A Comprehensive Analysis of Torrefaction Technologies for Producing Advanced Wood Pellets

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Glossary

Frequently used acronyms and terms

$/ty	*$ of CAPEX/t of annual capacity*
$/th	*$ of CAPEX per ton*hour*
CAPEX	*Capital expense*
c_p	*Heat capacity (kJ/kg*°K)*
CV	*Calorific value*
GJ	*Gigajoule*
GHG	*Green House Gasses (primarily* CO_2 *and* CH_4*)*
GOP	*Gross Operating Profit = Revenue – Cost (OPEX). In this model, it includes feedstock cost, OPEX, Loan Amortization, and Transportation. No SG&A or taxes.*
h	*hour*
h_e	*Enthalpy (kJ/kg)*
ΔH	*Enthalpy change*
HGI	*Hardgrove Grindability Index*
HHV	*Higher heating Value*
^oK	*Degree Kelvin*
LHV	*Lower Heating value*
MC% d.b.	*Moisture content, dry base in % of dry matter*
MC% w.b.	*Moisture content, wet base in % of total matter*
ME	*Mass/Energy (Balance)*
MJ	*Megajoule*
MPI	*Moisture Penetration Index*
o.d.	*oven dry, 0% moisture content*
OPEX	*Operations expense*
SCADA	*Supervisory, Control And Data Acquisition*
SG&A	*Sales, General & Administration*
t	*metric ton*
y	*year*

Executive summary

Researchers have looked for decades for ways to make biomass more useful as a coal substitute and have found heat treatment (torrefaction) to be helpful. Thermal treatment of biomass results in a higher gravimetric and volumetric energy density, which lowers the transportation and logistics cost per GJ delivered. There are several technologies to perform thermal treatment of biomass to achieve the effects mentioned above.

- Anaerobic heat treatment (severely depleted oxygen in the ambient)
- Oxidative heat treatment (oxygen-containing ambient, 5-21%)
- Hydrothermal heat treatment (aqueous with either alkaline or acidic additives)
- Steam treatment, with or without steam explosion

Many publications show that all these treatment forms have the desired effect, but to varying degrees and at a different cost. Some do have less desirable side effects.

In this report, we focus on the anaerobic torrefaction of woody biomass only. We submitted an independent review of steam treatment with steam explosion already.

For dry and anaerobic torrefaction, different reactor types are in use. Torrefaction technologists developed various strategies to lower cost, improve the process's safety, and avoid undesirable side effects. We comment on these. The typical results we observed are that the torrefaction processes studied have a dry mass loss between 20% and 55% with a corresponding energy loss of 10-27%. None of the studied cases converted the mass loss in marketable byproducts to offset the lost energy value; in all cases, the energy loss supplied part of the energy for pre-drying the feedstock.

The loss of calorific value and the increased OPEX and CAPEX compared to regular white pellets leads to a higher cost per GJ delivered. Further, the reduced GJ/y output from the same installed capacity adds to the significant profitability reduction of torrefied vs. white pellets. However, this statement is only correct when the market pays the same $/GJ delivered rate for either product.

As the torrefied pellets can be transported and stored in the open, just like coal, power plants will incur a much lower conversion cost to either co-firing pellets with coal or substitute coal entirely with pellets. If they are willing to pay a higher rate for the higher value GJ, the torrefaction solution may become attractive. We quantify the required price difference for the baseline conditions we chose.

The baseline conditions for CAPEX, energy cost, labor cost, and nameplate capacity are mainstream but do not reflect specific projects. A developer must evaluate Individual projects on their own set of conditions.

Introduction

Biomass as a substitute for fossil fuels is attractive as it can be "carbon-neutral." Biomass is carbon-neutral when only the same amount of biomass is harvested from a defined area as regrows in the same area and the same year. I.e., if the regrowth time of biomass to maturity is 50 years, only 2% of the defined area can be harvested each year. A fraction of this biomass would have to be used to offset the fossil fuels used for transportation (Diesel). However, the larger fraction could be counted as carbon-neutral fuel substituting coal at power plants or manufacturing other biofuels. For the biomass to work as a coal substitute, it has to be dried and densified. In its natural state, it could not be used economically, or even technically, in coal power plants without significantly derating the plants and requiring significant conversion investments.

- The most common densification processes are
- Drying, grinding/milling, and pelletization for white pellets
- Drying, grinding/milling followed by heat treatment and pelletization or briquetting for torrefied pellets or briquettes

The principal advantages of the drying and densification processes are

- Uniform size of the particles (10–12mm × 6mm), uniform density and moisture content
- Moisture content (6–8% H_2O)
- Less costly to transport, convey, and feed into burners using existing systems
- Higher heating value ~18.5 GJ/t – 24 GJ/t (15.9 – 20.6 MMBTU/ton)
- Multiple uses such as power generation, domestic heating, biofuels production
- High export value.

FutureMetrics was commissioned to deliver a comprehensive report on the current and expected development of the market for thermally treated woody feedstock and provide a techno-economic analysis of torrefaction's current status. This report is an economic and technical comparison to traditional "White Pellets" with several different torrefaction processes. We highlight the advantages and challenges of individual methods and the resulting pellets or briquettes. Another form of thermal treatment is steam-explosion. We supplied a report on that technology already. We did not cover other thermal treatments such a hydrothermal at atmospheric pressure or high pressure or technologies with different end products such as syngas, hydrogen, cellulosic ethanol, or liquid biofuels. We are not commenting on the individual technology developers' economic and financial statistics, only on the technology they offer.

We compared each of the torrefaction technologies to a white pellets plant with the same input capacity. We picked a medium-sized plant as a model with 200,000 t/y o.d. feedstock capacity. The feedstock moisture content (MC) we calculated for was 50%.

We made the following assumptions

- 200,000 t/y o.d. input produces theoretically 208,000 t/y white pellet output @ 4% MC. We use 200,000 t/y output where the 4% MC of the pellets offsets the volatiles loss and the fines and dust losses during drying.
- The derating of the output of torrefied pellets plants is determined by the mass loss of o.d. material in the process, e.g., a torrefaction process with 25% mass loss will produce 150,000 t/y output of o.d. pellets in the chosen comparisons model.
- The energy content for 4%MC pellets is 18.3GJ/t, for torrefied pellets as stated by the participants 22-30 GJ/t.
- We set Labor requirements and rates conservatively, based on empirical values. We used the same rates, except for HM3 for contrast.
- We assumed the market price for 1 ton of pellets with 18.3 GJ/t delivered to Tokyo to be $185, resulting in $10.11/GJ. We used this number as a baseline for our economic calculations.
- We used a $70/t o.d. feedstock cost and a fuel cost of $50/o.d. ton unless noted otherwise.
- As CAPEX differs from a white pellet plant, we included loan amortization and interest in our GOP comparison.
- We used a bulk density of 640kg/m^3 for white pellets and a bulk density of 730-750 kg/m^3 for torrefied pellets. We applied a shipping cost of $7.05/m^3 plant to port and $13.46/m^3 Port of Vancouver to Tokyo.

The study relied on the participants' inputs. We did not have the opportunity to visit any of the participating companies or plants. Some participants could not provide as granular information than others as their experts or the requested data were not available at this time. In these cases, we restricted our comments to what we could learn and did not attempt to make a comparison.

Participants

ADF	**Portugal**	Isabel Santos, Chief Marketing Officer https://www.adfuelsolutions.com
Airex-Energy	**Canada**	Sylvain Bertrand, CEO https://www.airex-energy.com
ATS	**USA**	Thomas Causer, Vice President and COO https://www.atscat.com
BC Biocarbon	**Canada**	No specific contact https://www.bcbiocarbon.com
CEG	**Netherlands**	Stuart Paskett, VP https://cegeneration.com
HM3	**USA**	Mary McSwain, Communications https://HM3e.com
IBTC	**Austria**	Michael Wild, President International Biomass Torrefaction Council https://ibtc.bioenergyeurope.org
TSI	**USA**	Andrew Johnson, GM Sales &Marketing https://www.tsi-inc.net/
Yilkins	**Netherlands**	Joris Spaan, Business Development https://yilkins.com/

Torrefaction Commonalities

Wood biomass typically has the following elemental composition on a dry mass basis,

Carbon	50 %
Oxygen	41%
Hydrogen	6%
Nitrogen, Sulfur, Ash	3%

The combustible elements of wood are

Carbon	88 %
Hydrogen	12 %

The energy ratio of wood combustion is

Energy from Carbon	67 %
Energy from Hydrogen	33 %

Torrefaction breaks up and reduces low energy-containing oxygen-rich compounds, such as hemicelluloses. In the torrefaction process, the biomass is heated to a temperature of approx. 240-320°C in an oxygen-depleted ambient for a time between a few seconds to 20 minutes, resulting in loss of moisture and partial loss of the biomass's volatile matter. Removing part of the volatile matter changes the characteristics of the original biomass. The material turns from hydrophilic to hydrophobic and becomes more brittle. With the removal of the lighter, volatile part of the biomass, the remaining material's heating value gradually increases from 19 MJ/kg to approx. 22-24 MJ/kg for torrefied wood.

Torrefied biomass typically has the following elemental composition on a dry mass basis [1],

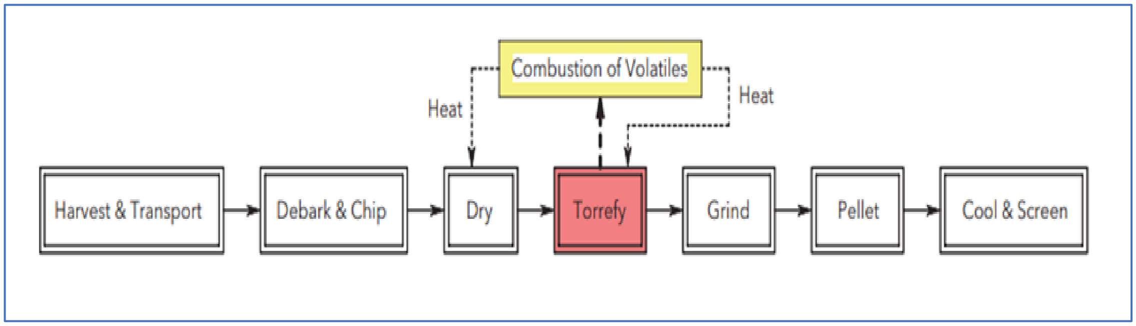
Carbon	56-60%
Oxygen	31-37%
Hydrogen	6%
Nitrogen, Sulfur, Ash	1-3%

The combustible matter to total matter ratio increased from 56% of the untreated o.d. mass to 66% of the torrefied o.d. biomass.

All torrefaction technologies produce the following benefits

- Higher volumetric and gravimetric energy content than white pellets
- Water tolerance to enable uncovered transportation and storage (like coal)
- Grindability (HGI from 23-50)
- Unlimited mix ratio with coal for co-firing
- Low biodegradability

All torrefaction technologies deal with the challenge of mass loss, between 20 and 30% d.b., from the applied feedstock, and a corresponding energy content loss of typical 10-14 %. Higher torrefaction temperatures drive higher mass and energy loss and affect pellets' durability due to increasing lignin loss. However, higher torrefaction temperatures also raise the energy content (energy density) in the remaining biomass. From an economic perspective, the optimum for pellets or briquettes for industrial uses (power generation) may be in the torrefaction temperature range of 240°C-275°C.



Courtesy Dr. Donald R. Fosnacht – NRRI University of Minnesota

Figure 1: Basic torrefaction process flow

There is another flow describing the torrefaction of previously formed pellets. We are not looking at this flow as there is no economic merit in it. Torrefying already created pellets results in low bulk density and compromised durability of the product.

What is Torrefaction?

Torrefaction can be considered a low-temperature form of pyrolysis, similar to roasting coffee beans. The process is very similar to one of the oldest human crafts, charcoal burning. A woodpile was covered with earth, and only as much oxygen as needed to achieve the necessary temperature for carbonization was allowed in. Torrefaction is a more controlled process where the heat is supplied from external fuel and oxygen is kept out of the system, increasing the yield as well as safety. As illustrated in Fig.2 at 275°C, about 50% of the hemicellulose gets degraded, while more than 95% of the lignin and the cellulose remain intact.

The typical mass loss associated with torrefaction is between 23-35% of the o.d. biomass, with higher torrefaction temperature even more.

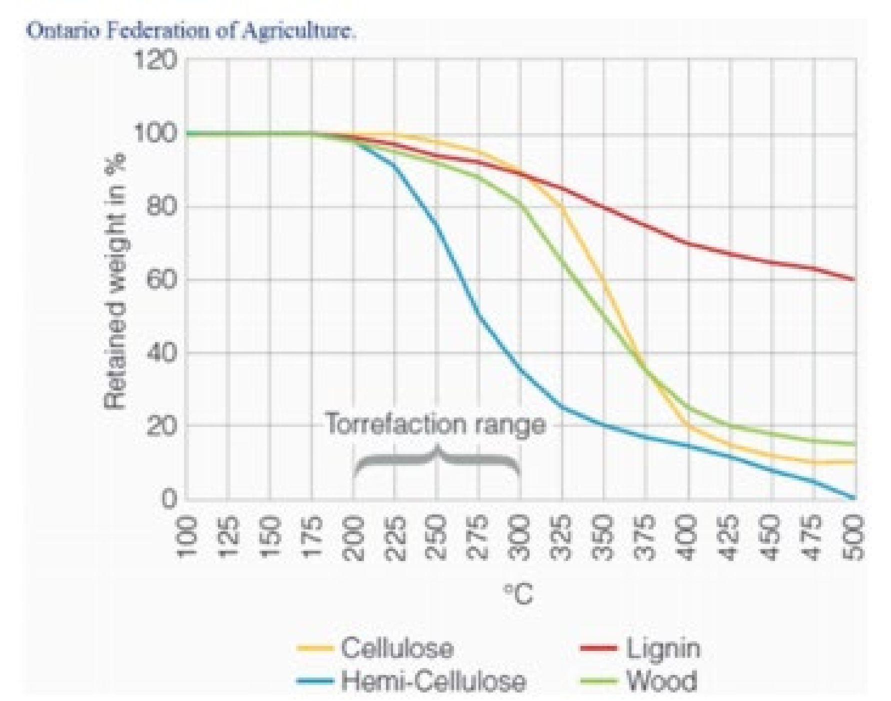


Figure 2: Weight retention vs. torrefaction temperature [2]

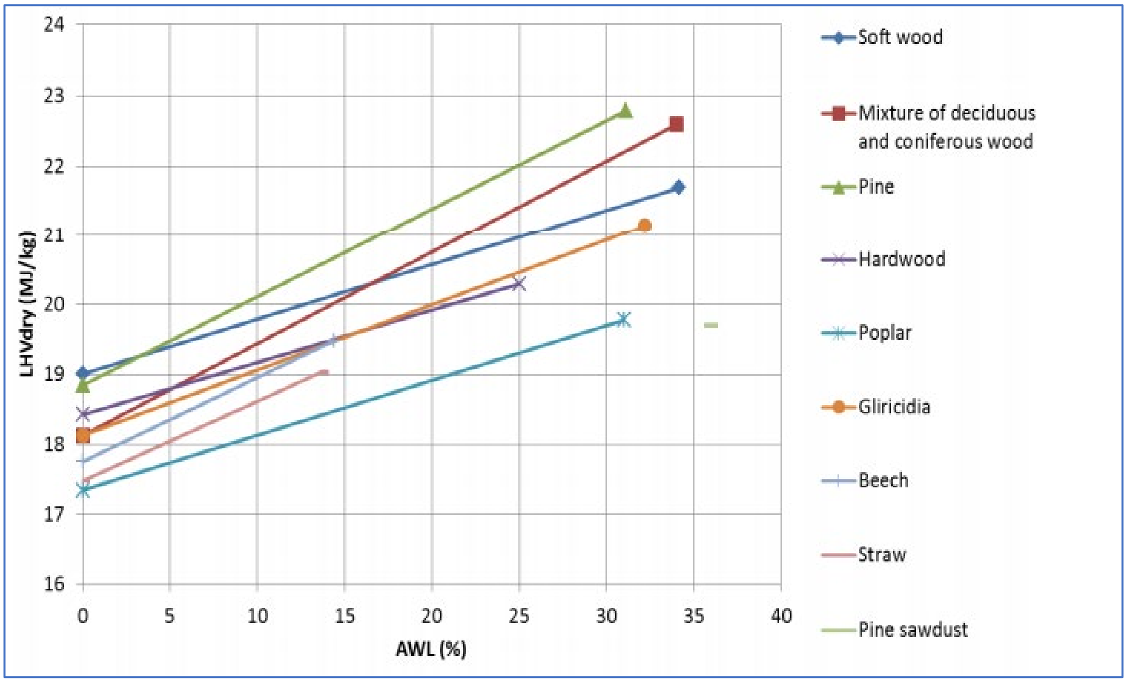
Why torrefaction?

The torrefaction process improves the biomass by rendering it water-resistant and grindable and increasing its gravimetric and volumetric energy density. While white pellets need to be stored in dry conditions to remain usable, torrefied, or other heat-treated biomass can be transported and stored like coal in the open. Removing a significant amount of the water-soluble hemicellulose and leaving the insoluble lignin and cellulose content mostly intact, the torrefied product is rendered hydrophobic.

Further, torrefied biomass is friable and grinds in the power plants' pulverizers similar to coal, without costly modifications. Power plants can use it in any mix ration with coal. White pellets have a limited pellet/coal mix ratio, typically < 10%. The hemicellulose has lower gravimetric density and energy density than lignin and cellulose; hence the torrefied biomass has a higher energy density than the dry feedstock, yielding lower transportation cost in $/GJ delivered. The downside of the densification is the mass and energy loss from the applied feedstock associated with thermal processing, as the feedstock comes at a cost. While almost all of the feedstock's energy remains in the sellable product in white pellets, torrefied pellets or briquettes retain only about 86-90% of the feedstock's original energy content, in one case even less than that. Only when the torrefaction's advantages outweigh the value loss of 10-14% of the feedstock energy content does torrefaction make economic sense. This report will compare white pellets vs. torrefied pellets.

Torrefaction processes

The technology of carbonizing biomass in an oxygen-free environment has evolved for a long time; it started thousands of years ago with charcoal production for smelter use and led to various processes today. Some of these processes aim at the production of gas, bio-oils, or even hydrogen. Some techniques are dry; others use hydrothermal pyrolysis. The methods we studied are all dry and based on wood biomass as feedstock. The products are torrefied biomass, oil/tar, and gasses. In biomass torrefaction processes, the co-production of oils and tars is not desirable; hence relatively low temperatures are used. The BC Biocarbon process is an exception; it uses the tars and oils as a binder for the char. The torrefied biomass is compacted into pellets or briquettes to improve the raw torrefied fiber's low bulk density and lower the risk of dust explosions. Torrefied biomass typically has a moisture content between 3-6%, in some rare cases going as high as 10%. In addition to the mass loss associated with torrefaction, some feedstock or product is used to deliver supplementary Energy for drying the biomass. If low-cost lower-grade fuel, such as hog fuel, is available, the drying cost could be reduced. In Fig. 3, the relationship of anhydrous weight loss (AWL) and the resulting LHV for various biomass species is illustrated [3].



Courtesy of IBTC

Figure 3: LHV o.d. increase vs. mass loss (AWL) by species

The volatile compounds resulting from the degradation of hemicellulose are typically burned for heat reclaim. The reclaimed heat is then used in the pre-dryer to dry the green feedstock. The energy needed for drying green biomass with 50% MC is only partially covered by burning the torrefaction gasses. The heat demand needs to be satisfied by burning additional fuel. For MC < 25%, the torrefaction gasses' energy reclaimed would be sufficient to cover the dryer's energy demand fully. These numbers are important as they play a significant role in the economic feasibility of the process. Some companies are beginning to look into extracting value from the torrefaction gasses. The gasses of a 200 kt/y input plant contain .45t/h furfural and methanol, each. At current market prices and an extraction cost of $ 350/t, this could mean a profit addition of 17 $/t of pellets or $ .77/GJ.

The removal of most of the water-soluble hemicellulose during torrefaction renders the product water-resistant and hydrophobic, allowing for open storage. An additional benefit is that the torrefied product contains less available nutrients for microorganisms and fungi, so it has much lower biodegradability than white pellets. The product is brittle (friable) and can be ground into a powder, like coal, making it a very suitable feedstock for co-firing with coal in any mix ratio. A lower torrefaction temperature leaves the lignin mostly intact and increases its percentage by removing the hemicellulose. Lignin acts as a lubricant during the pelletization and lowers the energy consumption in the pellet presses.

Many pyrolysis/torrefaction reactors have been developed and introduced, most using well-proven thermal processor designs (rotary furnaces, belt dryers, fluidized bed dryers, vibrating belt dryers, cyclone reactors, etc.). Table 1 is a list of companies that operated commercial or pilot torrefaction plants in 2015. The highlighted ones are the participants of our study. Some of them have abandoned torrefaction or mothballed their reactors for various reasons; some have left the market altogether while a few new ones have entered. The challenges that caused a few companies to put their efforts on hold or abandon them altogether were primarily quality of the product, cost, and competitive pressure, combined with risk aversion by off-takers to subscribe to contracts without a broad supplier base. This picture may change as a few developers have addressed some of the shortfalls, most notably product quality, process robustness, and heat reclaim for pre-drying. The cost challenge from losing typically 25-30% of the mass, albeit only 11-14% of the energy content, remains. They all use convection and conduction heat transfer processes at or near atmospheric pressure, except for Rotawave who used microwaves to heat the biomass. We do not cover Rotawave as the heating energy for torrefaction in their process is electrical energy, rendering the process more expensive for most places, except those where a surplus of otherwise unmarketable electrical energy may be available.

The reactors have different strengths and weaknesses, so it is important to know the feedstock and the desired product characteristics to pick the best-suited one. One of the participants focused on a gas management system that could be integrated with any reactor and has efficient heat reclaim, process safety, and product quality.

Table 1 is an updated list of who developed torrefaction technology in 2015; it shows many, but not all of the developers in the market. Yellow highlight indicates companies who are part of this study. Light red indicates companies who abandoned their effort, closed down plants, got acquired, or went out of business.

