nostalgia"- supplementary fare. According to observations of the railway staff, the average passengers, whilst exactly discriminating between diesel and steam traction, do not differentiate between old and new steam trains.

The rolling stock of the Schafberg Railway now consists of:

Rolling Stock of the Schafberg Railway as from 1996							
Engine No.	Type	Built	Coaches	Seats	Train Crew	Productivity	Speed
999.102…106	Steam	1893	1	60	3	100 %	7 km/h
5099.001, 002	Diesel	1965	Railcar	77	2	192.5 %	12 km/h
999.201	Steam	1992	2	110	2	275 %	12 km/h
999.202 - 204	Steam	1996	2	105	2	262.5 %	12 km/h

Table 4: Rolling Stock of the Schafberg Railway as from 1996. Productivity relates to the number of passengers per train crew member in relation to the oldest steam train. The seating capacity of the diesel railcars has been reduced to 70 passengers as from 2001 for reason of fire safety.

Fig. 19: No rule without exception. Modern steam train of the Schafberg Railway in winter operation

While the modern steam locomotives carry the major part of the traffic on both the Brienz-Rothorn and the Schafberg Railway, locomotive No. 1 of the Montreux–Glion – Rochers-de-Naye has the task of increasing the attractions of this otherwise electric railway. Ancient wooden “Belle Époque” coaches are being used, which look very good, but are not of lightweight construction. As this steam train is in contrast to the electric railcars, a “steam”- supplementary fare is charged. Due to the different operating concept and the restriction marked in the timetable (“in fine weather only”), the locomotive No. 1 does only about half the mileage the other new steam locomotives do. The entire steam operation on this railway relies on the one locomotive, there is no spare locomotive and hardly any spare parts!

Fig. 20: The drive mechanism of the new steam locomotives is of modern technology, but none the less attractive to watch.

10. REBUILDS AND MODERNISATIONS

The following locomotives have been rebuilt using *modern steam* technology:

- 0-4-0 900 mm gauge tank locomotive, Borkumer Kleinbahn
- 2-10-0 Standard gauge locomotive 52 8055, Eisenbahnfreunde Zollernbahn e.V.
- HG 2/3 Rack and adhesion metre gauge locomotive, Brig-Visp-Zermatt Railway

All have been converted to light oil firing. The most comprehensive modernisation was done to 52 8055, which proved that *modern steam* technology is not limited to rack locomotives. A new light oil firing system, ten times more powerful, had to be developed and this created quite a few headaches, especially in view of undesired noise and vibrations. In the end we succeeded, but with hindsight, an entirely new design of the locomotive would have made life much easier.

Fig. 21: Modernised 52 8055 with a test train. With the new lightweight drive, equipped with roller bearings throughout, 41 % of the reciprocating masses were balanced compared to 15 % on the original design. The result was a very smooth ride even at maximum speed, whilst the original 52 class locomotives were notorious for their rough riding behaviour.

Fig. 22: Modernised oil-fired 52 8055 leads un-rebuilt coal-fired 52 7596 on the Orient Express. Each time a coal fired locomotive was used, the entire train had to be cleaned from soot and coal particles. Using 52 8055 saved a lot of man-hours of train cleaning alone.

It must be stressed that modernisation does not generally give the same excellent results that can be achieved with entirely new designs. The old components usually severely limit the scope for engineering re-design. As a consequence, the economic and technical results are usually much closer to those of the old design than to those that could be achieved with an all new locomotive.

11. NEW STEAM ENGINES FOR PADDLE SHIPS

Between 1933 and 1977 the Swiss Compagnie Générale de Navigation sur le Lac Léman (CGN), which operates passenger ships on Lake Geneva, converted six paddle steamers to diesel-electric drive in order to save on operating costs. Four were still in service in 1996. By that time, because diesel and electric units have a generally shorter life expectancy than steam engines, the time to replace the propulsion units was clearly close at hand. It seemed quite clear at first that new diesel-electric drives would be installed, but a new concept of the author to control a steam engine from the bridge by means of a remote control in combination with automatic boiler controls would enable steamships to run with the same number of staff as diesel ships of equivalent size. In this way the previously biggest economic disadvantage of the traditional steamer could be eliminated.

Fig.23: The "Montreux" was built in 1907 as a coal fired paddle steamer by the well-known Swiss company Sulzer Ltd.

Fig. 24: The "Montreux" after conversion to diesel-electric drive, which improved the economics but certainly not the aesthetics.

Fig. 25: Equipped with a new economic steam engine remote-controlled from the bridge, the entirely refurbished "Montreux" delights passengers, onlookers and accountants.

The paddle steamer re-entered commercial service on 19th May 2000, when it was leading the parade of the four other traditional paddle steamers.