Developer	Technology	Location(s)	Capacity (t/y)
AFS	Rotary drum	Oliveira de Azeméis (Port)	3,000
Agri-Tech Producers LLC (US/SC)	Screw reactor	Raleigh (USA/NC)	Undefined
Agri-Tech Producers LLC (USA/SC)	Screw reactor	Allendale (USA/SC)	13,000
Airex (CAN/QC)	Cyclonic bed	Bécancour (CAN/QC)	16,000
Airex (CAN/QC)	Cyclonic bed	Rouyn-Noranda (CAN/QC)	Undefined
Airex (CAN/QC)	Cyclonic bed	Trois-Rivières (CAN/QC)	Undefined
Andritz (AT)	Rotary drum	Frohnleiten (AT)	10,000
Andritz (DK) / ECN (NL)	Moving bed	Stenderup (DK)	10,000
Arigna Fuels (IR)	Screw reactor	County Roscommon (IR)	Undefined
ATS	Undefined	St.Louis (USA/MO)	15,000
BC Biocarbon	Pyrolysis Reactor		90,000
BioEndev (CAN)	Fluidised bed	Nova Scotia (CAN/NS)	Undefined
BioEndev (SWE)	Dedicated screw reactor	Holmsund, Umea (SWE)	16,000
CEA (FR)	Multiple hearth	Paris (FR)	Undefined
CENER (SP)	Rotary drum	Aoiz (ES)	Undefined
Clean Electricity Generation (UK)	Oscillating bed	Derby (UK)	30,000
CMI NESA (BE)	Multiple hearth	Seraing (BE)	Undefined
Earth Care Products (USA)	Rotary drum	Independence (USA/KS)	20,000
Grupo Lantec (SP)	Moving bed	Urnieta (ES)	20,000
HM3 (US)	Moving bed	Northern AZ (USA)	50,000
Horizon Bioenergy (NL)	Oscillating belt conveyor	Steenwijk (NL)	45,000
Integro Earth Fuels, LLC (USA)	Multiple hearth	Greenville (USA/SC)	11,000
LMK Energy (FR)	Moving bed	Mazingarbe (FR)	20,000
River Basin Energy (USA)	Undefined	Laramie (USA/WY)	Undefined
Rotawave, Ltd. (UK)	Microwave	Chester (UK)	Undefined
Solvay (FR) / NBE (USA)	Screw reactor	Quitman (USA/MS)	80,000
Teal Sales Inc (USA)	Rotary drum	White Castle (USA/LA)	15,000
Terra Green Energy (USA)	Multiple hearth	McKean County (USA/PA)	Undefined
Topell Energy (NL)	Fluidised bed	Duiven (NL)	60,000
Torr-Coal B.V. (NL)	Rotary drum	Dilsen-Stokkem (BE)	30,000
Torrec (FI)	Moving bed	Mikkeli (FI)	10,000
TSI	Rotary drum	Lynnwood, WA, USA	62,000
Wyssmont (USA)	Multiple hearth	Fort Lee (USA/NJ)	Undefined
Yilkins (NL)	Fluidized bed	Groningen (NL)	60,000

Table 1: Developers of torrefaction technology 2015 (with some updates)

One of the challenges for reactor design is that biomass has relatively low heat conductivity, hence to uniformly and expediently react the biomass, the individual particles will have to be small. Sizing the feedstock to small particle sizes is energy-intensive. Larger particles will either require longer dwell times in the reactor or experience a high thermal gradient from surface to core, leading to charring in the outer layers and incomplete torrefaction in the center. Non-uniform torrefaction results in a lower product quality with reduced yield, less water resistance, and lower durability of the pellets. Significant innovation has been the development of fluidized beds to get higher heat transfer efficiency in the dryers and reactors. The advantage of fluid beds is a turbulent contact between the hot gas and the solids. However, even with an improvement in the heat transfer rate to the biomass surface, the process remains limited by the heat conduction rate from the biomass particles' surface to the core. A limitation of fluidized beds is that they require a narrow distribution of particle sizes and fluid velocity to maintain the bed's stability. To operate a fluidized bed reactor requires very tight process control and tight particle size and velocity distributions.

For high solids yield, torrefaction should stop when water resistance and grindability of the resulting torrefied product are established. The compromise is with the resulting product's energy density and the slightly higher transportation cost per GJ. Only where transportation cost is high would higher densification offer an advantage.

Different Torrefaction Reactor types

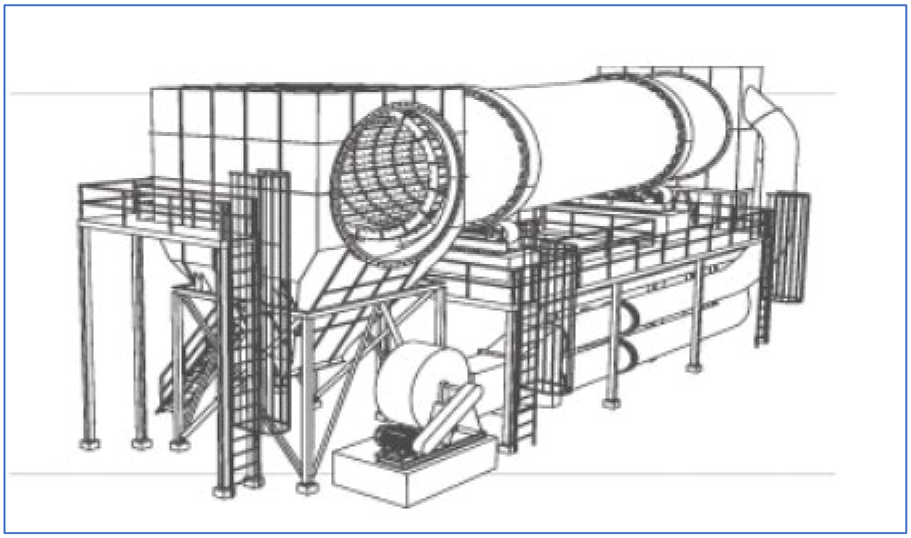


Figure 4: Rotating Drum Reactor [5]

Varying the torrefaction temperature, rotation speed, length, and slope angle of the drum controls the process. The drum rotation causes particles in the bed to mix correctly and exchange heat, but it also produces additional fines. Scaling up rotating drum dryers for wood up to 600 kt/y has been demonstrated. This massive scaling has not yet been done for torrefaction.

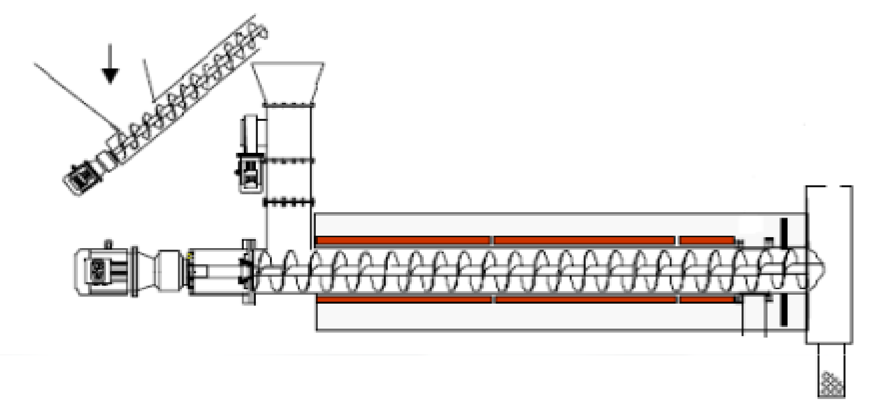


Figure 5: Auger screw-type reactor [5]

The screw reactor is a proven technology that can be placed both vertically as well as horizontally. A screw reactor is heated indirectly using a medium inside the hollow wall or hollow screw. There are variations of the reactor design where heat is applied directly by using a twin-screw system. A disadvantage of indirect heating is the potential formation of char on the hot zones. A screw reactor is heating rate limited because of the limited mixing of the biomass. The residence time inside the reactor is determined by the length and rotation speed of the screw. A screw reactor is relatively inexpensive, but the scalability is limited as the ratio of screw surface area to reactor volume decreases for larger reactors. Some reactor designs implement agitation gear, like T-fingers, for improved heat transfer, enabling larger reactor volumes.

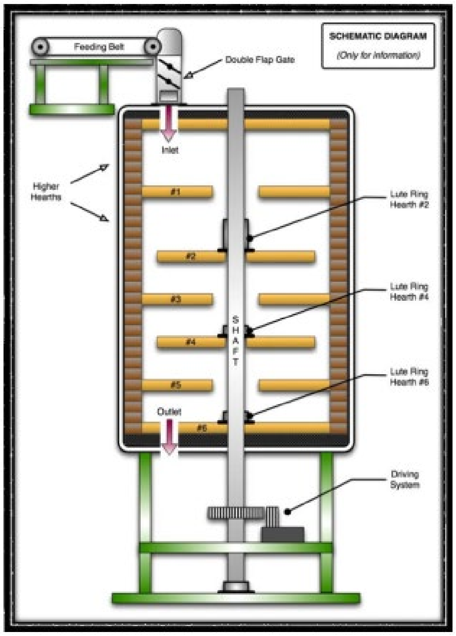


Figure 6: Multiple hearth furnace [5]

The MHF technology can process a wider variety of feedstock particle sizes, ranging from sawdust to larger chips and even scraps. The technology is well suited for research purposes since each step of the torrefaction sequence can be conveniently accessed for material and gas sampling. Besides, accurate adaptive temperature control and injection of additives are feasible. Typical processing time is 30 minutes from top to bottom, requiring high specific reactor volumes. MHF reactors have a low specific CAPEX ($/th) as they can be scaled up to 7-8 m in diameter.

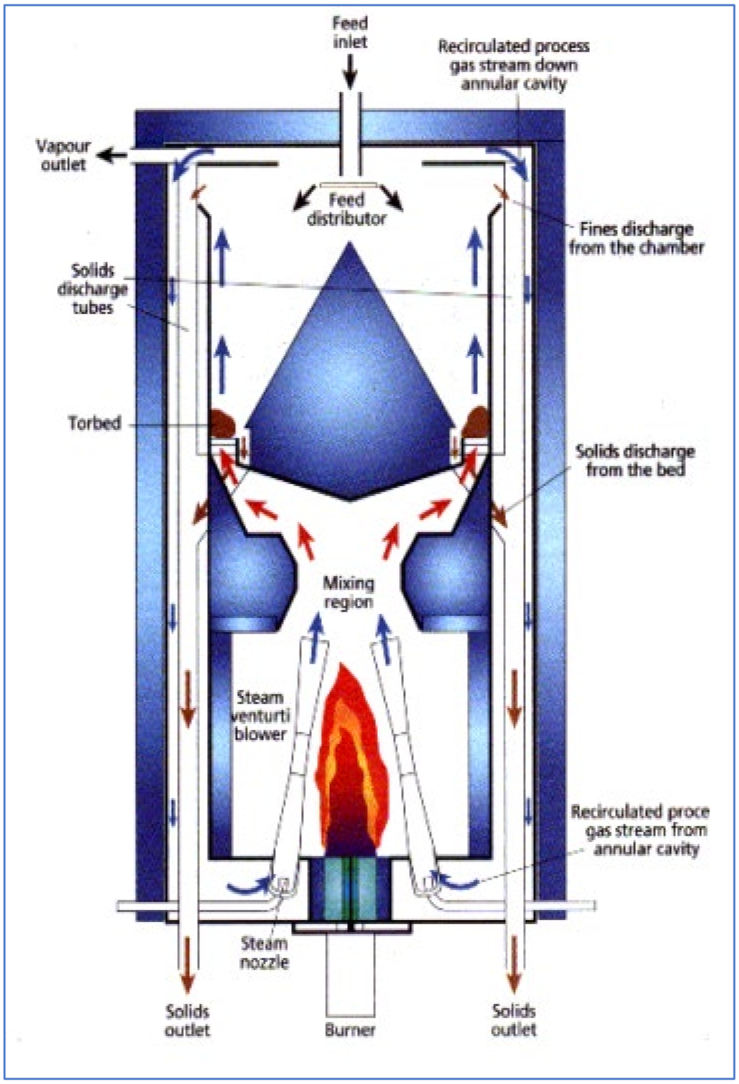


Figure 7: Fluidized bed reactor, toroidal configuration [5]

Fluidized Bed reactors can have different designs. In a toroid or torbed reactor, a heat-carrying medium blows from the bottom of the bed with high velocity (50 - 80 m/s) past stationary, angled blades. The gas flow gives the biomass particles inside the reactor both a vertical and a horizontal movement, resulting in toroid swirls that rapidly heat the biomass particles on the reactor's outer walls. The heat transfer rate is very high and makes for short dwell times (around 80 sec). The reactors can be built smaller as the throughput rate is high. The intense heat transfer accommodates a broader range of temperatures to achieve higher devolatilization in a controlled manner. The technology is adaptable to a wide range of feedstock but does require a very narrow particle size distribution.

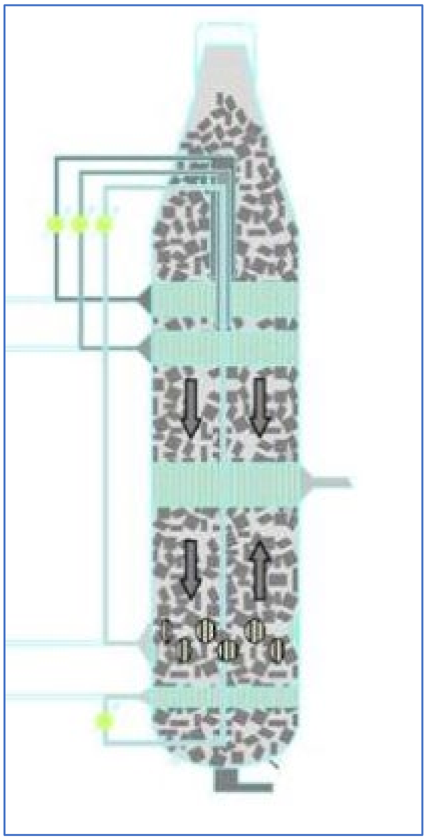


Figure 8: Moving bed reactor (MBR) [5]

An MBR is a low-cost and straightforward reactor type; it does not contain moving parts. The reactor has a constant volume, so the torrefaction time is controlled by the feed and exit rate; it typically is about 30 min at 300°C. The process is sensitive to gas channeling in larger devices, resulting in quality problems, charring, and non-uniform torrefaction.

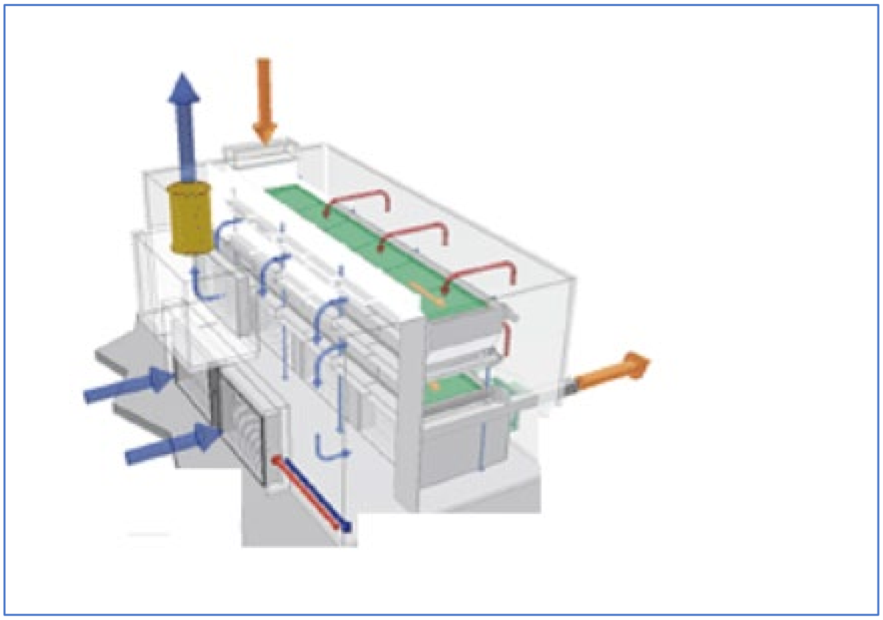


Figure 9: Vibrating belt or grate reactor [5]

Biomass particles are transported using a moving, porous belt or a vibrating grate and are directly heated. In a belt dryer type reactor, usually, multiple belts are placed on top of one another. While biomass particles fall from one belt on the other, mixing of the particles occurs, resulting in a more homogeneous product. Vibrating grate reactors are designed similarly. By controlling the belt speed or the grate vibration frequency, the residence time for all particles inside the reactor can be well controlled, particularly for belt reactors. A potential disadvantage is the clogging of the belt's open structure or the grate by torrefaction tars and particles. Further, due to the small volume, the reactor is not suitable for materials with low bulk densities.

Energy Density, Water Resistance and Grindability

Energy Density after torrefaction

The gravimetric and volumetric energy density increase in torrefied material results from the partial removal of low energy density components. Hemicellulose has a higher oxygen-carbon ratio and a lower calorific value than lignin and cellulose.

The dependence of the LHV of torrefied wood mass is illustrated in Fig.3 p.10 as a function of feedstock and dry mass weight loss (Anhydrous Weight Loss, AWL). The behavior of different wood species stems from the varying content of high calorific value resinous compounds. Softwood and pine are at the high end as they contain more resins than Hardwood.

Durability and water resistance of torrefied pellets

Minimum pellet durability requirements are detailed in BS EN ISO 17225-2 [6]. Premium pellets are expected to have a >97.5% durability. Higher durability of pellets also correlates well with lower energy requirements to grind the pellets and cost-saving for the buyer [7]. Higher durability of the pellets is desirable to avoid excessive dust formation and material losses during handling. Dust formation poses an increased fire and explosion risk as well as loss of calorific value.

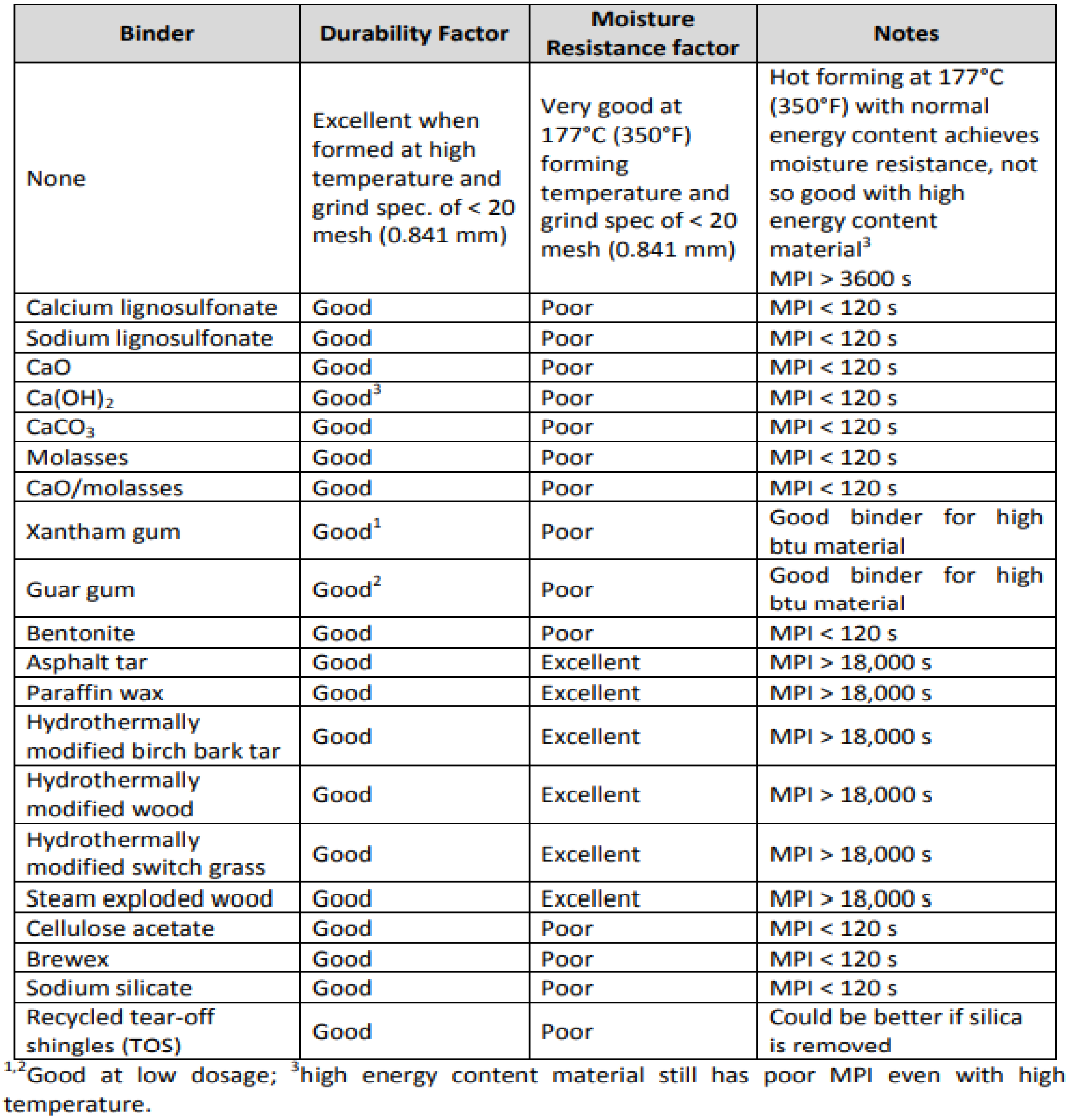
Once pellets are loaded onto a ship, fines formation is of no economic consequence to the seller as the fines will be paid for by the off-taker. However, the off-taker typically insists on the pellets' minimum durability as the fire and explosion risk is still present. The durability of pellets is primarily influenced by how much of the biomass's original lignin content is still present after torrefaction or whether a binder is used. Lignin acts as a glue to increase the elasticity of the more brittle and partially carbonized Cellulose fibers. Lignin further helps slow the penetration of water into the pellets as it acts as a hydrophobic coating.

Higher torrefaction temperatures increasingly reduce the lignin fraction in the torrefied biomass and result in lower durability of the pellets. As lignin softens or even melts during the densification (pelletization) process, it acts as a lubricant, reducing wear on the die and lowering the pellet presses' energy requirement. Higher energy needs for the pelletization process and shorter tool life are both unfavorable cost factors. For higher torrefied biomass with lower lignin content, binders are added to produce the lignin's missing effects.

Most binders are either starches, gums, lignin, lignosulfonates, tars, or waxes. They are usually added in the range of 1-5% of the torrefied biomass's weight. Typically, the cost of binders is at least $ 5 to treat one ton of product. While binders lower the energy consumption during pelletizing and improve the pellets' durability favorably, many affect the moisture resistance unfavorably.

In Table 2, the Moisture Penetration Index (MPI) is shown for different types of binders [9]. Binders that do not adversely affect the product's water-resistance include tars, waxes, lignin, and hydrothermally treated wood.

We advise caution for another reason; the use of non-renewable binders, such as waxes from petrochemical sources, may affect the "renewable" classification of the fuel. Currently, only some European Countries (UK, Netherlands, Denmark) have strict and extensive GHG emission accounting for the entire value chain of biomass; we expect that over the next few years other Countries may adopt similar measures.



Binder	Durability Factor	Moisture Resistance factor	Notes
None	Excellent when formed at high temperature and grind spec. of < 20 mesh (0.841 mm)	Very good at 177°C (350°F) forming temperature and grind spec of < 20 mesh (0.841 mm)	Hot forming at 177°C (350°F) with normal energy content achieves moisture resistance, not so good with high energy content material[3] MPI > 3600 s
Calcium lignosulfonate	Good	Poor	MPI < 120 s
Sodium lignosulfonate	Good	Poor	MPI < 120 s
CaO	Good	Poor	MPI < 120 s
Ca(OH)$_2$	Good[3]	Poor	MPI < 120 s
CaCO$_3$	Good	Poor	MPI < 120 s
Molasses	Good	Poor	MPI < 120 s
CaO/molasses	Good	Poor	MPI < 120 s
Xantham gum	Good[1]	Poor	Good binder for high btu material
Guar gum	Good[2]	Poor	Good binder for high btu material
Bentonite	Good	Poor	MPI < 120 s
Asphalt tar	Good	Excellent	MPI > 18,000 s
Paraffin wax	Good	Excellent	MPI > 18,000 s
Hydrothermally modified birch bark tar	Good	Excellent	MPI > 18,000 s
Hydrothermally modified wood	Good	Excellent	MPI > 18,000 s
Hydrothermally modified switch grass	Good	Excellent	MPI > 18,000 s
Steam exploded wood	Good	Excellent	MPI > 18,000 s
Cellulose acetate	Good	Poor	MPI < 120 s
Brewex	Good	Poor	MPI < 120 s
Sodium silicate	Good	Poor	MPI < 120 s
Recycled tear-off shingles (TOS)	Good	Poor	Could be better if silica is removed

[1,2] Good at low dosage; [3] high energy content material still has poor MPI even with high temperature.

Table 2: Moisture penetration index (MPI) for various binders of biomasses

Water-resistance and water uptake after exposure

The drying and subsequent torrefaction processes remove virtually all free water from the original biomass. Besides, during torrefaction, OH-radicals are substituted by unsaturated non-polar groups, which adds to the increased lignin ratio's hydrophobicity effect. The torrefied material's hydrophobic character renders it less prone to biodegradation (rotting), self-heating, and moisture uptake. During open storage and transportation, exposure of the product to high humidity and rain happens, leading to some water uptake. Moisture uptake degrades the durability and the calorific value of the fuel. J.H. Peng et al. [10] studied the hygroscopicity of 6 mm pellets made from torrefied wood at temperatures from 240-340°C. The control was regular white pellets; Peng et al. performed moisture up-take tests at 30°C and 90% relative humidity. Fig. 11 illustrates the hygroscopic characteristics of torrefied pellets without binder or additive as a function of time and torrefaction temperature. The ISO Technical Committee 238 is developing testing standards to determine hygroscopicity (sorption of relative humidity in the air), water absorbance, and freezing characteristics.

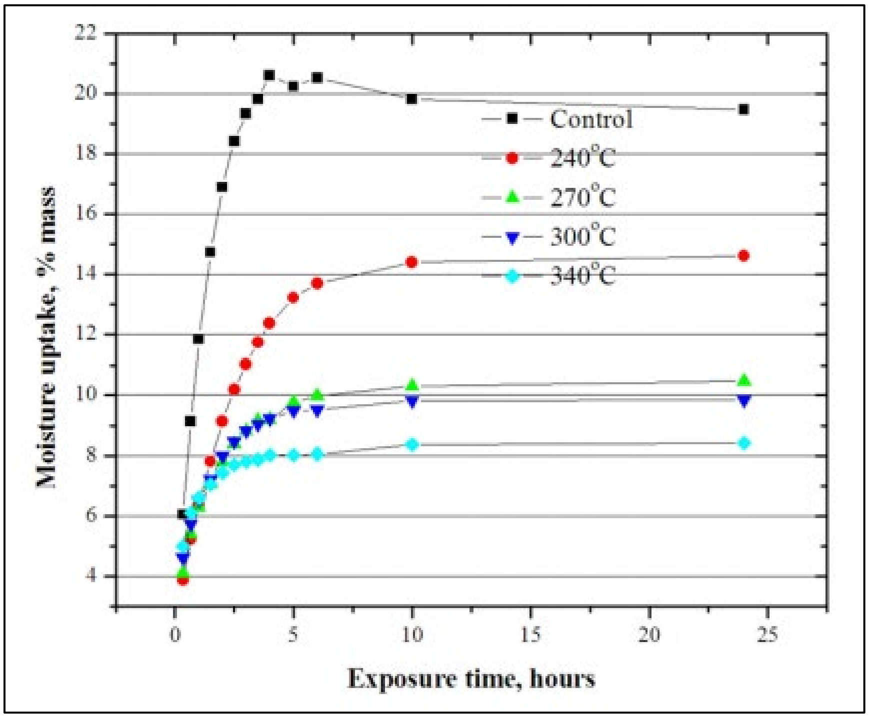


Figure 10: Moisture uptake @ 30°C/95% RH

Grindability

The drying of the biomass and the thermal decomposition of hemicellulose results in increased brittleness of the torrefied biomass. The increase in brittleness starts already in the drying phase; dehydration induces a shrinking of the lignocellulosic material. The shrinkage creates some stress in the wood fibers that result in micro-cracks or defect creations, which causes porosity and density changes. During drying, lignin passes through its glass transition and softens. Cellulose stress is released by creating cracks or fiber/network defects. Moreover, during cooling, the lignin solidifies in a tightened state. In this state, cracks can propagate easily. Thus, crack creations, density decrease, and material stiffening favor energy decrease and smaller particle sizes from the grinding process.[10]

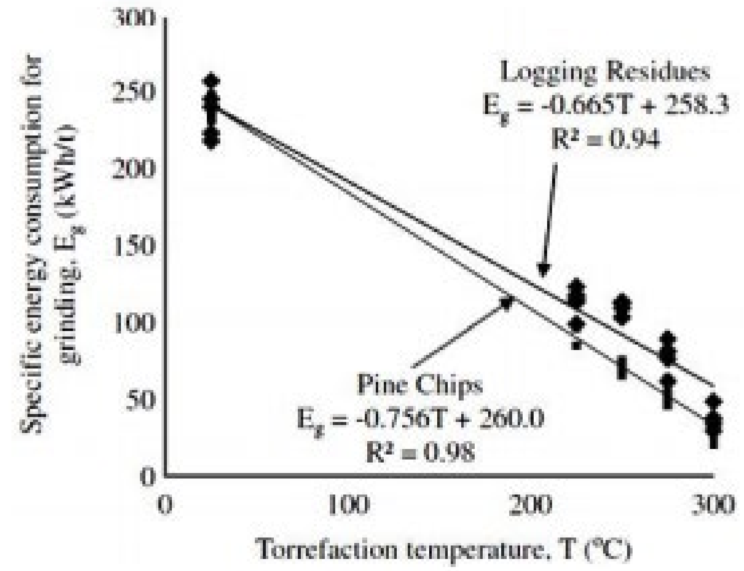


Figure 11: Energy consumption for grinding vs. torrefaction temperature

In the next segment, we evaluate individual processes based on the inputs from the developers or operators; we checked each for thermodynamic consistency. Some developers and operators offered mass-energy balances (ME balances) but used slightly different formats. We scaled each process to a 200,000 t/y o.d. input capacity equivalent, except where noted. CAPEX and OPEX figures were normalized for common elements of the plants, and the same feedstock cost, fuel cost, labor rates, and electrical energy rates were used for the comparison. The processes differ in the severity of torrefaction, mass loss, and supplemental fuel consumption for drying. Feedstock cost, fuel cost, labor rates, and energy rates vary by location; hence, calculating an actual project cost for the specific set of circumstances is necessary. Mass and energy loss from the feedstock's dry matter is a downside of thermal treatment processes that have to be compensated either by a higher price for the pellets/briquettes or by pursuing additional value streams. None of the studied processes included capturing and marketing biochemicals from the torrefaction gasses, but some developers consider it. Some of the contacted companies offered only sparse information that did not allow a robust techno-economic analysis.

Advanced Fuel Solutions (AFS)

Product and service description

AFS is a fairly young company located in Portugal, Área de Acolhimento Empresarial de Loureiro, lote 17, 3720-075 Oliveira de Azeméis.

AFS performs research and production of renewable fuels from forest biomass with high added value. AFS offers turnkey projects covering all the steps from conceptualization to commercialization of the project. The services include consultancy in defining the production process, defining and getting approval for the layout, technical proposals, EPC, completion of civil works, equipment installation, and start-up support.

AFS started its process by doing R&D in a fully equipped laboratory on the premises of its sister company YGE – Yser Green Energy SA lab. AFS built a 3000 t/y pilot plant for product development and process improvement. Currently AFS is finalizing its commercial unit of 100,000 t/y unit for torrefying biomass.

We received a data sheet that lists the product's elemental composition, geometry, LHV ranges, ash softening, and ash melting temperatures. These values refer more to the feedstock than the process; we do not include them in this report. AFS did not include information on durability, mass loss, or energy loss.

Process description

AFS claims to work on numerous woody biomass sources and multiple value streams from torrefied pellets, pyrolysis, and liquid biofuel. As for pellets, AFS provided very little information on the technology and the process. Their pellets are supposed to have an LHV of 22 GJ/t and do not require the use of a binder.

AFS uses a drum torrefaction reactor owned by KONZA RENEWABLE FUELS INC (USA)

AFS provided no further detailed process flow diagram or mass/energy balance of their process or any more detailed cost figures, other than a very high-level CAPEX estimate of $59M for a 200 kt/y input equivalent pellet plant.

Comments and Conclusion

Because of the scarce and highly generic nature of the provided information, we cannot analyze and validate the AFS process with regard to its thermal efficiency, or their product for economic feasibility. AFS seem to have a capable facility at their disposal, and some industry-renown researchers work there. We cannot offer an opinion about their ability to perform EPC services. Given the complexity of performing such services in countries with different work cultures, languages, and regulations, we would have loved to see more detail about their resources and experience with such undertakings. For further information, we suggest contacting them directly at info@adfuelsolutions.com.

Airex Energy – CarbonFX process

Product and service description

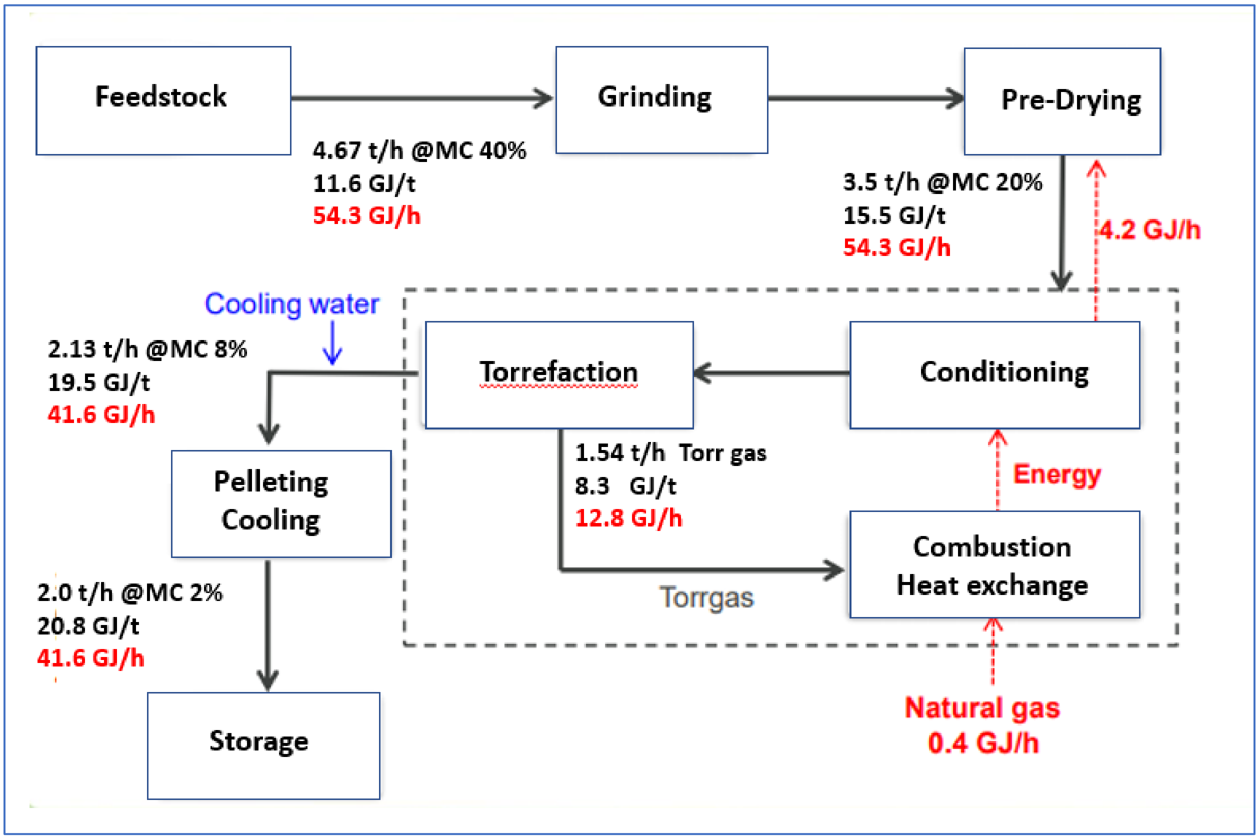
Airex offers a comparatively robust and straightforward integrated torrefaction system. The system's design allows for moderate torrefaction with limited mass and energy loss and higher torrefaction up to bio-coke.

Process description

Hammermills reduce the biomass to sawdust consistency with a narrow size distribution. The small particle size and the tight size distribution are crucial to product properties and consistent quality as the dwell time in the torrefaction reactor is very short. It is then pre-dried using residual heat from the combustion process. The green feedstock's moisture content is reduced from 50% to 20+/- % in the pre-dryer.

The pre-dried feedstock is then moved into a conditioning chamber and transported through it by endless screws. The conditioning chamber is double-walled. The combustion gasses heat the space between the double walls; the biomass gets heated indirectly through contact with the inner wall. The heat evaporates the residual moisture in the biomass. At the end of the conditioning chamber, the biomass is then entrained in the hot flue gasses from the combustion chamber and moved into the torrefaction reactors.

The biomass enters the vertical reactor's top, following a downward cyclonic path to the sustentation ring at the reactor's base. The sustentation ring creates turbulence and forces the biomass to remain suspended in the reactor. The biomass's total dwell time in the reactor is 2 to 3 seconds at about 400^{o}C. As the torrefied biomass exits the reactor, it is sprayed with water to cool it, increasing the moisture content to 8%. The very high temperature of the flue gas prevents deposits and the low volume of biomass in the reactor at any given time; in Airex's example, about 1.7 kg for a 3 second dwell time adds a safety margin. The torrefaction process is very tunable to higher carbon content by lengthening the dwell time in the reactor.



Courtesy of Airex

Figure 12: Airex process flow and mass/energy flow diagram

The reintroduced moisture content is then partially removed in the pelleting process. The exiting product has an MC of 2%. According to Airex Energy, additives (binders and moisture repellants) may be added as needed to the product before pelletization. The dwell time in the torrefaction reactor determines the degree of carbonization. Longer dwell time will result in higher mass loss and more energy in the torrefaction gasses. For the use as a coal substitute, it would be optimal to reduce the energy loss as much as possible and still achieve good densification, durability, and water resistance. For such conditions, binders and additives are not necessary.

Airex Energy has not provided a more detailed gas/mass flow diagram. Still, from a summary energy balance perspective, we conclude that the energy necessary to drive the water out of the green feedstock is accounted for by the energy loss and the addition of .2 GJ/t of output. The ME flow diagram shown is from a 15 kt/y demonstration system. The reported dry mass loss in the process is 29%, while the energy content loss is 23%; as the system is quite flexible, there may be room to improve on those numbers by adjusting the degree of torrefaction. The use of propane as a supplementary heat source costs about $ 2.80 per ton of output; with the addition of a solid fuel furnace, the same thermal energy from lower grade solid fuel would only be about $ .70/t of production.

Economics of the Airex Energy CarbonFX process

CAPEX

Airex estimates the incremental CAPEX for a 200 kt/y equiv. plant at $6.75M.

We constructed the CAPEX table from typical CAPEX figures for the respective generic modules for a regular white pellet plant with a 200,000 t/y capacity. Debarker and log take out, conveyors, chippers have been sized to deal with the same volume of feedstock needed for 200,000 t/y of white pellet output. The heat plant is integrated into the torrefaction/gas management system.

Airex Torrefaction Plant	**CAPEX ['000 $]** **White**	**CAPEX ['000 $]** **Torrefied**
Log debarker/log take out	$1,800	$1,800
Silos/conveyors	$7,000	$7,000
Chippers	$1,150	$1,150
Heat Plant	$3,500	-
Dryer	$4,500	$4,500
Torrefaction/Gas management	**$0**	**$11,250**
Pelletizing system	$3,900	$2,900
Sum Production modules	**$21,850**	**$28,600**
BoP	**$3,750**	**$3,750**
EL/SCADA	**$3,950**	**$3,950**
Civil Engineering Infrastructure	**$6,550**	**$6,550**
Sum of Installation	**$36,100**	**$42,850**
Project execution	$3,950	$3,950
Total Project	**$40,050**	**$46,800**

Table 3: Airex CAPEX for 200kt/y input equivalent plant

The debt/equity ratio is set at	**60/40**
The amortization assumption is set at	**12 years linear**
The interest rate is set at	**5%**

OPEX

Labor Cost

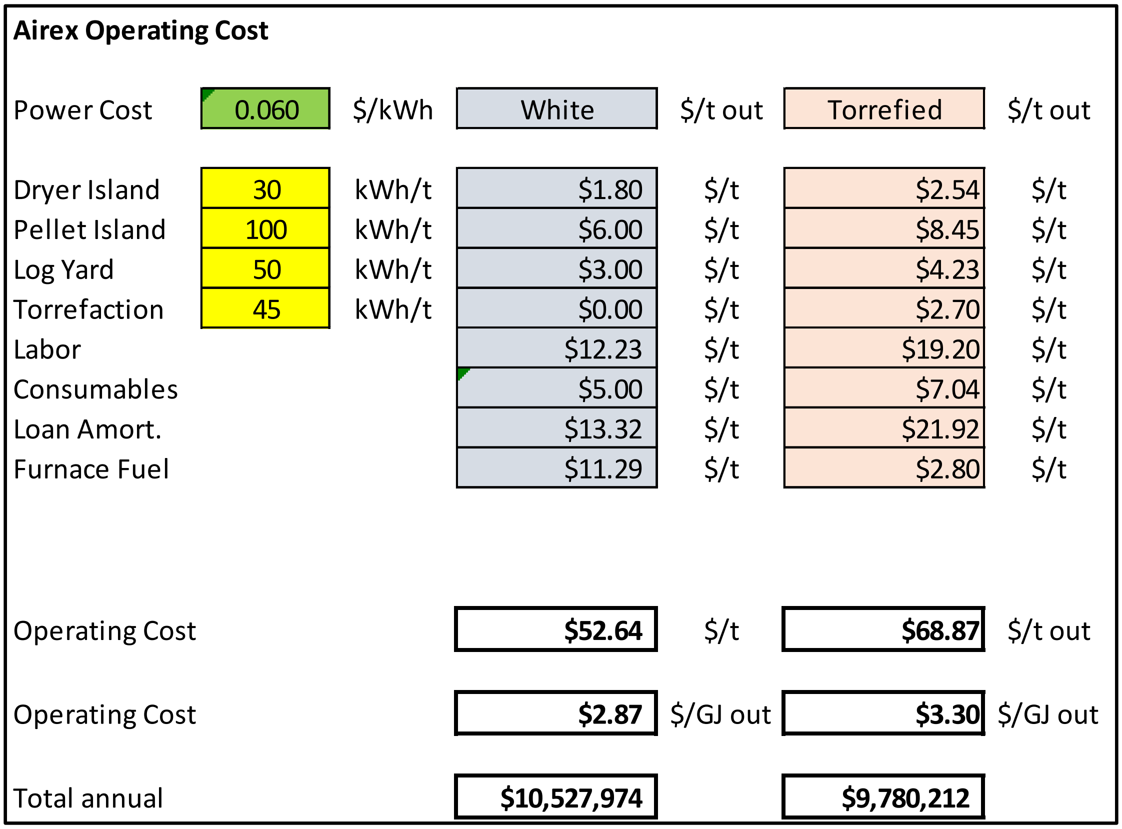
We used a typical headcount and labor cost profile for a White Pellet plant of 200 kt/y capacity with the personnel needed to operate and maintain the torrefaction system (highlighted).

Benefits and Fringes	28%	
Labor rate average	$27.3	$/h
Labor rate average (loaded)	$35.0	$/h
Average work time /week	40	h/week
Estimate labor cost	$2,730,000	$/y

Estimated staffing requirements - 200kt/y input equiv. torrefaction plant					
Postion	Staff category	Staff per shift	Number of shifts	Staff required	Comments
Material handling	Driver/Plant operator	1	4	4	Wood / log yard driver
Plant operator - material preparation	Driver/Plant operator	1	4	4	Grinding, chipping, milling, conveyance
Plant operator - energy system	Driver/Plant operator	1	4	4	Boiler / dryer / balance of plant
Plant operator - pellet production	Driver/Plant operator	1	4	4	Torrefaction, gas management, pellet press
Production assistant	Unskilled labor	1	4	4	General production assistance, cleaning, etc.
Shift supervisor	Process control operator	1	4	4	Shift supervision, operator assistance
Maintenance technician - mech / el.	Mech/elec/control technician	1	3	3	
Plant manager	Operations manager	1	1	1	
Administration (office, laboratory, etc.)	Administrator	2	1	2	
Material handling	Driver/Plant operator	1	1	1	Wood receiving, shiploading, biomass fuel
Logistics	Administrator	1	1	1	Misc. / weighbridge operator
Production manager	Engineering manager	1	1	1	Production/energy plant
Maintenance manager	Equipment maintenance manager	1	1	1	Plant maintenance
Maintenance technician (locksmith, fitter)	Mech/elec/control technician	2	1	2	
Maintenance technician (electrican)	Mech/elec/control technician	2	1	2	
Control systems engineer	Mech/elec/control technician	1	1	1	
		Total estimated staff		**39**	

Table 4: Airex labor and payroll assumptions

Other Operating Expenses



Airex Operating Cost

Power Cost	0.060	$/kWh	White	$/t out	Torrefied	$/t out
Dryer Island	30	kWh/t	$1.80	$/t	$2.54	$/t
Pellet Island	100	kWh/t	$6.00	$/t	$8.45	$/t
Log Yard	50	kWh/t	$3.00	$/t	$4.23	$/t
Torrefaction	45	kWh/t	$0.00	$/t	$2.70	$/t
Labor			$12.23	$/t	$19.20	$/t
Consumables			$5.00	$/t	$7.04	$/t
Loan Amort.			$13.32	$/t	$21.92	$/t
Furnace Fuel			$11.29	$/t	$2.80	$/t
Operating Cost			**$52.64**	$/t	**$68.87**	$/t out
Operating Cost			**$2.87**	$/GJ out	**$3.30**	$/GJ out
Total annual			**$10,527,974**		**$9,780,212**	

Table 5: Airex Operating cost (w/o feedstock)

We calculated the OPEX numbers per t/output. The lower number for the total annual for torrefied pellets results from the reduced output due to mass loss and the substantially reduced fuel cost for the dryer.

The CIF Vancouver-Tokyo cost difference for Airex pellets with the given baseline is $.84/GJ. The additional cost of torrefaction in this model is $ 1.29/GJ, of which $ .45/GJ is offset by lower transportation cost. The incremental CAPEX of $6.75M adds $.145/GJ to the cost.