The new steam engine for the "Montreux" had been ordered at the end of 1997, following a feasibility study. It was the first ship steam engine to be built in Switzerland since 1928! As with to the modern rack steam locomotives, the ship steam engine was tested and instrumented extensively before delivery (figure 26).

Fig. 26: Test stand with boiler, main steam pipe and steam engine exactly positioned as on the ship. The gear is from the obsolete diesel-electric drive and used here to increase the speed of the water brake.

The two-cylinder steam engine produces a continuous indicated power of 710 kW at 50 revs/min. With a bore of 560mm and a stroke of 1200 mm, the engine is rather impressive. Joy-valve gear has been chosen so that a 1000 kW three-cylinder version can be built without the need of a complete new design.

Fig. 27: Smooth and silent running even at full speed and power are synonymous with steam engines on paddle ships. This allows an open engine room, increasing the attractiveness to the passengers. An open engine room would be quite impossible on diesel ships where the best in acoustic insulation is needed to make it acceptable for the passengers.

With a reliability of 100 % since then, the steam engine installation has done very well indeed.

12. PROJECTS

12.1 Steam Locomotives for Tourist Trains

This paper is the first to publish the convincing economic results of the modern rack steam locomotives. The fact that the operating costs of *modern steam* power are not higher than the operating costs of diesel traction is largely unknown. It is therefore not surprising that most railway managers are still convinced that steam traction can only be considered for tourist trains. As long as this view prevails, justified or not, it makes sense to primarily search the market for projects linked with tourism.

The following details are from a selection of locomotive projects, most of them based on initial requests by a railway.

<u>Narrow Gauge Steam Locomotives for India</u>

The well-known 2 foot (610 mm) gauge Darjeeling is a spectacular line incorporating several loops and switch-back sections. As one of only two railways, the Darjeeling Railway has been declared a World Heritage Site by the UNESCO. The railway used to be operated exclusively by "B"-class locomotives, the design of which dates back to the 1880's. A crew of five is used on these small locomotives, quite a lot even by Indian standards! Diesel locomotives have been introduced recently, following the clean sweep policy of Indian Railways to eliminate steam. Nowadays there is more steam operation in tiny Switzerland than in giant India! The few operable Darjeeling steam locomotives have mainly been relegated to a new short-distance tourist train. Train operation on the Darjeeling railway is only a shadow of its former self and one can only wonder why UNESCO tolerates this.

However, in an attempt to keep some steam traction on this famous line, global tenders had been issued for three new oil fired steam locomotives. DLM presented an offer for an all-new design incorporating the latest *modern steam* technology with the external appearance closely resembling the old "B"-class locomotives. These locomotives would outperform the diesel locomotives by hauling five instead of four coaches at a higher uphill speed.

Fig. 28: New oil fired steam locomotive as proposed to the Indian Railways for the Darjeeling line. The distinct external appearance, which is characteristic for the Darjeeling Railway was intentionally retained in view of the UNESCO World Heritage status.

<u>Tank Locomotive for European Narrow Gauge Lines</u>

Back in 1990, the then DR (Deutsche Reichsbahn) heard of SLM's intention to build new rack steam locomotives and showed interest to buy no less than 30 new steam locomotives

(10 for metre gauge, 20 for 750mm gauge). Following this request, a modern 2-10-2 tank locomotive was initially proposed, incorporating all the features of the *modern steam* technology, but later SLM pulled out: the rack tank locomotives were not yet built and the order books were full.

Both SLM and DR exist no more, but the steam operated narrow gauge lines have survived. Most lines are now privatised, but two lines near Dresden remain with DB. The infrequent service and a maximum speed of 30 km/h on 750 mm gauge and 40 km/h on the metre gauge make these lines unsuitable for commuters. This was different in the days of communism when there was simply no alternative. Today commuters go by car or bus, and many lines in the former East Germany have been closed for lack of passengers. Not so the steam operated railways, where the tourists are more than happy to fill the trains. Even though the trains are mostly used by tourists nowadays, these lines are not typical tourist railways, offering a daily time-tabled service.

Whilst most of these lines have recognised the value of steam traction, DB is still unconcerned. As DB is now running trains as a subcontractor to the Verkehrsverbund Oberelbe, being paid by kilometres run, they have little interest in ticket revenue. DB's interest is to lower operating costs, for which the standard answer nowadays is diesel railcars. But who will use them on these lines? Modern steam locomotives provide a much better solution in terms of attractiveness, transport capacity and operating costs per seat. Since the track has been upgraded on all lines, DLM is offering a 2-8-2 with an axle load of 12.5 tons instead of the 2-10-2 with an axle load of 10 tons. Whilst the same tractive effort is retained, the maximum speed can be raised to 70 km/h, equal to the speed the railcars would achieve.

Fig. 30: DLM proposal for a narrow gauge 2-8-2 destined mainly for the steam operated lines in the eastern part of Germany.