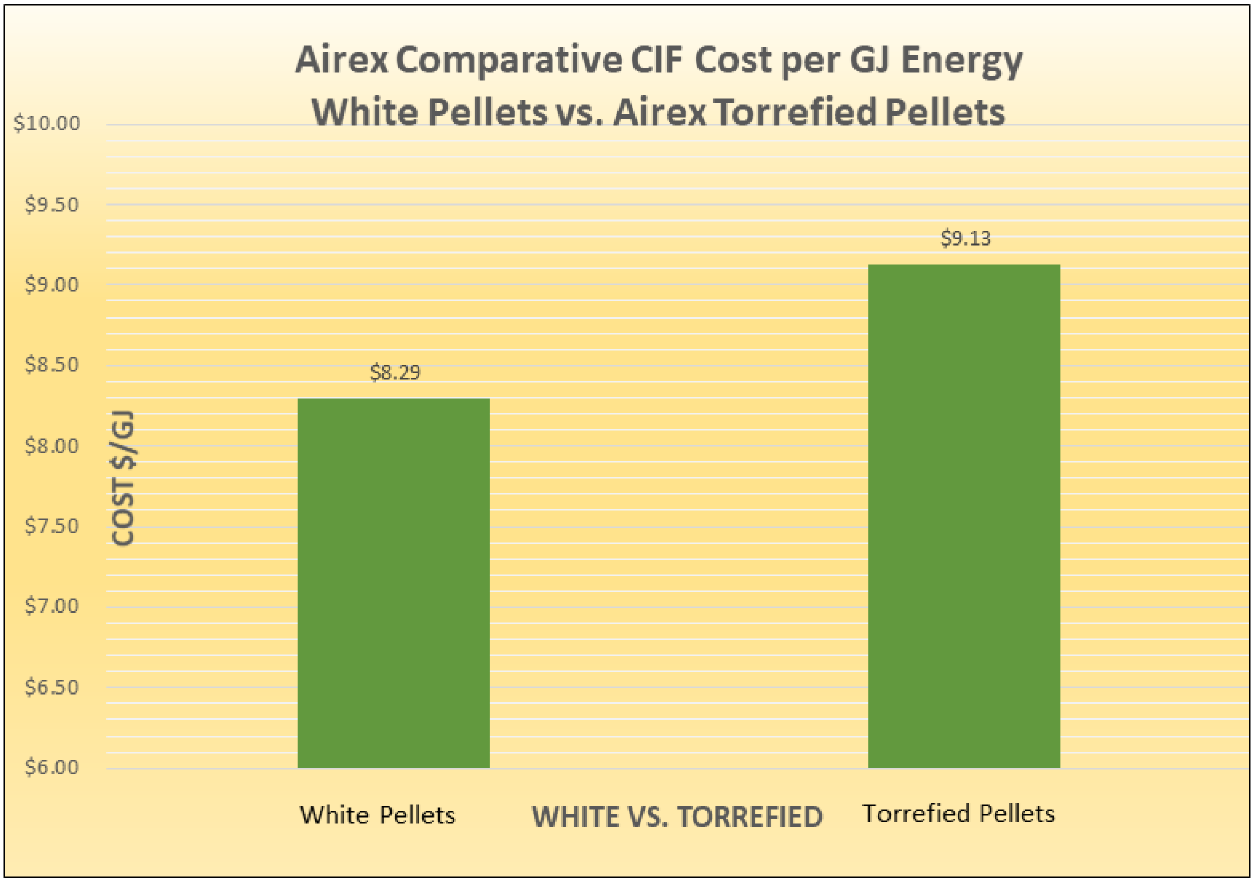


Figure 13: Airex CIF Vancouver-Tokyo cost $/GJ

	White	Torrefied
Hourly Output - GJ/Hour	489	396
Hourly Revenue	$4,940	$4,001
Hourly Cost	$4,054	$3,616
GOP hourly	$885	$385
GOP annual	$6,640,316	**$2,886,157**
Δ GOP vs. White Pellets		**-$3,754,158**
Increase/Decrease		**-56.5%**

Table 6: Airex GOP comparison to white pellets

Airex IP

Country	Pat. Number	Pat. Title	Status 12/2020
CAN	2874789	**Methode and Apparatus for Torrefaction of Biomass with a Cyclonic Bed Reactor**	Granted
EU	13793325.5		Pending
US	9683187		Granted
US	10450523		Granted
CAN	2698176	**Energy Recuperating Filtration Apparatus**	Granted
US	8142551		Granted
US	9174157		Granted

Table 7: Airex IP

Comments and Conclusions

The numbers Airex Energy shared with us included a much lower feedstock cost than we used in our assumptions. Airex stated that the fiber cost in one ton of torrefied pellets (bio-coal) was CAN $ 70. That translates to a pellet feedstock cost of US$ 37.27 o.d. While such low cost exists in the market, they are not very common, except for low-grade biomass, such as hog fuel. In our calculations, we used $70/t o.d. We also used an exit MC of 4%; we do not believe that the pelletization process reduces the MC from 8% to 2%, 8% to 4% seems more realistic. Airex Energy provided information on a process flow that shows 27% mass loss and 23% energy loss from the original CV of the Feedstock; for that amount of mass loss, the CV of the product in GJ/t should be 22 GJ/t if the feedstock is a mix of deciduous and coniferous wood. That translates into an energy loss of 19% as opposed to 23%. We used the 19% number. Compared to white pellets under similar circumstances, the relatively low GOP result suggests that markets should be considered that pay more per GJ for the value-added properties torrefied pellets have (grindability, water resistance, higher carbon content). These pellets may be of interest as a renewable fuel or raw materials for metallurgical purposes or the chemical industry. As coal alternative for power plants, the cost would have to be lower to attract investment.

Advanced Torrefaction Systems (ATS)

Product and service description

ATS offers a torrefaction and gas management system that integrates into torrefied pellet or briquette plants. ATS performs design and EPC functions to match the system to third-party pellet plants, including the necessary data collection and control systems. ATS can match the gas management system to any torrefaction reactor, drum, belt, or vertical. The torrefaction gas management system includes a low-temperature catalytic oxidizer (platinum group metals catalyst on a corrugated iron substrate) to facilitate virtually complete oxidation of the gas's VOCs. The catalytic oxidation does not require excess oxygen (air) to destroy the VOCs and enables the use of the virtually oxygen-free flue gas as the purge gas for the reactor. The ATS offer includes all gas ductwork, the catalytic oxidizer, fans with redundancy, three heat exchangers/gas coolers, full instrumentation and control system including control dampers, insulation with covering, off-site assembly, delivery to the customer's site, and commissioning. The company suggests using at least two modular systems for 200 kt/y; the combined CAPEX would be between $M 6 – 7; we will use $M 6.5 in our economic calculations. Note that the CAPEX number does not include the reactor, conveyors, dryers, or densification equipment.

Process description

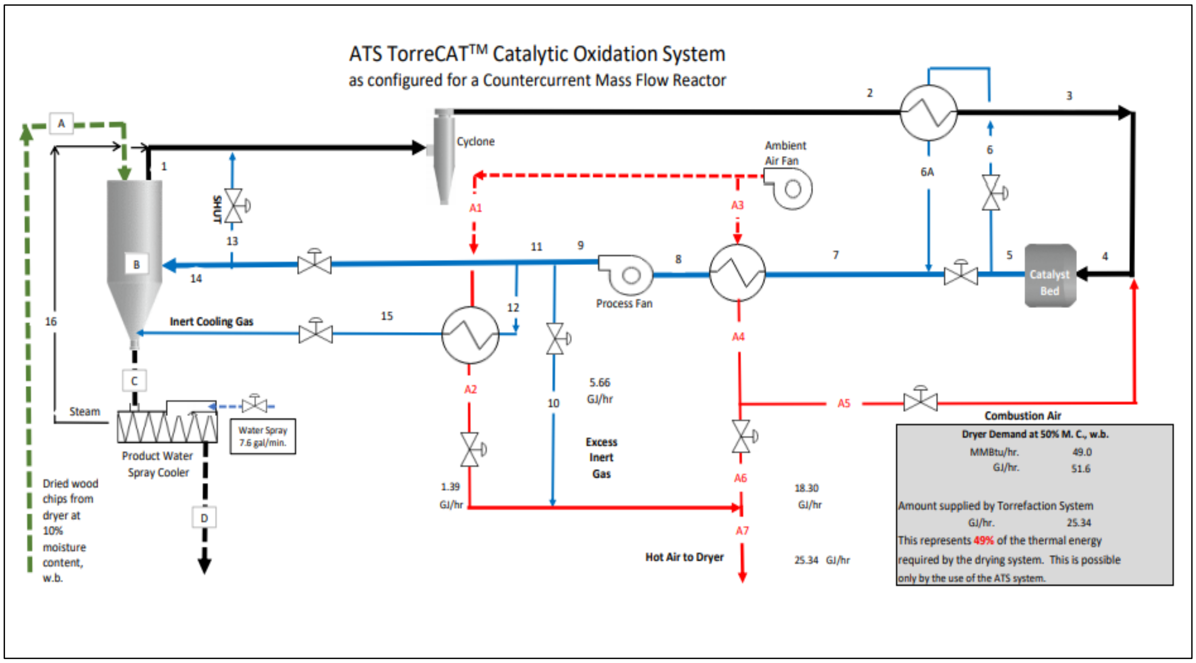
The torrefaction process of ATS, as shown in this example, runs at 270°C. The ATS system can operate at either higher or lower torrefaction temperatures. The feedstock is dried from typically 50% MC w.b. to 10%MC w.b. before entering the torrefaction reactor.

During the torrefaction process, the feedstock loses its residual water content and experiences a dry mass loss of 25%. The mass loss is primarily due to the degradation of hemicellulose into gaseous compounds. The corresponding loss of calorific value (CV) of the feedstock is lower than the mass loss percentage, as the specific hemicellulose CV is lower than that of lignin and cellulose.

The gas management system fulfills the function to flush the torrefaction gasses out of the reactor with an oxygen-depleted gas flow. The dilution of torrefaction gasses minimizes polymerization or condensation of the volatile organics and deposition of the higher molecular weight compounds in the ducts. Further, dilution prevents the retention of volatiles or condensates in the torrefied product and results in a clean product without intense odor or the propensity to self-heating. The high volume of purge gas stabilizes the gas flow from the reactor and makes it more manageable. The diluted torrefaction gasses are fed into the catalytic oxidizer, where all VOCs are oxidized. The exothermic energy of the oxidation process is reclaimed and used for pre-drying the feedstock. For a 50% MC feedstock, the recovered energy in this process supplies a little less than 50% of the required heat to dry the feedstock to a residual MC of 10%. Supplemental heat to dry the feedstock is supplied by burning lower-cost fuels, such as hog fuel. The catalytic oxidation offers the advantage that no surplus air is required to combust the volatiles fully. The reduction of deposits in the ducts and heat exchangers lengthens the time interval between necessary cleanings, reducing cost and downtime.

The efficient reclaim of heat for drying reduces the extra energy required for drying to about 51% of the amount needed to dry feedstock for white pellet production under otherwise the same conditions.

Process flow and Mass-Energy balance of the ATS process



Courtesy of T. Causer ATS

Figure 14: ATS process flow and mass/energy flow diagram

The product is steam stripped and cooled with a water spray at the exit of the reactor. The exclusion of oxygen from the system and cooling before exposure to the atmosphere minimizes fire or explosion risk. In case of an emergency, the system can be flooded with inert gas, blower fans, and controls would be on the emergency power supply and safely enable venting of exhaust gasses through the smokestack during cool down.

ATS Gas Flow		Gas Flows														
			1	2	3	4	5	6	6A	7	8	9	10	11	12
		Torrefaction Gases Generated	**Torregas from Reactor**	**Torregas from cyclone**	**Torregas after Process HE**	**Torrgas + Comb. Air into CAT**	**Torregas from CAT**	**Inert Gas into Process HE**	**Inert gas after Process HE**	**Hot Inert Gas to H.E. #1**	**Inert gas from H.E. #1**	**Inert Gas from Process Fan**	**Excess Inert Gas**	**Inert Gas After Excess Inert gas**	**Inert Gas to H.E. #2**
Total Mass, t/h	t/h	6.1	87.6	88.9	88.9	98.6	98.6	34.1	34.1	98.6	98.6	98.6	17.1	81.4	6.0
Water	t/h	3.6	32.9	34.3	34.3	34.3	35.5	12.3	12.3	35.5	35.5	35.5	6.2	29.3	2.1
Carbon Dioxide	t/h	0.5	17.5	17.5	17.5	17.5	20.6	7.1	7.1	20.6	20.6	20.6	3.6	17.0	1.2
Carbon Monoxide	t/h	0.1	0.1	0.1	0.1	0.1									
Acetic Acid	t/h	0.4	0.4	0.4	0.4	0.4									
Formic Acid	t/h	0.3	0.3	0.3	0.3	0.3									
Methanol	t/h	0.3	0.3	0.3	0.3	0.3									
Lactic Acid	t/h	0.4	0.4	0.4	0.4	0.4									
Furfural	t/h	0.3	0.3	0.3	0.3	0.3									
Hydroxyacetone	t/h	0.1	0.1	0.1	0.1	0.1									
Oxygen	t/h	0.0				2.3									
Nitrogen	t/h	0.0	35.1	35.1	35.1	42.5	42.5	14.7	14.7	42.5	42.5	42.5	7.4	35.1	2.6
Std.Volume flow	m^3/h	5934.6	83203.4	84948.3	84948.3	92882.6	93545.2	32313.3	32313.3	93536.7	93536.7	93536.7	16267.9	77268.8	5649.2
Act. Volume flow	m^3/h	9247.7	125393.0	127572.8	150912.0	169658.7	246988.7	84746.1	63099.2	224816.8	175005.5	160874.9	27980.8	132894.1	9714.9
Temperature	^{o}K	450	450	448	527	535	768	768	568	699	544	544	544	544	544

ATS Solids and Air flows		Solids Flow						Air Flows						
		A	B	C	D	E	F	4	6	6A	7	2	5	8
		Raw Wood to Dryer	**Dried Wood From Dryer**	**TW at Line 14 entrance ring**	**TW exiting Reactor**	**TW from Water Spray Cooler**	**Finished product**	**Air 4 Ambient Air into HE1**	**Air 6 Heated Air FROM HE1**	**Air 6 Minus Air 7 Comb. Air**	**Air 7 Combustion Air**	**Ambient Air into H.E. #2**	**Heated Air FROM H.E. #2**	**Air 8 = Air 6A + Air 5 + Excess Inert Gas**
Total Mass	t/h	34.1	18.9	12.8	12.8	13.2	13.2	63.0	63.0	53.3	9.7	6.3	6.3	76.7
Water	t/h	17.0	1.9	-	-	0.4	0.4	0.1	0.1	0.1	0.0	0.0	0.0	6.3
Carbon Dioxide	t/h							-	-	-				3.6
Carbon Monoxide	t/h							-	-	-				-
Acetic Acid	t/h							-	-	-				-
Formic Acid	t/h							-	-	-				-
Methanol	t/h							-	-	-				-
Lactic Acid	t/h							-	-	-				-
Furfural	t/h							-	-	-				-
Hydroxyacetone	t/h							-	-	-				-
Oxygen	t/h							14.8	14.8	12.5	2.3	1.5	1.5	14.0
Nitrogen	t/h							48.1	48.1	40.7	7.4	4.8	4.8	52.9
Wood	t/h	17.0	17.0	12.8	12.8	12.8	12.8	-	-	-				-
Temperature	^{o}K	298	350	543	473	353	298	298	630	630	630	298	514	598

Table 8: ATS mass flow

Economics of the ATS process

CAPEX

The CAPEX for the ATS TorreCAT module required for 200 kt/y input equivalence is $M 5.5.

We constructed the CAPEX table from typical figures for a white pellet plant with a comparable capacity. Debarker and log take out, conveyors, chippers, and boilers are sized to process feedstock volume for a 200,000 t/y white pellet output. The resulting torrefied pellet output will be lower by the fraction of mass loss. In the case of ATS, the output will be 150,000 t/y torrefied pellets. The heat plant size is reduced compared to a white pellet plant as more than 50% of the heat demand to dry the feedstock comes from the torrefaction gasses combustion.

ATS Torrefaction Plant		CAPEX ['000 $]	CAPEX ['000 $]
		White	**Torrefied**
	Log debarker/log take out	$1,800	$1,800
	Silos/conveyors	$7,000	$7,000
	Chippers	$1,150	$1,150
	Heat Plant	$3,500	$2,500
	Dryer	$4,500	$4,500
Torrefaction/Gas management		**$0**	**$7,500**
	Pelletizing system	$3,900	$2,900
Sum Production modules		**$21,850**	**$27,350**
	BoP	**$3,750**	**$3,750**
	EL/SCADA	**$3,950**	**$3,950**
	Civil Engineering Infrastructure	**$6,550**	**$6,550**
Sum of Installation		**$36,100**	**$41,600**
	Project execution	$3,950	$3,950
Total Project		**$40,050**	**$45,550**

Table 9: ATS Capex for 200kt/y input equiv. plant

The debt/equity ratio is set at	**60%/40%**
The amortization assumption is set at	**12 years linear**
The interest rate is set at	**5%**

OPEX

Labor Cost

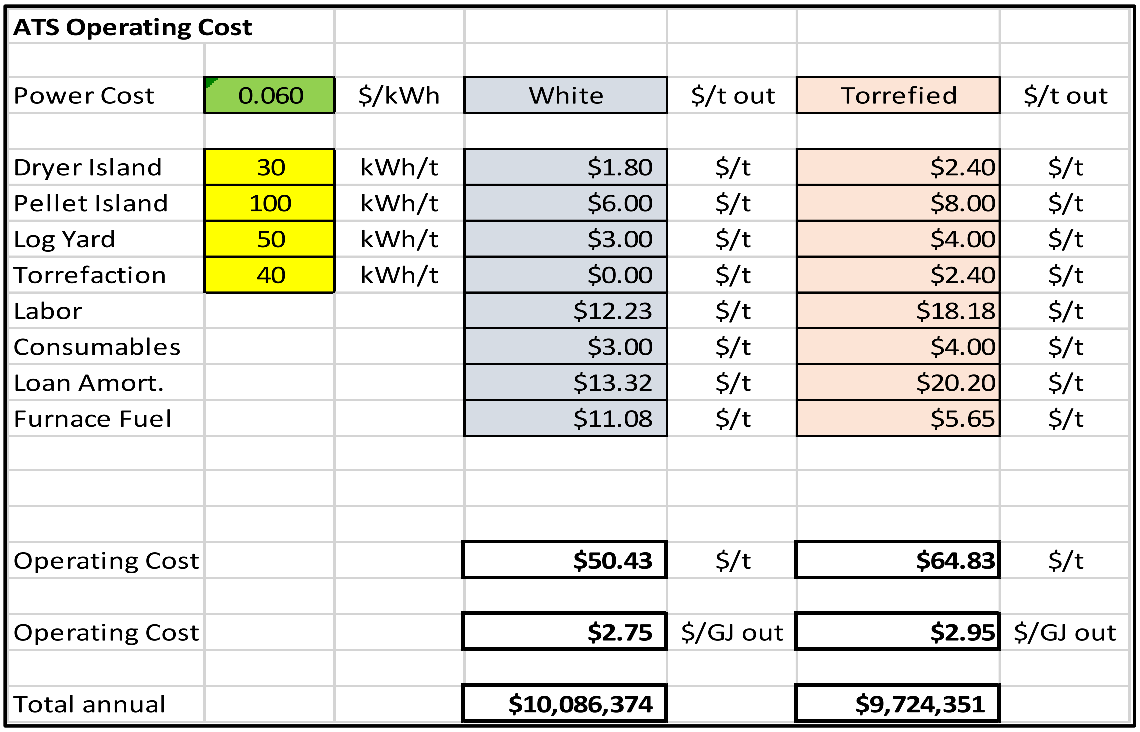
We based the Labor Cost on a typical head count profile for a white pellet plant of 200 kt/y capacity. We added the personnel needed to operate and maintain the torrefaction system (highlighted).

Benefits and Fringes	28%	
Labor rate average	$27.4	$/h
Labor rate average (loaded)	$35.0	$/h
Average work time /week	40	h/week
Estimate labor cost	$2,730,624	$/y

Estimated staffing requirements - 200kt/y input equiv. torrefaction plant					
Postion	Staff category	Staff	Number	Staff	Comments
		per shift	of shifts	required	
Material handling	Driver/Plant operator	1	4	4	Wood / log yard driver
Plant operator - material preparation	Driver/Plant operator	1	4	4	Grinding, chipping, milling, conveyance
Plant operator - energy system	Driver/Plant operator	1	4	4	Boiler / dryer / balance of plant
Plant operator - pellet production	Driver/Plant operator	1	4	4	Torrefaction, gas management, pellet press
Production assistant	Unskilled labor	1	4	4	General production assistance, cleaning, etc.
Shift supervisor	Process control operator	1	4	4	Shift supervision, operator assistance
Maintenance technician - mech / el.	Mech/elec/control technician	1	3	3	
Plant manager	Operations manager	1	1	1	
Administration (office, laboratory, etc.)	Administrator	2	1	2	
Material handling	Driver/Plant operator	1	1	1	Wood receiving, shiploading, biomass fuel
Logistics	Administrator	1	1	1	Misc. / weighbridge operator
Production manager	Engineering manager	1	1	1	Production/energy plant
Maintenance manager	Equipment maintenance manager	1	1	1	Plant maintenance
Maintenance technician (locksmith, fitter)	Mech/elec/control technician	2	1	2	
Maintenance technician (electrican)	Mech/elec/control technician	2	1	2	
Control systems engineer	Mech/elec/control technician	1	1	1	
		Total estimated staff		**39**	

Table 10: ATS Labor and payroll assumptions

Other Operating Expenses



ATS Operating Cost						
Power Cost	0.060	$/kWh	White	$/t out	Torrefied	$/t out
Dryer Island	30	kWh/t	$1.80	$/t	$2.40	$/t
Pellet Island	100	kWh/t	$6.00	$/t	$8.00	$/t
Log Yard	50	kWh/t	$3.00	$/t	$4.00	$/t
Torrefaction	40	kWh/t	$0.00	$/t	$2.40	$/t
Labor			$12.23	$/t	$18.18	$/t
Consumables			$3.00	$/t	$4.00	$/t
Loan Amort.			$13.32	$/t	$20.20	$/t
Furnace Fuel			$11.08	$/t	$5.65	$/t
Operating Cost			**$50.43**	$/t	**$64.83**	$/t
Operating Cost			**$2.75**	$/GJ out	**$2.95**	$/GJ out
Total annual			**$10,086,374**		**$9,724,351**	

Table 11: ATS Operating cost (w/o feedstock)