The problem is that the diesel railcars would be subsidised by 90 %, whereas the modern steam locomotives are not, which is unfair competition. The "logic" behind this argument is that suburban traffic is losing money and therefore has to be subsidised, whereas steam locomotives are used in tourism, which is expected to make a profit! Some of the railways now try to convince the Government to equally subsidise the modern steam locomotives, realising it's the best solution for them.

<u>Tank Locomotive for European Standard Gauge Lines</u>

When a local committee took the initiative to re-activate the scenic standard gauge line from Merano to Malles in northern Italy, they proposed to use modern steam locomotives in combination with modern panoramic coaches, resembling the ones that had been built for Swiss narrow gauge railways. The artist's impression shows how well the new steam locomotive would match the coaches. Push-pull operation was also suggested whereby the locomotive would have been remote-controlled from the driving trailer car. But in 1997 the time was not ripe for such unconventional ideas. Later on diesel railcars were ordered, proving that it takes a long time to change a paradigm.

Fig. 31: Artist's impression of a modern standard gauge steam train. Drawing by H.R. Kaegi

More projects can be found on the DLM-Homepage: www.dlm.ag or www.dlm-ag.ch

12.2 Steam Locomotives for Industrial Use

Diesel locomotives nowadays have a virtual monopoly on shunting duties. Technically this is a bit difficult to understand, as the diesel engine has some shortcomings, which do not make it an ideal shunting locomotive. As the diesel engine alone cannot start under load, an electric or hydraulic transmission is necessary, making it a rather complicated and expensive locomotive. In service the diesel engine idles for most of the time, doing no useful work but polluting the environment with toxic and carcinogenic exhaust gases, noise and vibrations. Measurements show that diesel locomotives on shunting duties run at idling speed 75 % of the time. When the author checked the mileage and the operating hour meters of several shunting locomotives, the average speed turned out to be between 1.5 and 4.5 km/h! Because there is no energy storage, the diesel engine has to follow load in shunting duty frequent changes of the traction, thereby producing emissions of very bad quality.

Modern steam technology, employing old refurbished as well as new ideas, could provide a much more environmental-friendly shunting locomotive. For part of the trip, for instance in tunnels, completely emission-free operation could be guaranteed.

13. SUMMARY AND PROSPECTS

Eleven years of experience show that the new rack steam locomotives have acquitted themselves very well. The requirements laid down in the specification have been met or exceeded. Compared with other prototype motive power the commissioning time was extremely short, enabling the locomotives to assume commercial operation soon after delivery.

Most of the shortcomings of traditional steam traction have been eliminated on these modern locomotives. In operational readiness, availability and personnel costs they can match diesel and electric traction. Fuel costs now amount to a very low percentage of the operational costs. The comparison of operating costs on the Brienz-Rothorn Railway shows that they are five to ten times lower than those of old steam power, but more important, equal to those of diesel traction under the same conditions. Environmental nuisance is no longer a problem with the new oil fired steam locomotives. It has been demonstrated in practice that the CO- and NOx-emissions are even less than those from comparable diesel locomotives equipped with the latest engines.

The fact that the operating costs of new steam locomotives are not higher than those of good diesel locomotives opens up a new field of applications. Whereas the use of modern steam locomotives has been justified by the needs of tourism, *modern steam* locomotives can now be considered for other traction purposes as well. The author is well aware of the fact that this kind of lateral thinking will take more time until the majority of railways start to consider evaluating *modern steam* traction. But the economic results of *modern steam* in both rail traction and marine applications justify a fresh and wholly unbiased review of the merits of steam traction, not only for tourism. By the way, who said that only tourists like to ride clean steam trains? Decisions are not only based on rational arguments such as travel time, frequency of service and ticket price, otherwise less people would use cars. Emotions are a factor we engineers tend to overlook, but emotions are a fact of life and when it comes to the emotion factor, steam is top. The railways could take advantage of this again.

It has to be emphasised that the convincing results with the new rack steam locomotives were achieved with a very small fraction of the development money spent for the development of diesel and electric locomotives. This in turn means that the development of the steam locomotive is far from having reached its peak. Even if the classical reciprocating drive is retained, which is essential for tourist trains, there is still a lot of potential for improvements. For normal traction purposes not linked with tourism, other forms of steam power (i.e. steam-electric) could be considered, but it must be borne in mind that the more one deviates from the principles of the classical steam locomotive, the more development work is needed and the higher the technical and financial risks may be.

This author is not going to predict the future. However the future of railways might just be a little brighter if all traction options were considered. Nowadays economic calculations can be done easily. One has to considered that comparative conditions are not only different in each country but also for each line. To find the economic optimum for each line, all three forms of motive power will have to be considered again: diesel, electric and ***modern steam***.

Acknowledgements

The author is happy to acknowledge the suggestions and help given in preparing this paper by Mr. George Carpenter and Hans Heiner Vogel.

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