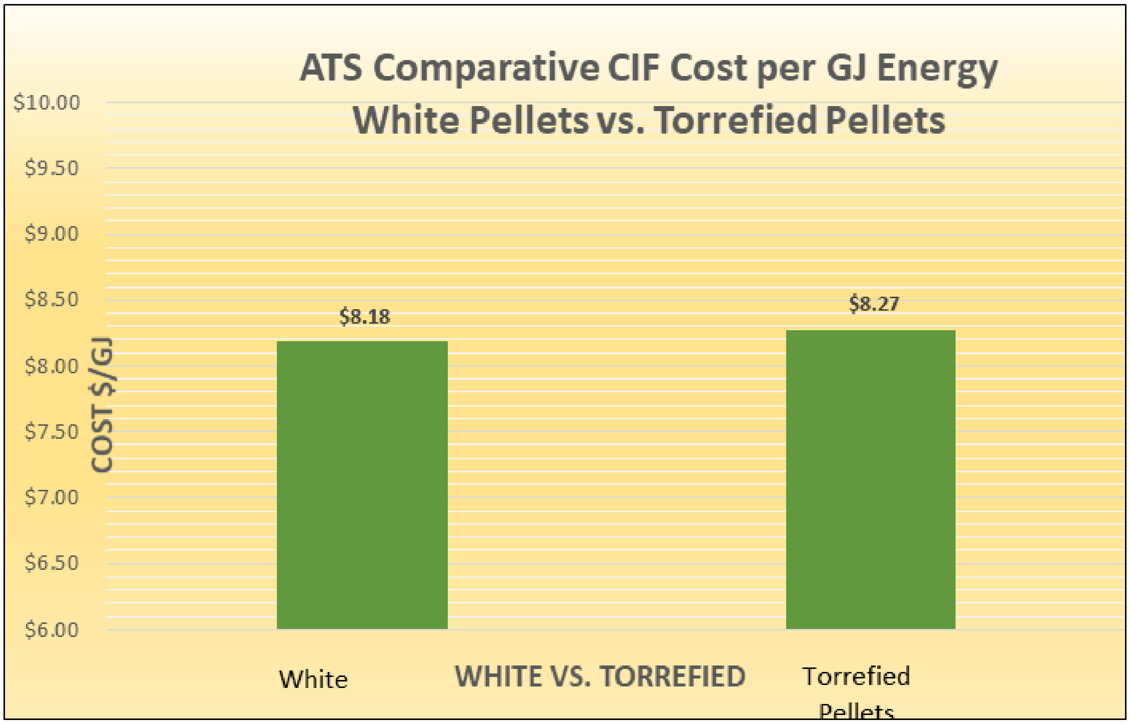


Figure 15: ATS CIF Vancouver-Tokyo cost $/GJ

	White	Torrefied
Hourly Output - GJ/Hour	489	440
Hourly Revenue	$4,940	$4,446
Hourly Cost	$4,001	$3,640
GOP hourly	$939	$806
GOP annual	$7,040,816	$6,042,302
Δ GOP vs. White Pellets		-$998,513
Increase/Decrease		-14.18%

Table 12: ATS GOP comparison to white pellets

ATS IP

Country	Pat. Number	Pat. Title	Status 12/2020
US	8,203,024	**Torrefaction Systems and Methods including Catalytic Oxidation and/or Reuse of Combustion Gasses directly in a Torrefaction Reactor, Cooler, and/or Dryer/Preheater**	Granted
CAN	2,844,735		Granted

Table 13: ATS IP

Comments and conclusions

The ATS process differentiates itself from other torrefaction processes by using a catalytic oxidizer to achieve full combustion of the torrefaction gasses at comparatively low temperatures and without the need for surplus oxygen. Using vast volumes of the oxygen-free flue gas to dilute and purge the torrefaction gasses out of the reactor and into the catalytic oxidizer avoids deposits in the ducts. Flushing out the torrefaction volatiles prevents them from adhering to the torrefied biomass' surface. The depletion of volatiles from the biomass particles surface results in a lower risk of fire, flash-over, self-heating risk, odor, and COD in the leachate. The heat reclaim and the gas management system are efficient. The combusted torrefaction gas supplies about 50% of the dryer's heat demand. ATS has a deep understanding of the mass and energy flow and balances. We believe the CAPEX figures to be reasonable yet somewhat optimistic. The CIF Vancouver-Tokyo cost for each type of pellets is very close. The incremental cost of torrefaction in this model is $ .59/GJ, of which $ .51/GJ is offset by lower transportation cost. The amortization of the incremental debt adds $.06/GJ to the cost. For this case, the lower Transportation and Logistics cost almost compensates for the energy loss. The GOP is lower due to fewer GJ/y produced from the fixed assets. If a premium of $.30/GJ can be obtained GOP parity to white pellets can be established.

BC Biocarbon

Product and service description

BC Biocarbon owns and operates production facilities that convert woody biomass to Biochar or carbon. We do not know if they offer their technology for sale or just their products.

Process description

BC Biocarbon's process differs significantly from the other reviewed torrefaction processes; we will refer to it as a pyrolysis process. Their approach uses hog fuel as feedstock and runs between 500-800°C. The mass and energy loss are much higher than for the other torrefaction technologies. The BC Biocarbon process produces sufficient heat from the pyrolysis gasses to satisfy the dryers' energy demand and still have excessive thermal energy in the flue gas. The generated tars and oils that result from the high pyrolysis temperature are recombined with the carbonized biomass to serve as a binder. Then the biomass is pressed into briquettes with an HHV of 30 GJ/t, which is comparable to coal

For the reviewed case based on 360GJ/h output (comparable to an approximately 150,000 t/y output white pellet plant), the pyrolysis mass loss is 54.3% of the dry feedstock mass. The mass and energy loss are primarily due to driving out volatile compounds and partial carbonization of the biomass resulting in char, tars, and gaseous compounds. The corresponding loss of calorific value in the pyrolysis reactor is 27%.

The heat reclaim from the pyrolysis gasses exceeds the dryer’s heat demand; hence BC Biocarbon can work with less efficient dryers without economic penalty. The process flow starts with hog fuel at 45% MC run through a scalper and a magnetic separator, then onto a drag chain conveyor where it is distributed onto two identical belt dryers. The belt dryers use an air/flue gas mix at 130°C and a rate of 380 t/h to dry the hog fuel to 15%MC. The electrical energy consumption of a dryer is rated at 600 kW. The motors are Variable Frequency Drives (VFD), with a typical duty cycle of 50%.

The dried hog fuel is then distributed into two pyrolysis reactors via a drag chain conveyor, 15.5 t/h each, and heated to 500-800°C. The heating happens through partial burning of the hog fuel with air injected at a rate of 2.6 t/h. 13.9 t/h of gasses and tars are collected and routed out of the reactor. The resulting charcoal is extracted with a screw that is cooled with .5 t/h of water while the biochar is still under oxygen exclusion; the production rate is 3.16 t/h from each reactor.

A screw feeder with a tar injection nozzle moves the char-tar mix to a mixer/grinder. The tar's energy content is approximately 28 GJ/t; the mixing ratio is 50%/50%, resulting in a 6.1 t/h char/tar mix with an HHV of 30 GJ/t from each grinder/mixer.

The briquetting machine at the end of the process flow has a yield of 99% and produces 6 t/h of briquettes. There are two parallel tracks in the reviewed case, which means the process's total output is 12 t/h @ 30 GJ/t.

The gasses collected at a rate of 13.9 t/h from each reactor get burned with air and produce a combined flue gas stream of 234 t/h @ 420^{o}C with an energy content of 103 GJ/h in a 90% efficient burner. The dryers' energy demand is stated as 88 GJ/h, of which 43.5 GJ/h are needed to evaporate the MC of the Feedstock; the rest are losses and energy expelled with the exhaust gas. The residual heat, max. 14.7 GJ/h from burning, is available for auxiliary heating purposes.

Process flow and mass-energy balance

We studied the Process flow diagram and the mass-energy balance but cannot show them as they are marked proprietary.

Economics of the BC Biocarbon process

CAPEX

We have no input from BC Biocarbon on the CAPEX figure for the described flow. Our **estimate** of the $/t/y will be higher than for white pellet plants, mostly due to the tar and oil collection equipment and SCADA components. While the CAPEX per ton/year for white 200,000 t/y pellet plants is typically in the range of $225-240/ t/y, we will use $290/ t/y to estimate the economics of the BC Biocarbon process. The dry feedstock rate would make the BC Biocarbon plant equivalent to a 198,000 t/y white pellet plant.

BC Biocarbon Pyrolysis Plant	**CAPEX ['000 $]**	**CAPEX ['000 $]**
	White	**Torrefied**
Log debarker/log take out	$1,800	$1,800
Silos/conveyors	$7,000	$7,000
Chippers	$1,150	$1,150
Heat Plant	$3,500	$3,500
Dryer	$4,500	$4,500
Pyrolysis reactors, Tar management, Heat reclaim	**$0**	**$16,900**
Briquetting system	$3,900	$2,500
Sum Production modules	**$21,850**	**$37,350**
BoP	**$3,750**	**$4,500**
EL/SCADA	**$3,950**	**$4,500**
Civil Engineering Infrastructure	**$6,550**	**$6,550**
Sum of Installation	**$36,100**	**$52,900**
Project execution	$3,950	$4,500
Total Project	**$40,050**	**$57,400**

Table 14:BC Biocarbon Capex for 200 kt/y equiv. plant

The debt/equity ratio set as	**60/40**
The amortization assumption is set at	**12 years linear**
The interest rate set at	**5%**

OPEX

Labor Cost

We based the Labor Cost on a typical head count profile for a white pellet plant of 200 kt/y capacity. We added the personnel needed to operate and maintain the torrefaction system (highlighted).

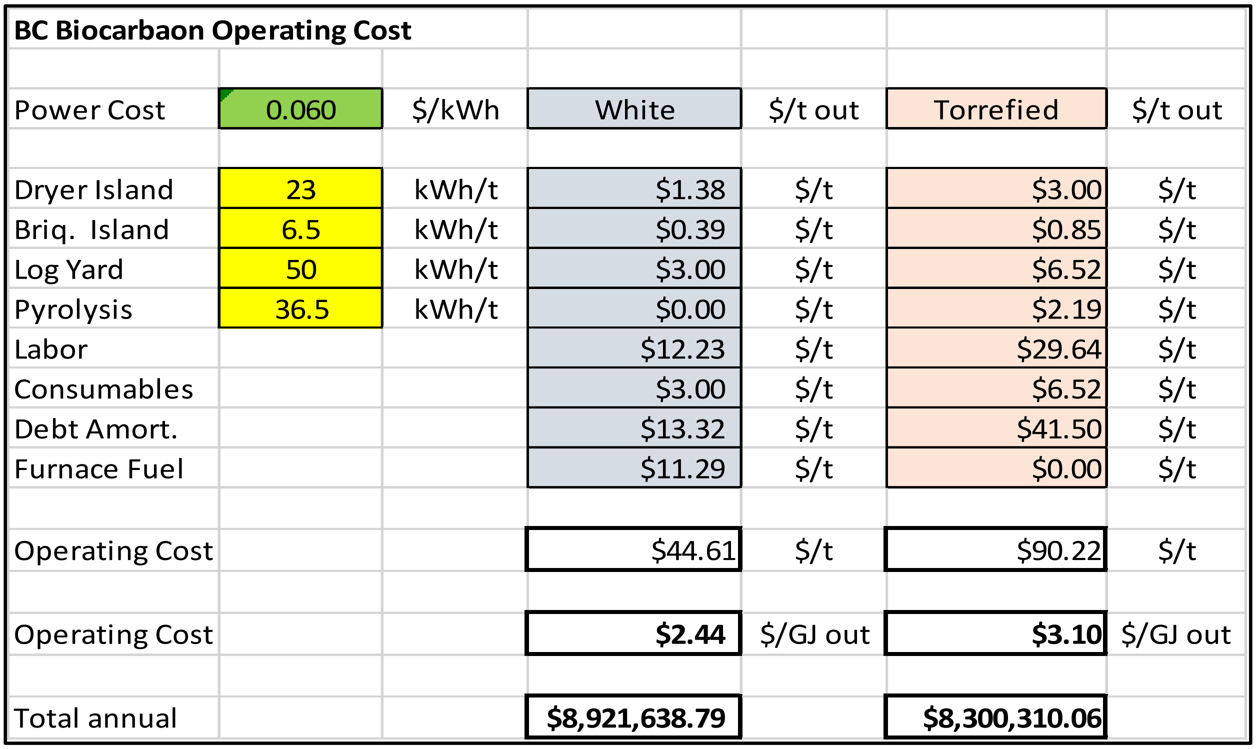
Benefits and Fringes	28%	
Labor rate average	$27.4	$/h
Labor rate average (loaded)	$35.0	$/h
Average work time /week	40	h/week
Estimate labor cost	$2,730,624	$/y

Estimated staffing requirements - 200kt/y input equiv. torrefaction plant					
Postion	Staff category	Staff per shift	Number of shifts	Staff required	Comments
Material handling	Driver/Plant operator	1	4	4	Wood / log yard driver
Plant operator - material preparation	Driver/Plant operator	1	4	4	Grinding, chipping, milling, conveyance
Plant operator - energy system	Driver/Plant operator	1	4	4	Boiler / dryer / balance of plant
Plant operator - pellet production	Driver/Plant operator	1	4	4	Pyrolysis, gas and tar management, briquetting
Production assistant	Unskilled labor	1	4	4	General production assistance, cleaning, etc.
Shift supervisor	Process control operator	1	4	4	Shift supervision, operator assistance
Maintenance technician - mech / el.	Mech/elec/control technician	1	3	3	
Plant manager	Operations manager	1	1	1	
Administration (office, laboratory, etc.)	Administrator	2	1	2	
Material handling	Driver/Plant operator	1	1	1	Wood receiving, shiploading, biomass fuel
Logistics	Administrator	1	1	1	Misc. / weighbridge operator
Production manager	Engineering manager	1	1	1	Production/energy plant
Maintenance manager	Equipment maintenance manager	1	1	1	Plant maintenance
Maintenance technician (locksmith, fitter)	Mech/elec/control technician	2	1	2	
Maintenance technician (electrican)	Mech/elec/control technician	2	1	2	
Control systems engineer	Mech/elec/control technician	1	1	1	
		Total estimated staff		**39**	

Table 15: BC Biocarbon Labor and payroll assumptions

Other Operating Expenses

There is one significant difference to consider in the comparison of white pellets with the "BC Biocoal" briquettes. "BC Biocoal" briquettes use hog fuel as feedstock, which is available at a much lower cost than feedstock for white pellets. In our comparison, we used $ 70/o.d. ton for pellet feedstock and $ 50/o.d. ton for hog fuel. Hog fuel is unsuitable as pellet feedstock. This feedstock cost difference and the lower power consumption of briquetting explains why the cost per GJ for the BC Biocarbon process is lower than for white pellets despite the energy loss of 27% in the process. For white pellets, all of the dryer energy demand is satisfied by external fuel, usually hog fuel, which is available at a significantly lower cost than pellet feedstock. The white pellet furnace fuel cost accounts for $11.29/t of white pellet output if the feedstock arrives with 50%MC. In the BC Biocarbon process, all of the drying energy demand comes from the combustion and heat reclaim of the torrefaction gas. The cost of that energy is already included in the loss of energy numbers. The residual thermal energy of 14.7 GJ/h could benefit profitability if it could be either sold or offset some other energy demand. If we were to assume a value of $4/GJ for that energy, it might add $ 441,000 per year to the GOP. We show it separately as this energy may not be available if the Feedstock's MC is 50% or higher. The electrical energy consumption in the BC Biocarbon data appears low, even with the use of VFD with a 50% duty cycle is considered.



BC Biocarbaon Operating Cost						
Power Cost	0.060	$/kWh	White	$/t out	Torrefied	$/t out
Dryer Island	23	kWh/t	$1.38	$/t	$3.00	$/t
Briq. Island	6.5	kWh/t	$0.39	$/t	$0.85	$/t
Log Yard	50	kWh/t	$3.00	$/t	$6.52	$/t
Pyrolysis	36.5	kWh/t	$0.00	$/t	$2.19	$/t
Labor			$12.23	$/t	$29.64	$/t
Consumables			$3.00	$/t	$6.52	$/t
Debt Amort.			$13.32	$/t	$41.50	$/t
Furnace Fuel			$11.29	$/t	$0.00	$/t
Operating Cost			$44.61	$/t	$90.22	$/t
Operating Cost			**$2.44**	$/GJ out	**$3.10**	$/GJ out
Total annual			**$8,921,638.79**		**$8,300,310.06**	

Table 16: BC Biocarbon operating cost (w/o feedstock)

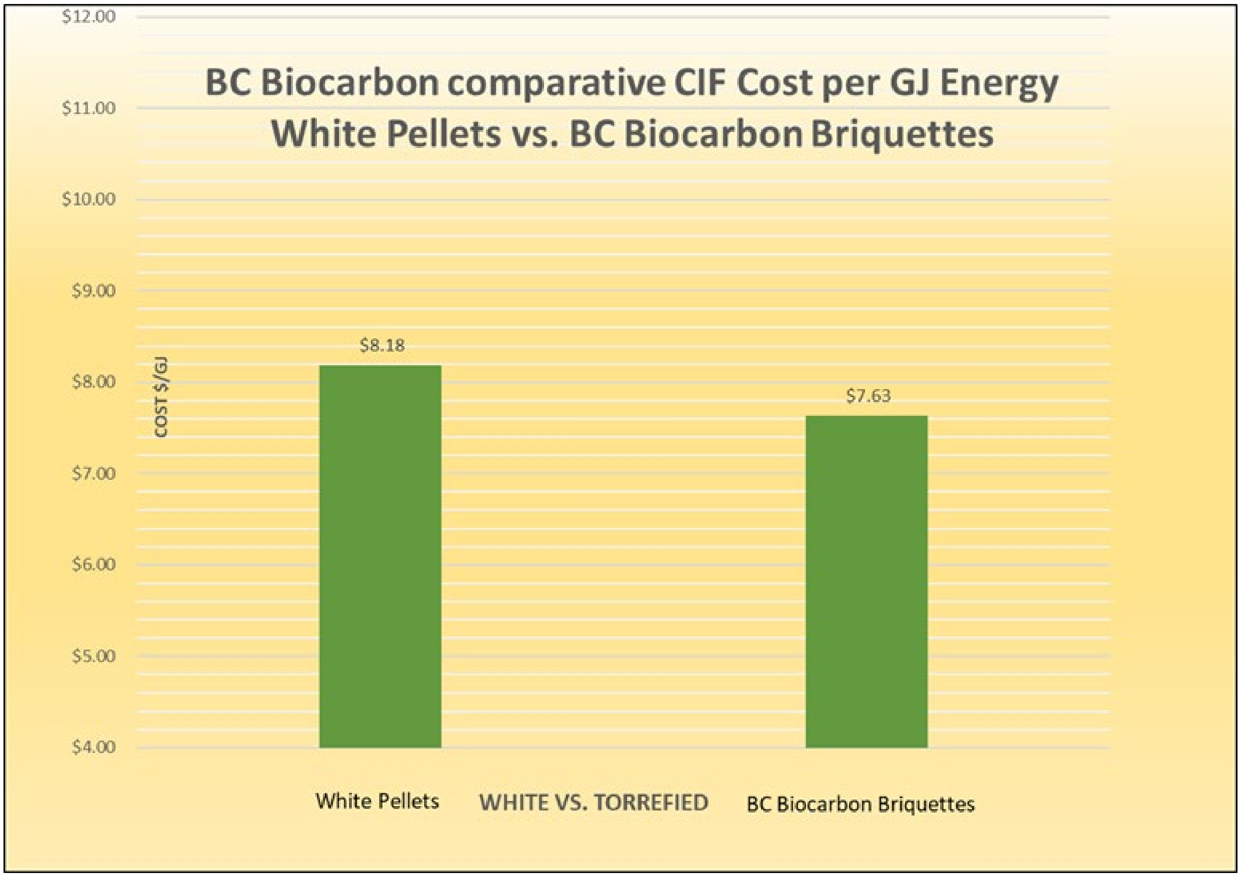


Figure 16: BC Biocarbon CIF Vancouver-Tokyo cost $/GJ

	White	BC Biocarbon	BC + excess heat
Hourly Output - GJ/Hour	489	357	357
Hourly Revenue	$4,940	$3,606	$3,606
Hourly Cost	$4,001	$2,724	$2,724
GOP hourly	$939	$882	$882
GOP annual	$7,040,816	$6,612,413	$6,612,413
Excess heat value @$4/GJ			$441,000
Δ GOP vs. White Pellets		-$428,402	$12,598
Increase/Decrease		-6.1%	0.2%

Table 17: BC Biocarbon GOP comparison to white pellets

Comments and Conclusions

Without selling the excess heat, the torrefied briquettes would have to fetch a $.16/GJ price premium to offer the same annual gross profit from the plant. A 27% lower output of GJ/y from the plant, compared with white pellets, drives the difference.

We still question the grindability aspect as the tar used as a binder for the briquettes may turn highly viscous when heated. The thick tar could gum up the grinder and could interfere with the function of a pulverizer. We were not able to get a definitive answer at this time.

The BC process comes closest to cost parity, with a slight advantage for the torrefied briquettes. The key is the use of low-cost feedstock that would be unsuitable for white pellets. Before concluding that the BC Biofuel briquettes may be a profitable way to use hog fuel, we suggest further studies. We do not know if the hog fuel's high mineral content (soil, small stones) might adversely impact the grinders, adding maintenance cost. Another crucial variable is that much of the volatiles are added back into the product in the BC Biocarbon case. The volatiles may affect the water resistance, the product's odor, the propensity of self-heating, and most certainly the leach water's COD when stored in the open. On the other hand, making briquettes instead of pellets is less energy consuming and less costly.

Clean Electricity Generation (CEG)

Product and service description

CEG has its HQ in the Netherlands and currently operates a torrefaction plant in Derby, UK, with a capacity of 30,000 t/y. The company offers both products as well as technology for owners/operators. The product spectrum includes pellets with varying degrees of carbonization, from mildly torrefied to get some density improvement, water-resistance, and grindability to highly carbonized pellets for metallurgical applications and activated carbon**.** CEG has built a torrefied pellet plant project in Vägary, Estonia, for Baltania OÜ. CEG delivers the torrefaction technology and EPCM (Engineering-Procurement-Construction-Management) service. The Baltania project will have a capacity of 160,000 t/y and is currently in the process of commissioning. After the plant goes on-line, CEG will produce pellets there

Process description

CEG's process is a rather well-proven concept and employs a vibrating bed modified dryer as a torrefaction reactor. As actual data from the Estonia project is not available yet, CEG offered only a high-level, qualitative, and relatively generic process flow but no data on mass and energy flows or balance. The process starts with the feedstock's sizing, followed by drying in a drum dryer to an MC of about 10%. The pre-dried biomass transfers into the vibrating bed torrefaction reactor, heated in the absence of oxygen. We did not get a quantitative input on the temperature. The degree of torrefaction is dialed in by the dwell time of the biomass in the reactor. With a vibrating bed reactor, the vibration frequency and the attack angle affect the particles' travel velocity in a controllable way. The fluidization of the biomass layer also facilitates a thorough mixing of the material, assuring uniform torrefaction. The torrefaction gasses flow into the oxidizer, where the volatiles are combusted. The resulting hot flue gas runs through a heat exchanger and transfers the thermal energy to the drying air. CEG offered no mass flows or temperatures. We cannot deduct the fraction of the flue gas used as a purge gas and heat transfer medium to facilitate the elementary process flow diagram's torrefaction process. The diagram does not include information about the torrefied mass cooling, whether it is done in a cooling screw or with water spray.

CEG indicated that binders might be needed for any energy density of the product > 21 GJ/t to obtain sufficient durability of the pellets. They suggested for products with an energy density of >21 GJ/t the binder fraction should be 2% or less. We did not get information on the nature of the binder or its cost. CEG posited that the binders they use are renewable. CEG cited competitive sensitivity as the reason to withhold details.

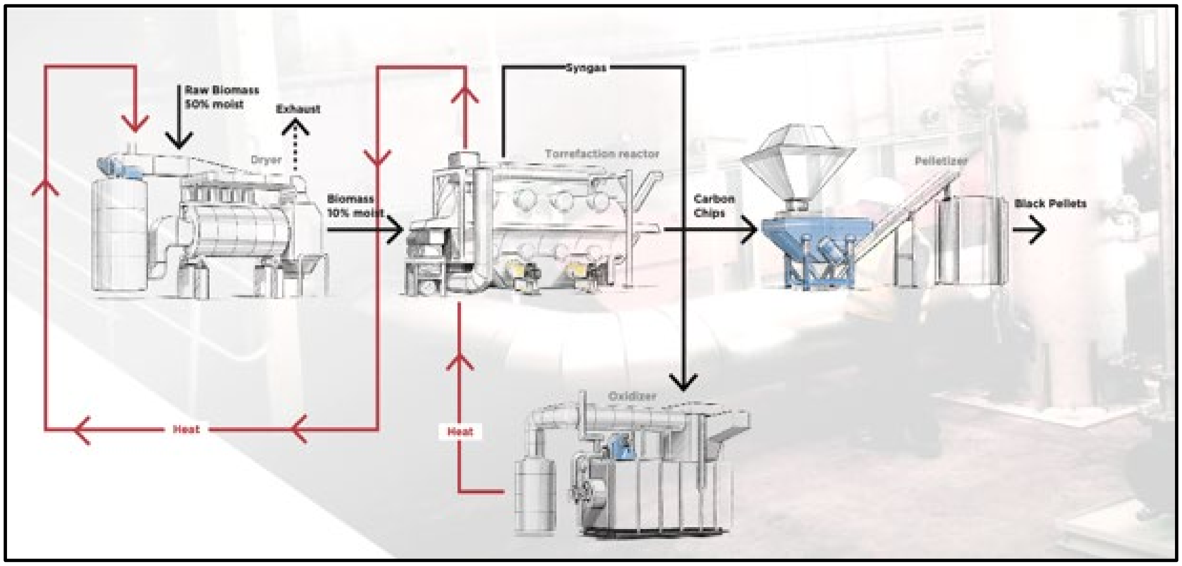


Figure 17: CEG Basic process flow diagram

As CEG has operated a sizable torrefaction facility for many years, we assume that safety and maintenance factors are well understood. CEG can scale the production capacity relatively easily by adding parallel torrefaction modules. The chippers, dryers, oxidizers, and pellet presses are designed to the desired end capacity.

CEG did not provide information on actual or expected OPEX and CAPEX at this time; the reasons offered for the refusal were either unavailability of the experts in charge of operational data due to the ongoing commissioning of the Baltania plant in Vägary, Estonia, or commercial sensitivity of the data. However, they mentioned the possibility of sharing some data later when data from the Estonia plant are available.

Safety is a concern; the process flow diagram does not indicate what volumes of purge gas (flue gas) is cycled through the reactor and whether steam stripping happens at the end of the cycle. It would be helpful to understand whether the product carries adsorbed volatiles with it that later could lead to flash-overs, self-heating, or even fires during the transportation or storage. CEG has Nitrogen generators in their process, most likely for start-up and flooding with inert gas in case of ignition. We did not receive additional information about safety measures, like a deluge system, fire suppression, or emergency dumping; the experts who could have provided the answers were fully occupied with the commissioning.

Comments and Conclusions

We believe that CEG has a professional team, as demonstrated by their Derby, UK facility's continuous operation. However, we could not construct a techno-economic summary of their process as the provided information was just too sparse to allow for that. CEG suggested revisiting the questions once their experts have concluded the Baltania plant's commissioning and are available again. If there is continued interest by May/June 2021, we could approach them again.

Following questions would be of importance to establish a more profound understanding:

- Product characteristics (as CEG proposes the use of binders, cost, durability, CV, water-resistance and water uptake, as well as leach water COD should be provided)
- Cooling of the product
- Safety measures
- Mass flows and mass/energy balance
- OPEX (especially cost adder for binder)
- CAPEX

HM3 (using the ATS TorreCAT gas management system)

Product description

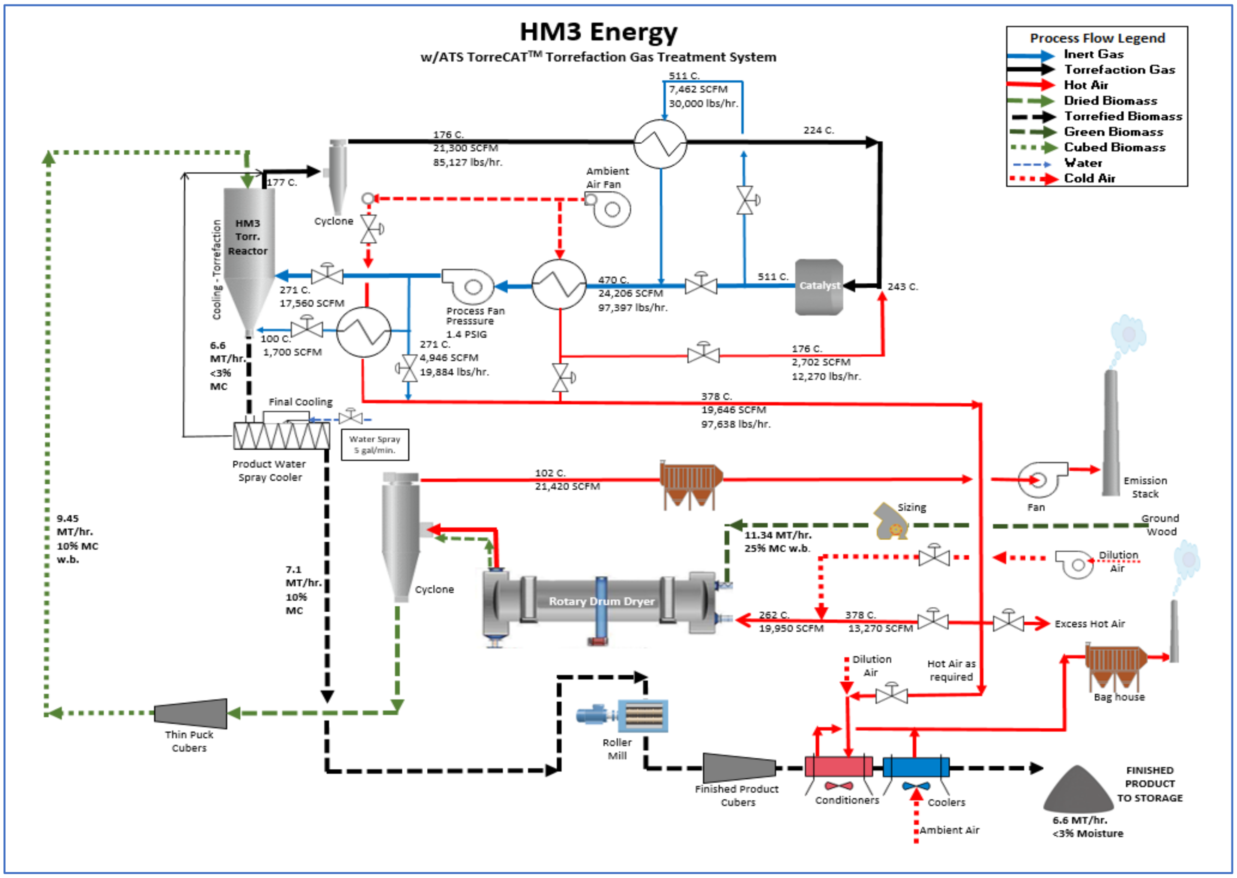
HM3 Energy is an owner/operator who uses the ATS TorreCAT gas management system and is currently designing a 50,000 t/y torrefaction facility for a site in Northern Arizona. HM3 plans to expand the facility at a later time. The feedstock will be ponderosa pine forestry slash seasoned for one year with an MC of 25% w.b. HM3 plans to export the product to Japan. The process is identical to the ATS process, with a thin puck press added and replacing the pellet presses with briquetting presses. We will calculate this particular case because of the low moisture content of the feedstock. As the facility must be flexible to process feedstock with higher MC, we will not downsize the heat plant or the dryer. However, for the feedstock's low MC, the torrefaction gasses' thermal energy reclaim will suffice to supply the dryer's energy demand.

Process description

HM3's torrefaction is based on the TorreCAT process from ATS and runs at about 270°C. It does have some differences, so it is shown separately from the ATS process. The feedstock for the HM3 process is seasoned and arrives at 25%MC. The feedstock is dried from the typical 25% MC w.b. to 10%MC w.b. and then compacted to thin pucks before entering the torrefaction reactor. The compaction achieves a more uniform size distribution and better torrefaction uniformity and allows a reactor size reduction. All other process elements are the same as displayed in the ATS TorreCAT part of this report. The gas flows for drying air are adjusted to account for the feedstock's reduced water load of 25%MC. The ME balance tables reflect the planned 50,000 t/y capacity. All other thermodynamic variables are like ATS's.

The HM3 product is steam stripped and cooled with a water spray at the exit of the reactor. The exclusion of oxygen from the system and cooling before exposure to the atmosphere minimizes fire or explosion risk. After exiting the reactor, the torrefied biomass is not pelletized but compacted in 1" x 1" x1.5" briquettes or "cubes." These are more robust in handling, less water-absorbing than the larger surface area pellets, and still grind well in coal pulverizers. In case of an emergency, the system can be flooded with inert gas, blower fans, and controls would be on the emergency power supply and safely allow venting of exhaust gasses through the smokestack during cool down.

Process flow and Mass/Energy balance of the HM3 process as provided by HM3 Energy and ATS



courtesy of T. Causer ATS

Figure 18: HM3 Process flow by ATS

Please note: The following mass flow tables are adjusted to metric and pertain to the initially planned capacity of 50,000 t/y. As future plant capacity expansions will be modular, this seemed the appropriate approach.

HM3 Gas flow		Gas Flows													
			1	2	3	4	5	6	6A	7	8	9	10	11	12
		Torrefaction Gases Generated	Torregas from Reactor	Torregas from cyclone	Torregas after Process HE	Torrgas + Comb. Air into CAT	Torregas from CAT	Inert Gas into Process HE	Inert gas after Process HE	Hot Inert Gas to H.E. #1	Inert gas from H.E. #1	Inert Gas from Process Fan	Excess Inert Gas	Inert Gas After Excess Inert gas	Inert Gas to H.E. #2
Total Mass, t/h	t/h	3.1	39.9	40.5	40.5	46.0	46.0	13.6	13.6	44.2	44.2	44.2	9.0	32.0	3.1
Water	t/h	1.8	16.5	17.1	17.1	17.1	17.7	6.1	6.1	17.7	17.7	17.7	3.1	14.6	1.1
Carbon Dioxide	t/h	0.3	8.8	8.8	8.8	8.8	10.3	3.6	3.6	10.3	10.3	10.3	1.8	8.5	0.6
Carbon Monoxide	t/h	0.1	0.1	0.1	0.1	0.1									
Acetic Acid	t/h	0.2	0.2	0.2	0.2	0.2									
Formic Acid	t/h	0.1	0.1	0.1	0.1	0.1									
Methanol	t/h	0.2	0.2	0.2	0.2	0.2									
Lactic Acid	t/h	0.2	0.2	0.2	0.2	0.2									
Furfural	t/h	0.1	0.1	0.1	0.1	0.1									
Hydroxyacetone	t/h	0.1	0.1	0.1	0.1	0.1									
Oxygen	t/h	0.0	0.0	0.0	0.0	1.1									
Nitrogen	t/h	0.0	17.5	17.5	17.5	21.2	21.2	7.3	7.3	21.2	21.2	21.2	3.7	17.5	1.3
Std.Volume flow	m^3/h	2967.3	35316.2	36,189	36,189	40,779	41,071	12,678	12,678	41,126	41,126	41,126	8,403	29,834	2,888
Temperature	°C	450	450	450	498	492	785	785	585	744	545	545	545	545	545

HM3 Solids and Air flows		Solids Flow						Air Flows						
		A	B	C	D	E	F	4	6	6A	7	2	5	8
		Raw Wood to Dryer	Dried Wood From Dryer	TW at Line 14 entrance ring	TW exiting Reactor	TW from Water Spray Cooler	Finished product	Air 4 Ambient Air into HE1	Air 6 Heated Air FROM HE1	Air 6 Minus Air 7 Comb. Air	Air 7 Combustion Air	Ambient Air into H.E. #2	Heated Air FROM H.E. #2	Air 8 = Air 6A + Air 5 + Excess Inert Gas
Total Mass	t/h	11.3	9.5	6.6	6.6	7.1	6.5	31.5	31.5	26.7	4.9	3.2	3.2	38.4
Water	t/h	2.8	1.0	0.1	0.1	0.6		0.1	0.1	0.1	0.0	0.0	0.0	3.2
Carbon Dioxide	t/h													1.8
Carbon Monoxide	t/h													
Acetic Acid	t/h													
Formic Acid	t/h													
Methanol	t/h													
Lactic Acid	t/h													
Furfural	t/h													
Hydroxyacetone	t/h													
Oxygen	t/h							7.4	7.4	6.3	1.2	0.8	0.8	7.0
Nitrogen	t/h							24.1	24.1	20.4	3.7	2.4	2.4	26.5
Wood	t/h	8.5	8.6	6.5	6.5	6.5	6.5							
Temperature	°K	298	350	543	473	353	298	298	630	630	630	298	514	598

Economics of the HM3 TorreCAT process

CAPEX

The CAPEX for the TorreCAT module for a 200 kt/y plant is $M 6.5. We have reduced the amount for the pelletizing presses to $M 2.8 for the briquetting system and added $K 300 for the thin puck press (forming the thin pucks after pre-dryer) to the Dryer CAPEX.

We constructed the CAPEX table from typical figures for a white pellet plant with a comparable capacity. Debarker and log take out, conveyors, chippers, and boilers are sized to process feedstock volume for a 200,000 t/y white pellet output. The corresponding torrefied pellet output will be lower by the fraction of the mass loss. In the case of HM3, the output will be 150,000 t/y torrefied pellets. The heat plant size is reduced compared to a white pellet plant as 50% + of the required heat to dry the feedstock comes from the burning of torrefaction gasses. We left the heat plant in the bill of material to allow for flexibility with the Feedstock's MC.

HM3 Torrefaction Plant	**CAPEX ['000 $]** **White**	**CAPEX ['000 $]** **Torrefied**
Log debarker/log take out	$1,800	$1,800
Silos/conveyors	$7,000	$7,000
Chippers	$1,150	$1,150
Heat Plant	$3,500	$2,500
Dryer	$4,500	$4,800
Torrefaction/Gas management	**$0**	**$6,500**
Pelletizing system or Cuber/Thin Puck press	$3,900	$2,800
Sum Production modules	**$21,850**	**$26,550**
BoP	**$3,750**	**$3,750**
EL/SCADA	**$3,950**	**$3,950**
Civil Engineering Infrastructure	**$6,550**	**$6,550**
Sum of Installation	**$36,100**	**$40,800**
Project execution	$3,950	$3,950
Total Project	**$40,050**	**$44,750**

Table 18: HM3 Capex for a 200kt/y input equiv. plant

The debt/equity ratio is set at	**60%/40%**
The amortization assumption is set at	**12 years linear**
The interest rate is set at	**5%**

OPEX

Labor Cost

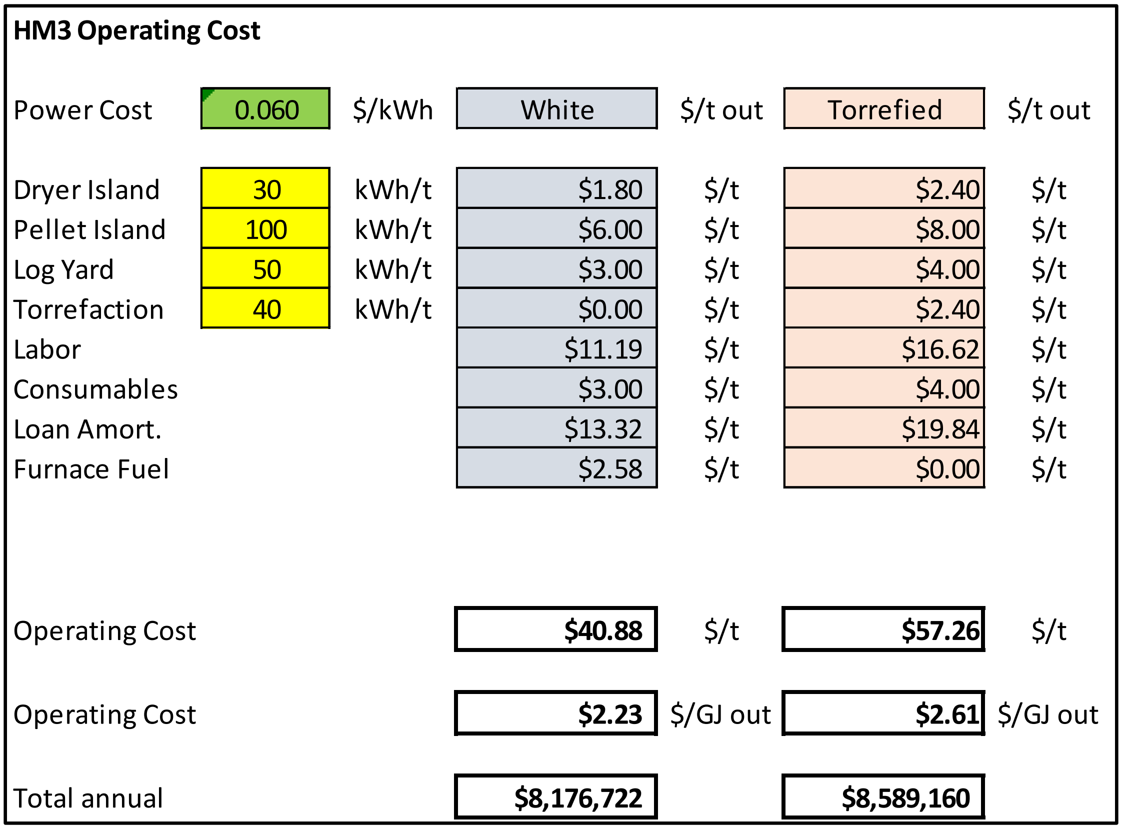
In this case, we based the Labor Cost on the HM3 input for a white pellet plant of 200 kt/y capacity in Arizona. We added the personnel needed to operate and maintain the torrefaction system (highlighted). We took the labor rate from HM3 supplied data.

Benefits and Fringes	32%	
Labor rate average	$24.24	$/h
Labor rate average (loaded)	$32.00	$/h
Average work time /week	40	h/week
Estimate labor cost	$2,496,000	$/y

Estimated staffing requirements - 200kt/y input equiv. torrefaction plant					
Postion	Staff category	Staff	Number	Staff	Comments
		per shift	of shifts	required	
Material handling	Driver/Plant operator	1	4	4	Wood / log yard driver
Plant operator - material preparation	Driver/Plant operator	1	4	4	Grinding, chipping, milling, conveyance
Plant operator - energy system	Driver/Plant operator	1	4	4	Boiler / dryer / balance of plant
Plant operator - pellet production	Driver/Plant operator	1	4	4	Torrefaction, gas management, pellet press
Production assistant	Unskilled labor	1	4	4	General production assistance, cleaning, etc.
Shift supervisor	Process control operator	1	4	4	Shift supervision, operator assistance
Maintenance technician - mech / el.	Mech/elec/control technician	1	3	3	
Plant manager	Operations manager	1	1	1	
Administration (office, laboratory, etc.)	Administrator	2	1	2	
Material handling	Driver/Plant operator	1	1	1	Wood receiving, shiploading, biomass fuel
Logistics	Administrator	1	1	1	Misc. / weighbridge operator
Production manager	Engineering manager	1	1	1	Production/energy plant
Maintenance manager	Equipment maintenance manager	1	1	1	Plant maintenance
Maintenance technician (locksmith, fitter)	Mech/elec/control technician	2	1	2	
Maintenance technician (electrican)	Mech/elec/control technician	2	1	2	
Control systems engineer	Mech/elec/control technician	1	1	1	
		Total estimated staff		**39**	

Table 19: HM3 Labor and payroll assumptions

Other Operating Expenses



HM3 Operating Cost

Power Cost	0.060	$/kWh	White	$/t out	Torrefied	$/t out
Dryer Island	30	kWh/t	$1.80	$/t	$2.40	$/t
Pellet Island	100	kWh/t	$6.00	$/t	$8.00	$/t
Log Yard	50	kWh/t	$3.00	$/t	$4.00	$/t
Torrefaction	40	kWh/t	$0.00	$/t	$2.40	$/t
Labor			$11.19	$/t	$16.62	$/t
Consumables			$3.00	$/t	$4.00	$/t
Loan Amort.			$13.32	$/t	$19.84	$/t
Furnace Fuel			$2.58	$/t	$0.00	$/t
Operating Cost			**$40.88**	$/t	**$57.26**	$/t
Operating Cost			**$2.23**	$/GJ out	**$2.61**	$/GJ out
Total annual			**$8,176,722**		**$8,589,160**	

Table 20: HM3 Operations cost (w/o feedstock)

The exceptionally low feedstock cost assumption of $ 39.68 /o.d. ton makes for a very low production cost. The cost inputs from HM3 showed only direct labor in the labor cost, while maintenance cost and administration cost were listed separately. In aggregate, the cost assumptions by HM3 and ours are very comparable. We added loan amortization into the OPEX to show the impact of different CAPEX spending between white pellets and torrefied pellets or briquettes

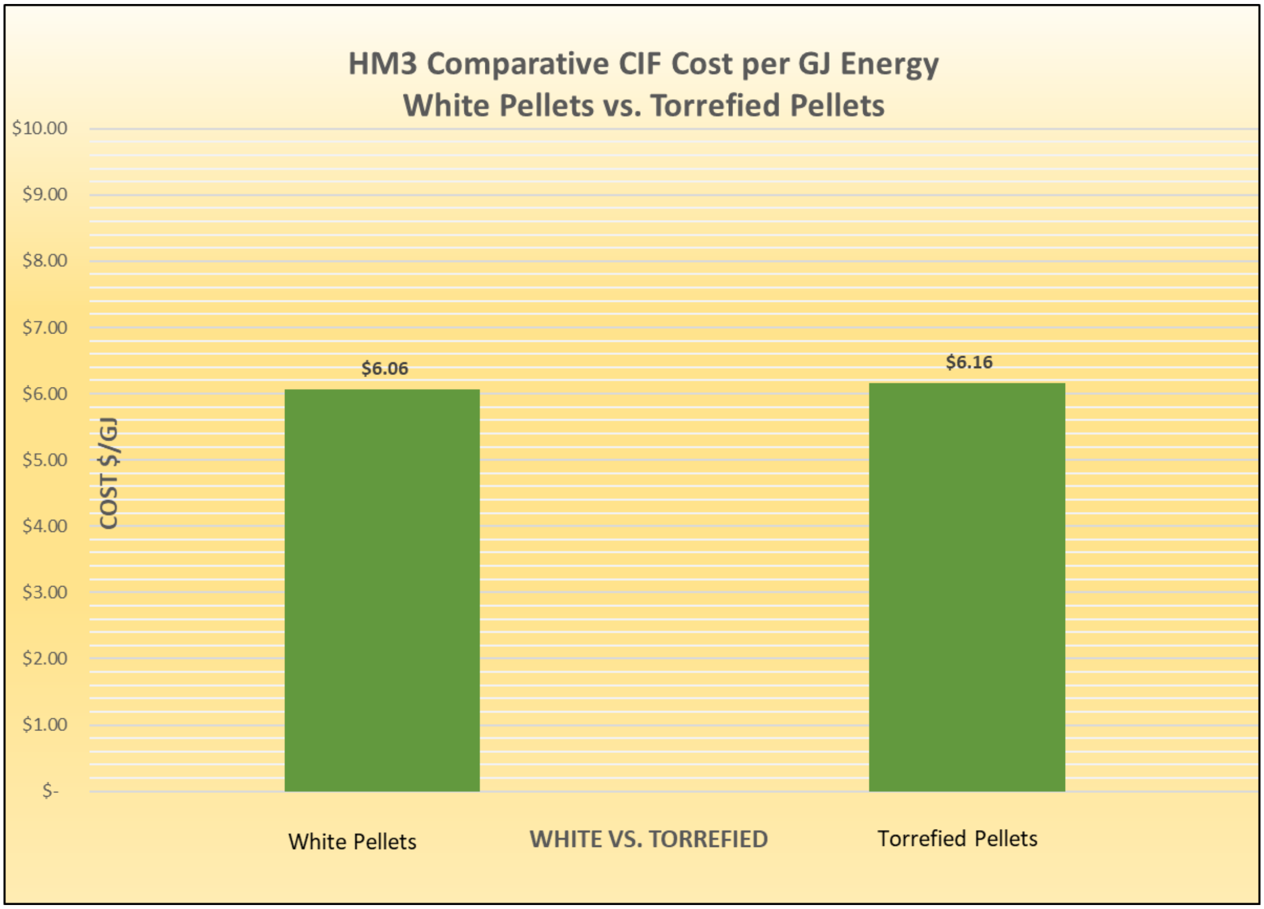


Figure 19: HM3 CIF Vancouver-Tokyo cost $/GJ

	White	Torrefied
Hourly Output - GJ/Hour	489	440
Hourly Revenue	$4,940	$4,446
Hourly Cost	$2,963	$2,749
GOP hourly	$1,976	$1,696
GOP annual	$14,823,224	**$12,723,454**
Δ GOP vs. White Pellets		**-2,099,771**
Increase/Decrease		**-14.2%**

Table 21: HM3 GOP comparison to white pellets

Comments and Conclusions

The HM3 approach uses the ATS TorreCat technology. The mass flows and ME balance are fundamentally similar to the ATS model, only adjusted to a different capacity. HM3 stated their labor headcount assumption somewhat optimistic, in our opinion. **We show the HM3 OPEX as a contrast to ATS, where ATS uses 50% MC feedstock HM3 uses 25% MC feedstock, hence the substantial cost difference.**

Notably, the assumption of seasoned, dryer feedstock at 25% MC eliminates the need for supplemental fuel for the dryer. Under these circumstances, the reclaimed energy from the torrefaction gas combustion meets the entire dryer energy demand. Under the assumption of 25% MC feedstock, the cost disadvantage of torrefied pellets shrinks to about $.10/GJ. We did leave the dryer capacity for both the white pellet comparison and the torrefied plant at a level to deal with 50%MC without derating. The production cost is $.61/GJ higher for HM3 torrefied pellets, but the lower transportation cost offsets $.51/GJ. However, due to the 10% lower GJ output per year from the same installed input capacity, the profitability difference is noticeable. For GOP parity, the price for torrefied briquettes or “cubes” in $/GJ delivered would have to be $.63/GJ higher. Some off-takers might be interested in paying a higher price if they could avoid substantial conversion CAPEX as well as higher OPEX. The addition of pressing the feedstock into uniform "thin pucks" before entering it into the reactor increases the torrefied biomass's uniformity. Briquetting instead of pelletizing further lowers the cost of densification and reduces fines generation.

The reason for the substantial difference between the ATS cost/GJ and the HM3 cost/GJ lies in the different feedstock cost assumption. We picked $70/t o.d. as a baseline, while HM3 used S39.68/t o.d. We left the HM3 supplied cost figure in to show how feedstock cost drives cost/GJ.

TSI

Product and service description

TSI is an experienced technology provider that develops and sells torrefaction technology to entities that want to build and operate a torrefied pellet plant. TSI currently does not own or operate a pellet plant, other than a research facility.

Process description

The sized feedstock is dried in an external dryer to 6.8 +/- 2% before entering the torrefaction reactor. In our model, we assume the green feedstock to have a MC of 50%. TSI's torrefaction process runs in a drum-type reactor with a gas inlet temperature of 380°C and a gas outlet temperature of 296°C, with a 15-minute dwell time of the biomass in the reactor. The feedstock loses about 28% of its ash-free dry mass in the reactor and about 15% of its energy content. The energy loss in the reactor is reclaimed from the torrefaction gas by combustion. The LHV of the combusted torrefaction gas from the TSI process is 10.5 GJ/t. The heat is extracted in a heat exchanger, potentially along with heat from the gas flows from torrefied biomass cooling and pellet cooling, to heat the drying air.

For the presented case, the mass loss in the torrefaction reactor is 29% of the dry organic mass, primarily due to driving out volatile compounds and the degradation of hemicellulose into gaseous compounds. The corresponding loss of calorific value in the torrefaction reactor is 15%. It is lower than the mass loss as the specific hemicellulose CV is lower than that of lignin and cellulose.

TSI's heat reclaim system covers 50% of the pre-dryer's energy demand for drying feedstock from 50% MC to 6.8%MC, the entry moisture level for the torrefaction reactor. The torrefaction gasses leaving the reactor are routed through a cyclone for dust separation before entering the recycling loop. The segregated dust gets recombined with the torrefaction solids or burned in the multi-fuel burn chamber. The TSI supplied ME balance diagram does not cover the torrefied biomass's cooling at the end of the torrefaction process. Water spray cooling is typical, and in verbal communication, TSI indicated they do that as well. There is also no indication of steam-stripping the product before pelletization, which would reduce the risk of carrying excessive volatiles with the torrefied material. Volatiles can produce an undesirable odor as well as increase the flammability risk.

Process flow and mass-energy balance as provided by TSI

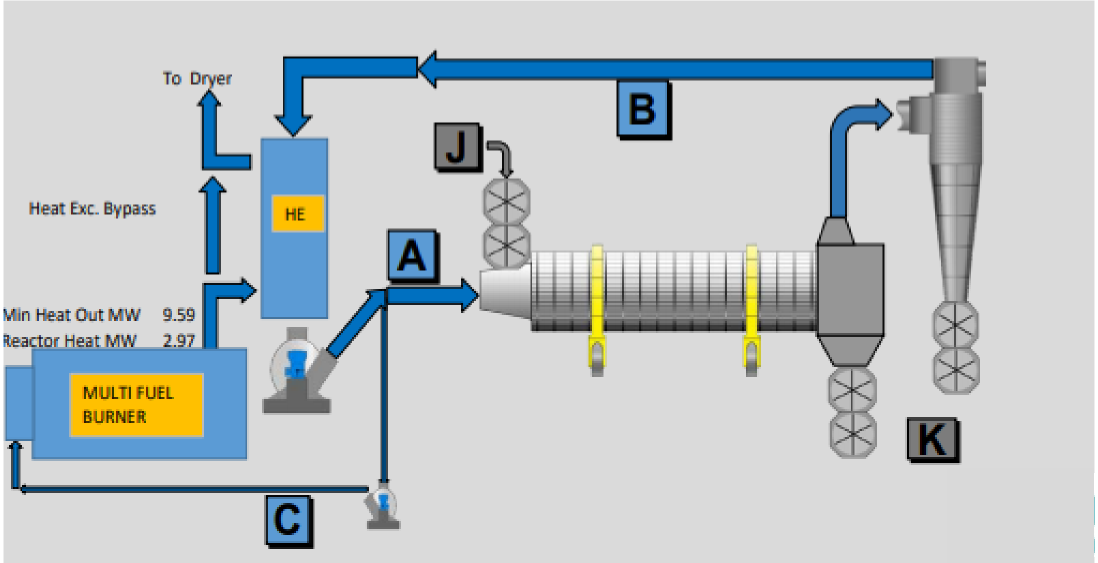


Figure 20: TSI basic process flow

Nominal Design Rates for 200 kt white pellet plant input equivalent	**Rate**	**Units**
organic material	**25.7**	**t/h**
ash	**0.4**	**t/h**
water	**1.9**	**t/h**
Input in torr reactor	**28.0**	**t/h**
Nominal Torreactor Rates		
initial biomass material @ 6.8% MC	**25.7**	**t/h**
mass loss in torrefaction	**7.5**	**t/h**
final torr organic material	**18.2**	**t/h**
initial ash	**0.4**	**t/h**
final ash	**0.4**	**t/h**
initial MC	**1.9**	**t/h**
final water	**0.4**	**t/h**
water evaporated	**1.5**	**t/h**
final torr solids + water	**19.0**	**t/h**
Nominal Torr gas Rates		
Torr gas generated	**7.5**	**t/h**
estimated steam	**0.0**	**t/h**
estimated leakage	**-0.4**	**t/h**
total torr gas	**7.2**	**t/h**
Torr gas est. LHV	**-10.5**	**GJ/t**
Torr gas heat generation est. with 95% combustion efficiency	**-71.3**	**GJ/h**

Table 22: TSI mass flow rates for a 200kt/y input equiv. plant

Gas Flow				**Solids Flow and MC%**		
	A	B	C		J	K
Units	Reactor inlet	Recirc. gas	Torr gas fuel	Units	from pre-dryer	torrefied biomass
t/h	165.9	173.7	7.8	t/h	28.0	20.5
m^3/h	267,204	279,806	12,602	t/h o.d.	26.1	18.6
°C	379	296	296	MC %w.b.	6.8%	2.0%

Table 23: TSI mass flows from process diagram

Torr reactor heat load	**Units**	**Rate**	**Units**	**h_e or C_p**	**Units**	**Δ H**
Biomass o.d. and ash in	t/h	26.1	kJ/kg*°K	-1.882	GJ/h	13.8
Heat demand of torrefaction	t/h	10.2	kJ/kg	-349	GJ/h	2.5
Total water in	t/h	1.9	kJ/kg	2,907	GJ/h	5.5
Air leakage - estimated	t/h	0.3	kJ/kg*°K	-1.004	GJ/h	0.0
Temperature - inlet	°C	16		-1.840		0.0
Temperature - outlet	°C	296				0.0
Heat load subtotal					GJ/h	22.0
Estimated heat loss (4%)					GJ/h	1.0
Total torr reactor					**GJ/h**	**23.0**

Table 24: TSI Torrefaction reactor heat load

With the described mass loss of 29% dry matter and an HHV of 19.06 of the o.d. feedstock, the heat generation from combusting the torr gas is insufficient to provide all the dryer's heat demand. The underlying assumptions are that the dryer is 77% efficient (TSI input), the burner is 95% efficient (typical), and the system's heat loss is 4%. For this set of circumstances, the dryer's heat supply can be 62.1 GJ/h (with heat reclaim from the cooler). The heat demand of the dryer to evaporate 24.8 t/h of water is 80.9 GJ/h. The given scenario requires 20% supplementary heat from low-grade hog fuel or other sources.

Economics of the TSI process

CAPEX

This CAPEX number is for a 200kt/y input equivalent plant that will handle the same feedstock volume as needed for a comparable 200kt/y output white pellet plant. The numbers in blue are the incremental CAPEX figures for the torrefaction features. The heat plant CAPEX was reduced as some of the dryer heat demand is satisfied by the torrefaction gasses.

TSI Torrefaction Plant	CAPEX ['000 $]	CAPEX ['000 $]
	White	**Torrefied**
Log debarker/log take out	$1,800	$1,800
Silos/conveyors	$7,000	$7,000
Chippers	$1,150	$1,150
Heat Plant	$3,500	$2,500
Dryer	$4,500	$4,500
Torrefaction / Gas management	**$0**	**$30,500**
Pelletizing system	$3,900	$2,900
Sum Production modules	**$21,850**	**$50,350**
BoP	**$3,750**	**$3,750**
EL/SCADA	**$3,950**	**$3,950**
Civil Engineering Infrastructure	**$6,550**	**$6,550**
Sum of Installation	**$36,100**	**$64,600**
Project execution	$3,950	$3,950
Total Project	**$40,050**	**$68,550**

Table 25: TSI Capex for a 200kt/y input equiv. plant

The debt/equity ratio is set at	**60/40**
The amortization is set at	**12 years linear**
The interest rate is set at	**5%**

OPEX

Labor Cost

We used a typical head count profile for a White Pellet plant of 200 kt/y capacity. We added the personnel needed to operate and maintain the torrefaction system (highlighted).

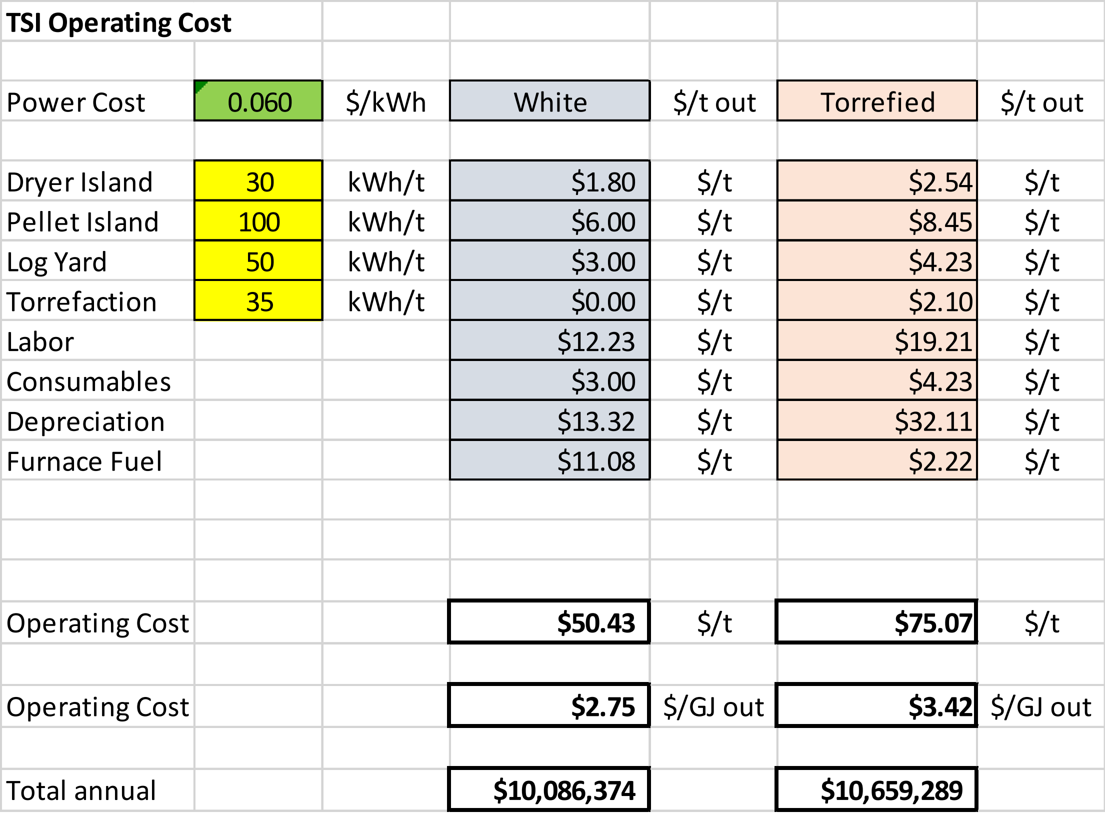
Benefits and Fringes	28%	
Labor rate average	$27.4	$/h
Labor rate average (loaded)	$35.0	$/h
Average work time /week	40	h/week
Estimate labor cost	$2,730,624	$ /y

Estimated staffing requirements - 200kt/y input equiv. torrefaction plant					
Postion	Staff category	Staff per shift	Number of shifts	Staff required	Comments
Material handling	Driver/Plant operator	1	4	4	Wood / log yard driver
Plant operator - material preparation	Driver/Plant operator	1	4	4	Grinding, chipping, milling, conveyance
Plant operator - energy system	Driver/Plant operator	1	4	4	Boiler / dryer / balance of plant
Plant operator - pellet production	Driver/Plant operator	1	4	4	Torrefaction, gas management, pellet press
Production assistant	Unskilled labor	1	4	4	General production assistance, cleaning, etc.
Shift supervisor	Process control operator	1	4	4	Shift supervision, operator assistance
Maintenance technician - mech / el.	Mech/elec/control technician	1	3	3	
Plant manager	Operations manager	1	1	1	
Administration (office, laboratory, etc.)	Administrator	2	1	2	
Material handling	Driver/Plant operator	1	1	1	Wood receiving, shiploading, biomass fuel
Logistics	Administrator	1	1	1	Misc. / weighbridge operator
Production manager	Engineering manager	1	1	1	Production/energy plant
Maintenance manager	Equipment maintenance manager	1	1	1	Plant maintenance
Maintenance technician (locksmith, fitter)	Mech/elec/control technician	2	1	2	
Maintenance technician (electrican)	Mech/elec/control technician	2	1	2	
Control systems engineer	Mech/elec/control technician	1	1	1	
		Total estimated staff		**39**	

Table 26: TSI Labor and payroll assumptions

Other Operating Expenses

For white pellets, all of the dryer energy demand is satisfied by external fuel, usually hog fuel, which is available at a significantly lower cost than pellet feedstock. The white pellet furnace fuel cost accounts for $11.29/t of white pellet output if the feedstock arrives with 50%MC. In the TSI process, 80% of the drying energy demand comes from the combustion and heat reclaim of the torrefaction gas and the cooler. The cost of that energy is already included in the loss of energy numbers. The remaining 20% of the dryer energy demand come from burning lower cost hog fuel @ $ 25/green ton (50% MC). We based the cost calculation per ton on an actual output of 142,000 t/y. The built-in assumption of combustion efficiency is 95%.



TSI Operating Cost						
Power Cost	0.060	$/kWh	White	$/t out	Torrefied	$/t out
Dryer Island	30	kWh/t	$1.80	$/t	$2.54	$/t
Pellet Island	100	kWh/t	$6.00	$/t	$8.45	$/t
Log Yard	50	kWh/t	$3.00	$/t	$4.23	$/t
Torrefaction	35	kWh/t	$0.00	$/t	$2.10	$/t
Labor			$12.23	$/t	$19.21	$/t
Consumables			$3.00	$/t	$4.23	$/t
Depreciation			$13.32	$/t	$32.11	$/t
Furnace Fuel			$11.08	$/t	$2.22	$/t
Operating Cost			**$50.43**	$/t	**$75.07**	$/t
Operating Cost			**$2.75**	$/GJ out	**$3.42**	$/GJ out
Total annual			**$10,086,374**		**$10,659,289**	

Table 27: TSI Operations cost (w/o feedstock)

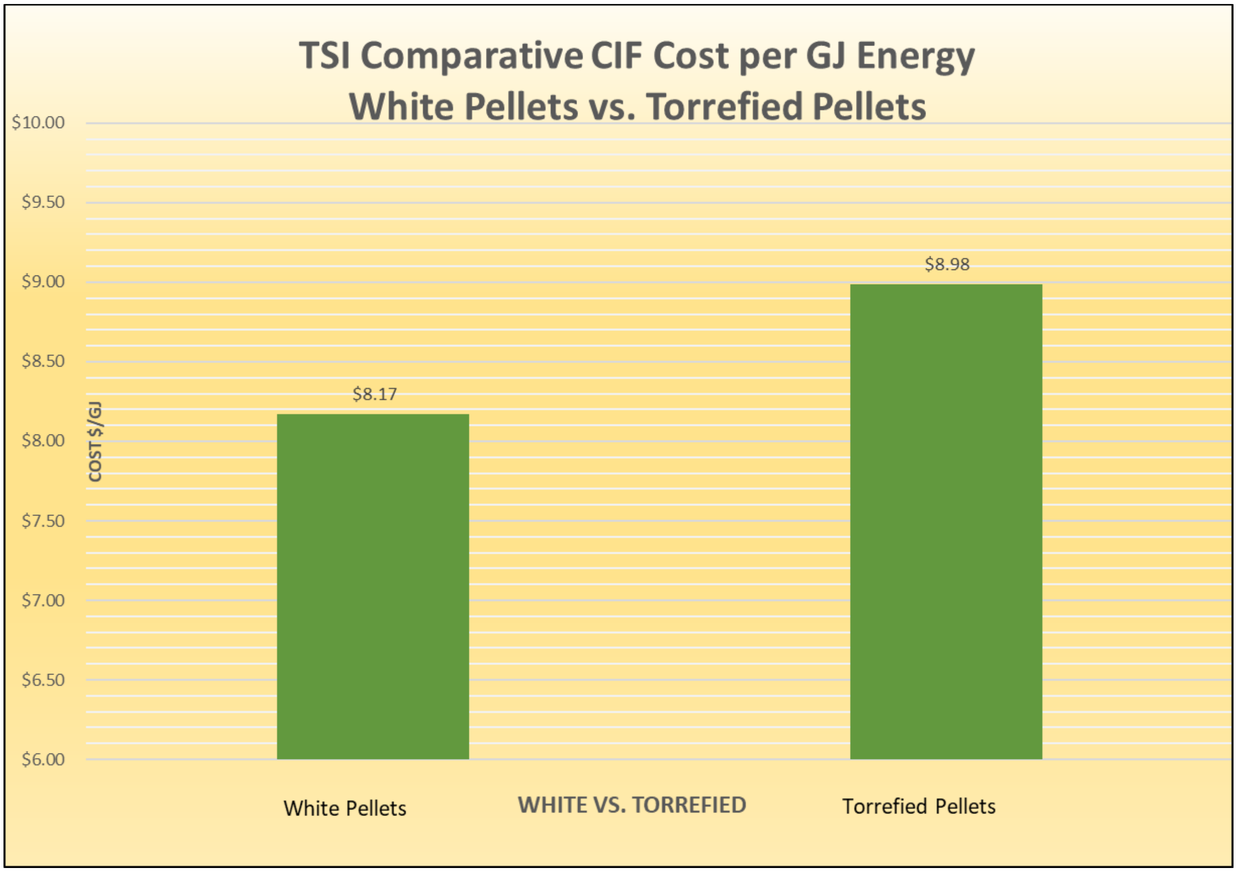


Figure 21: TSI CIF Vancouver-Tokyo cost $/GJ

	White	**Torrefied**
Hourly Output - GJ/Hour	489	416
Hourly Revenue	$4,940	$4,199
Hourly Cost	$3,995	$3,734
GOP hourly	$944	$465
GOP annual	$7,082,132	$3,487,831
Δ GOP vs. White Pellets		-$3,594,301
Increase/Decrease		-50.8%

Table 28: TSI GOP comparison with white pellets

Comments and Conclusions

The OPEX cost to produce torrefied pellets is $ 1.32/GJ higher than for white pellets; $ .51 is recovered by a lower transportation and logistics cost. The remaining $ .81/GJ are due to incremental loan amortization, the loss of energy from the feedstock, and the higher labor cost. We believe that TSI used very conservative CAPEX figures as the incremental CAPEX they claim as needed is well above the average of other developers. Others may be too optimistic, so CAPEX is a variable an owner/operator should thoroughly examine before embarking on a specific project.

The torrefied pellets would have to fetch a $1.15/GJ price premium to offer the same annual gross profit from the plant as a comparable white pellets plant would earn. There are several drivers for the substantial difference, a 15% lower output of GJ/y from the plant, a significantly higher CAPEX, resulting in a 26% higher OPEX per GJ than white pellets.

Requiring a significantly higher premium than other torrefaction technologies to obtain GOP parity would make it a little harder for TSI plants to compete against others. However, we think it would be prudent to examine the CAPEX and the degree of torrefaction needed when a specific project emerges. There is no fundamental reason why there is such a glaring difference. We consider it entirely possible that TSI was particularly conservative with their CAPEX projections. TSI is a competent developer; it is possible that while they were conservative, others might have been a little too optimistic.

Yilkins

Product and service description

Yilkins offers a torrefaction system for integration into a pellets plant or briquette plant. The company performs design and EPC functions to match the system up to a third-party pellet plant. The company developed the process and the necessary SCADA based on Siemens S7 to ensure the process remains balanced. The torrefaction system is designed for a high degree of flexibility to accept various feedstocks. It can be adjusted to accommodate a wide range of "as received" MC. The system uses proprietary, patented fluidized bed dryers for high efficiency. Yilkins licenses the technology to owners/operators of pellet plants. Currently, the requested annual license fee amounts to \$ 6/t of annual capacity.

Process description

The green feedstock is milled to a chip size with a maximal thickness of 5mm and a length of 50mm. The sized feedstock is dried from maximal 70% MC w.b., but typically 50% MC w.b. to 38 %MC w.b. in the pre-dryer and then to 8% MC in the swirl dryer before entering the torrefaction reactor. Yilkins' torrefaction process can run up to 350°C but typically runs between 290 and 320°C. The typical dwell time in the reactor is between 1-3 minutes but can be up to 20 min. At the baseline conditions, the feedstock loses about 23% of its dry mass in the torrefaction reactor, corresponding to 10% of its energy content. However, we used an energy loss of about 15% in our economic calculations. The additional 5% of the feedstock's inherent energy gets fed back into the combustion chambers to have sufficient energy to dry the feedstock. The latent energy of the torrefaction gasses is released as thermal energy in the combustion chambers. The combustion's thermal energy and the reclaimed energy from the gas flows are used to dry the feedstock. The pellet cooling is extracted in heat exchangers and used to heat the drying air. Yilkins developed an effective heat recovery system that re-uses the process heat for drying. For feedstock with lower MC, the need for consuming pellets for heat may be reduced or even eliminated. If the combustion chambers could accept green hog fuel in place of pellets, the profitability could be improved by about \$ 3/t.

The mass loss in the torrefaction reactor is primarily due to driving out volatile compounds and the degradation of hemicellulose into gaseous compounds. At the described torrefaction conditions, lignin and cellulose are not affected much. The corresponding loss of the feedstock's original energy content in the torrefaction reactor is lower than the mass loss because the specific hemicellulose CV is lower than that of lignin and cellulose.

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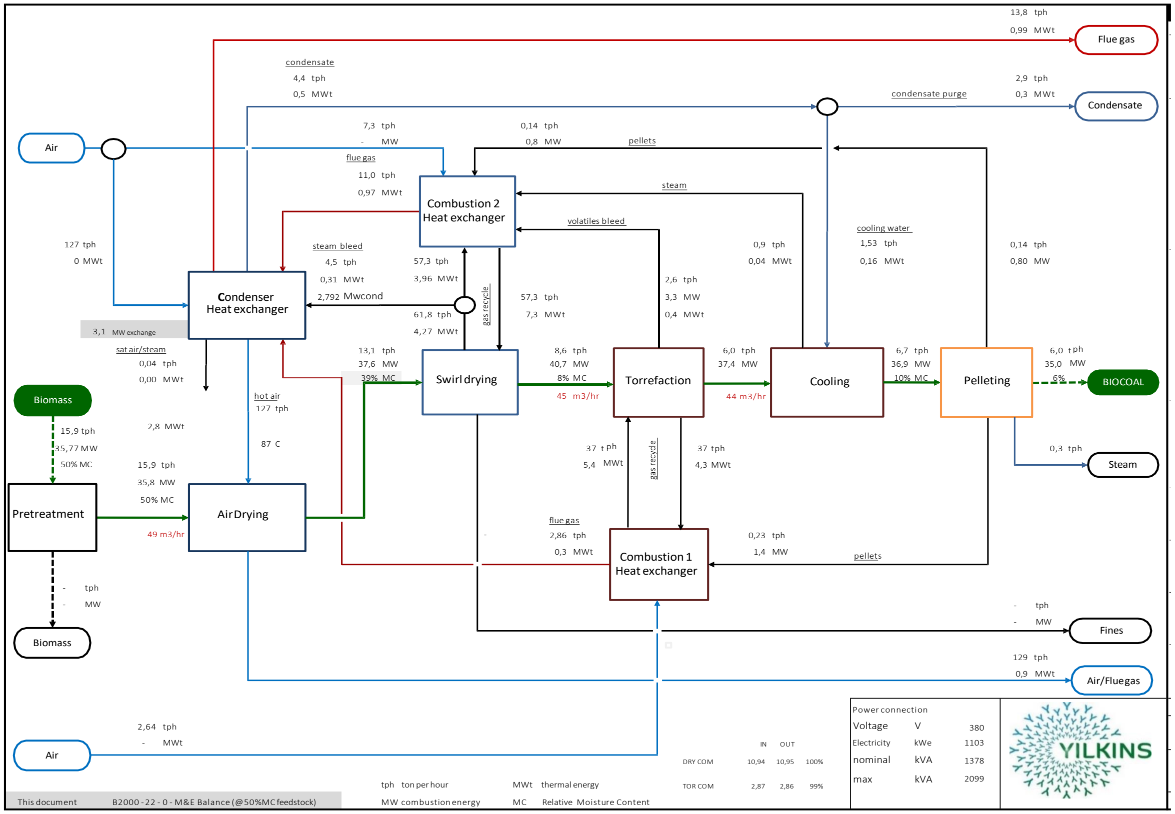


Figure 22: Yilkins Process flow and ME balance

		Mass Flows (t/h)				Energy Flows (MW)		
		in	out	delta		in	out	delta
Pretreatment								
Biomass @ 50%MC		26.7	26.7	0.0		60.1	60.1	0.0
Output to "Biomass"		0.0	0.0	0.0		0.0	0.0	0.0
Pretreatment Sum		26.7	26.7	**0.0**		60.1	60.1	0.0
Feedstock Predrying								
Biomass		26.7	22.0	4.7		60.1	63.1	-3.0
Air from condenser heatexchanger		213.2	216.6	-3.4		4.7	1.5	3.2
Feedstock Pre-drying Sum		239.9	238.6	1.3		64.8	64.6	0.2
Swirl Drying								
Biomass		22.0	14.4	7.6		63.1	68.3	-5.2
Gas recycling combustion heatexchanger 2		96.2	103.8	-7.6		12.3	7.2	5.0
Swirl drying Sum		118.2	118.2	0.0		75.4	75.6	-0.2
Torrefaction Reactor								
Biomass		14.4	10.1	4.4		68.3	62.8	5.5
Gas recycling Combustion Heatexchanger 1		62.1	62.1	0.0		9.1	7.2	1.8
Volatiles to Combustion Heatexchanger 2		0.0	4.4	-4.4		0.0	6.2	-6.2
Torrefaction Reactor Sum		76.6	76.6	0.0		77.4	76.2	1.2
Combustion Heatexchanger 1								
air in		4.4	0.0	4.4		0.0	0.0	0.0
Pellets in		0.4	0.0	0.4		2.4	0.0	2.4
fluegas out		0.0	4.8	-4.8		0.0	0.5	-0.5
Gas recycling Combustion Heatexchanger 1		62.1	62.1	0.0		7.2	9.1	-1.8
Combustion Heatexchanger 1 Sum		66.9	66.9	0.0		9.6	9.6	0.0
Cooling								
Biomass		10.1	11.2	-1.2		62.8	62.0	0.8
Cooling water from Condensate		2.6	0.0	2.6		0.3	0.0	0.3
Steam		0.0	1.5	-1.5		0.0	0.1	-0.1
Cooling Sum		12.6	12.8	-0.1		63.1	62.0	1.0
Pelletizing								
Biomass		11.2	10.1	1.2		62.0	58.8	3.2
Pellets out		0.0	0.6	-0.6		0.0	3.7	-3.7
Dissipated water		0.0	0.5	-0.5		0.0	0.0	0.0
Pelletizing Sum		11.2	11.2	0.1		62.0	62.5	-0.5
Combustion heatexchanger 2								
Gas reccycling from /to Swirl dryer		96.2	96.2	0.0		6.6	12.3	-5.6
Volatiles from Torrefaction		4.4	0.0	4.4		5.5	0.0	5.5
steam from Cooler		1.5	0.0	1.5		0.1	0.0	0.1
Pellets		0.2	0.0	0.2		1.3	0.0	1.3
air		12.3	0.0	12.3		0.0	0.0	0.0
Gas to Condenser Heatexchanger			18.5	-18.5		0.0	1.6	-1.6
Combustion heatexchanger 2 Sum		114.6	114.7	-0.1		13.6	13.9	-0.3
Condenser Heatexchanger								
air		213.2	213.2	0.0		0.0	4.7	-4.7
flue gas		0.0	23.2	-23.2		0.0	1.6	-1.6
Condensate		0.0	7.4	-7.4		0.0	0.8	-0.8
steam bleed from Swirl Dryer		7.6	0.0	7.6		5.2	0.0	5.2
gas from Combustion Heatexchanger		18.5	0.0	18.5		1.6	0.0	1.6
sat. air/steam		0.0	0.1	-0.1		0.0	0.0	0.0
flue gas from Combustion Heatexchanger 1		4.8	0.0	4.8		0.5	0.0	0.5
Condenser Heatexchanger Sum		244.1	243.9	0.2		7.3	7.1	0.2

Table 29: Yilkins mass-energy balance

Economics of the Yilkins process

CAPEX

Based on Yilkins inputs, we estimate the CAPEX for a Yilkins Torrefaction plant input equivalent to a 200 kt/y White Pellet plant at $ M 47. We got to that number by upscaling the Yilkins input (46kt/y plant) with an economy-of-scale factor of 1.65 for each doubling. Yilkins provided some CAPEX input; the blue numbers were included in their figure and upscaled to the 200kt/y input equiv. level.

Yilkins Torrefaction Plant	**CAPEX ['000 $]**	**CAPEX ['000 $]**
	White	**Torrefied**
Log debarker/log take out	$1,800	$1,800
Silos/conveyors	$7,000	$7,000
Chippers	$1,150	$1,150
Heat Plant	$3,500	$2,500
Dryer	$4,500	$4,500
Torrefaction/Gas management	**$0**	**$7,900**
Pelletizing system	$3,900	$2,900
Sum Production modules	**$21,850**	**$27,750**
BoP	**$3,750**	**$3,750**
EL/SCADA	**$3,950**	**$3,950**
Civil Engineering Infrastructure	**$6,550**	**$6,550**
Sum of Installation	**$36,100**	**$42,000**
Project execution	$3,950	$3,950
Total Project	**$40,050**	**$45,950**

Table 30:Yilkins Capex for a 200 kt/y input equiv. plant

The debt/equity ratio is set at	**60/40**
The amortization is set at	**12 years linear**
The interest rate is set at	**5%**

OPEX

Labor Cost

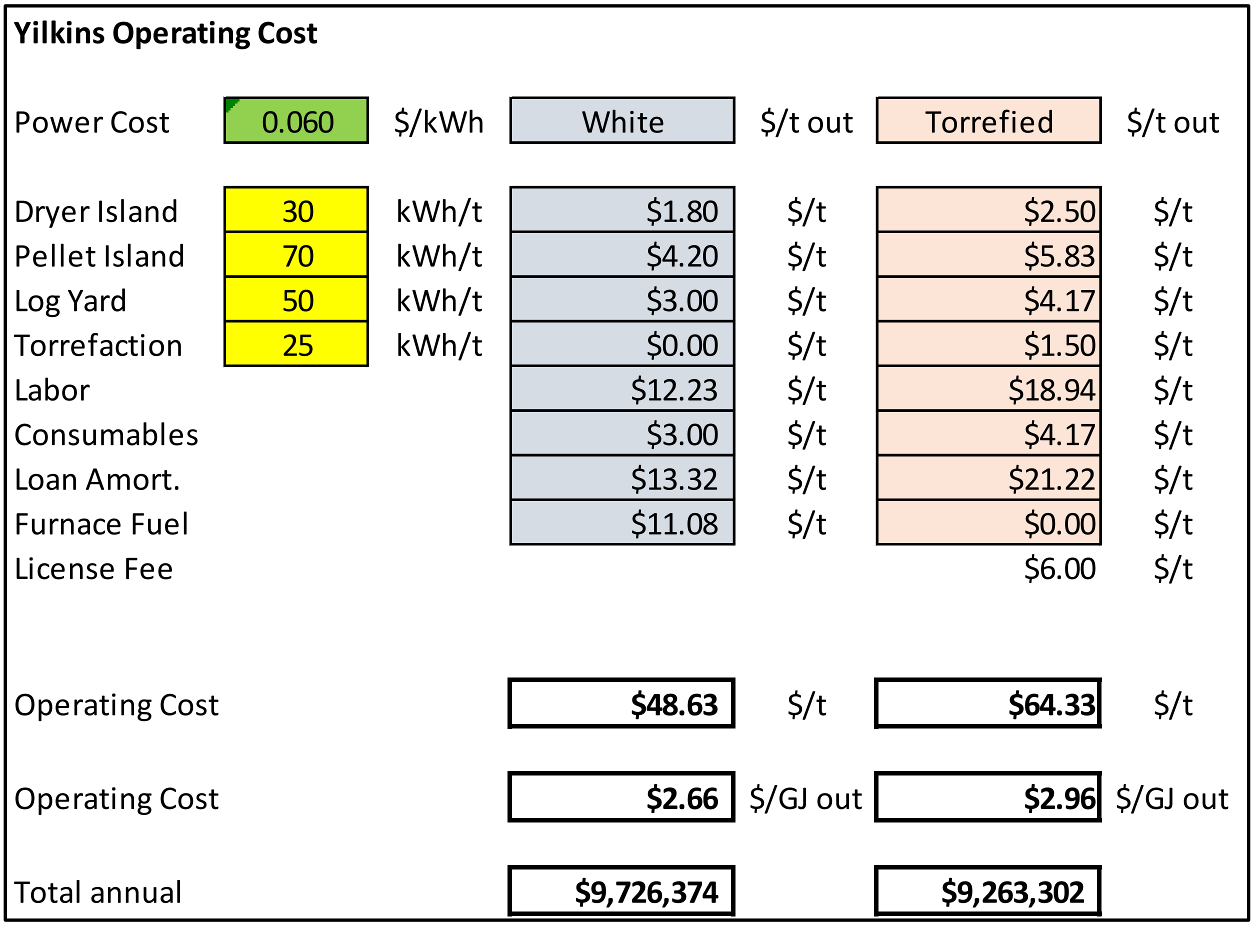
Labor cost has been calculated using a typical head count profile for a White Pellet plant of 200 kt/y capacity. We added the incremental personnel needed to operate and maintain the torrefaction system (highlighted).

Benefits and Fringes	28%	
Labor rate average	$27.4	$/h
Labor rate average (loaded)	$35.0	$/h
Average work time /week	40	h/week
Estimate labor cost	$2,730,624	$/y

Estimated staffing requirements - 200kt/y input equiv. torrefaction plant					
Postion	Staff category	Staff	Number	Staff	Comments
		per shift	of shifts	required	
Material handling	Driver/Plant operator	1	4	4	Wood / log yard driver
Plant operator - material preparation	Driver/Plant operator	1	4	4	Grinding, chipping, milling, conveyance
Plant operator - energy system	Driver/Plant operator	1	4	4	Boiler / dryer / balance of plant
Plant operator - pellet production	Driver/Plant operator	1	4	4	Torrefaction, gas management, pellet press
Production assistant	Unskilled labor	1	4	4	General production assistance, cleaning, etc.
Shift supervisor	Process control operator	1	4	4	Shift supervision, operator assistance
Maintenance technician - mech / el.	Mech/elec/control technician	1	3	3	
Plant manager	Operations manager	1	1	1	
Administration (office, laboratory, etc.)	Administrator	2	1	2	
Material handling	Driver/Plant operator	1	1	1	Wood receiving, shiploading, biomass fuel
Logistics	Administrator	1	1	1	Misc. / weighbridge operator
Production manager	Engineering manager	1	1	1	Production/energy plant
Maintenance manager	Equipment maintenance manager	1	1	1	Plant maintenance
Maintenance technician (locksmith, fitter)	Mech/elec/control technician	2	1	2	
Maintenance technician (electrican)	Mech/elec/control technician	2	1	2	
Control systems engineer	Mech/elec/control technician	1	1	1	
		Total estimated staff		**39**	

Table 31: Yilkins Labor and payroll assumptions

Other Operating Expenses



Yilkins Operating Cost

Power Cost	0.060	$/kWh	White	$/t out	Torrefied	$/t out
Dryer Island	30	kWh/t	$1.80	$/t	$2.50	$/t
Pellet Island	70	kWh/t	$4.20	$/t	$5.83	$/t
Log Yard	50	kWh/t	$3.00	$/t	$4.17	$/t
Torrefaction	25	kWh/t	$0.00	$/t	$1.50	$/t
Labor			$12.23	$/t	$18.94	$/t
Consumables			$3.00	$/t	$4.17	$/t
Loan Amort.			$13.32	$/t	$21.22	$/t
Furnace Fuel			$11.08	$/t	$0.00	$/t
License Fee					$6.00	$/t
Operating Cost			**$48.63**	$/t	**$64.33**	$/t
Operating Cost			**$2.66**	$/GJ out	**$2.96**	$/GJ out
Total annual			**$9,726,374**		**$9,263,302**	

Table 32: Yilkins Operations cost (w/o feedstock)

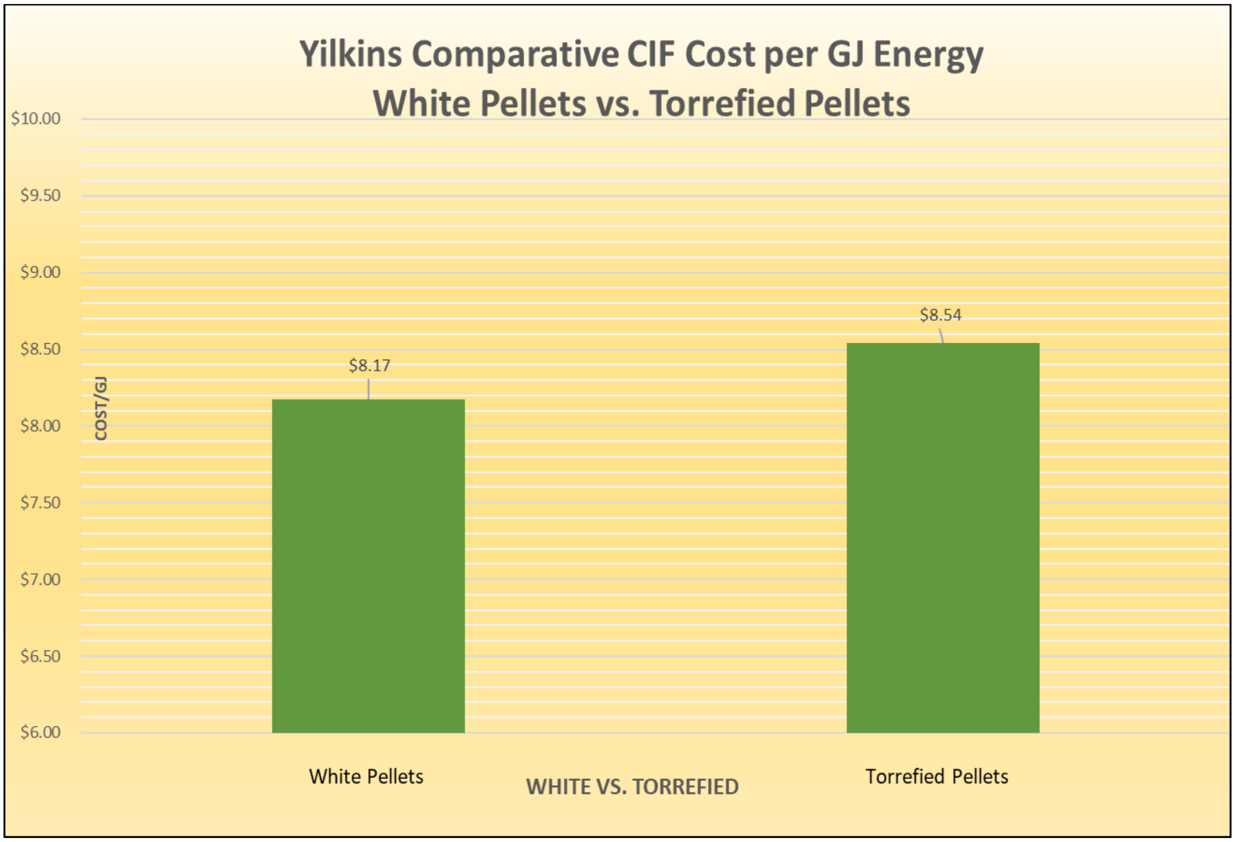


Figure 23: Yilkins CIF Vancouver-Tokyo cost $/GJ

	White	Torrefied
Hourly Output - GJ/Hour	489	418
Hourly Revenue	$4,940	$4,223
Hourly Cost	$3,995	$3,571
GOP hourly	$944	$653
GOP annual	**$7,082,132**	$4,895,704
Δ GOP vs. White Pellets		-$2,186,428
Increase/Decrease		-31%

Table 33: Yilkins GOP comparison to white pellets

Comments and Conclusions

The primary factor for the higher cost of torrefied pellets is the 28% mass loss from the feedstock that does not happen with white pellets. The energy loss is lower at 15%. 10% points are attributable to loss of volatiles and hemicellulose destruction in the torrefaction process, while 5% points are caused by using pellets as supplemental fuel. The aggregate heat re-use efficiency needs to be 84% to work with the numbers provided; this appears doable but requires very efficient heat recovery. The higher cost to produce torrefied pellets is $ .83/GJ; $ .46 is compensated by lower transportation and logistics costs. The remaining $ .37 is due to incremental amortization, the loss of energy, the slightly higher labor cost, and the asked license fee of $ .27/GJ.

The significantly lower GOP profitability compared to white pellets results from a lower GJ output of the torrefaction factory with the same feedstock consumption and the same intake capacity (feedstock 400,000 t/y @ 50% MC) as the white pellet comparison. If the off-takers paid a price premium of $ .70/GJ, the profitability would be equal.

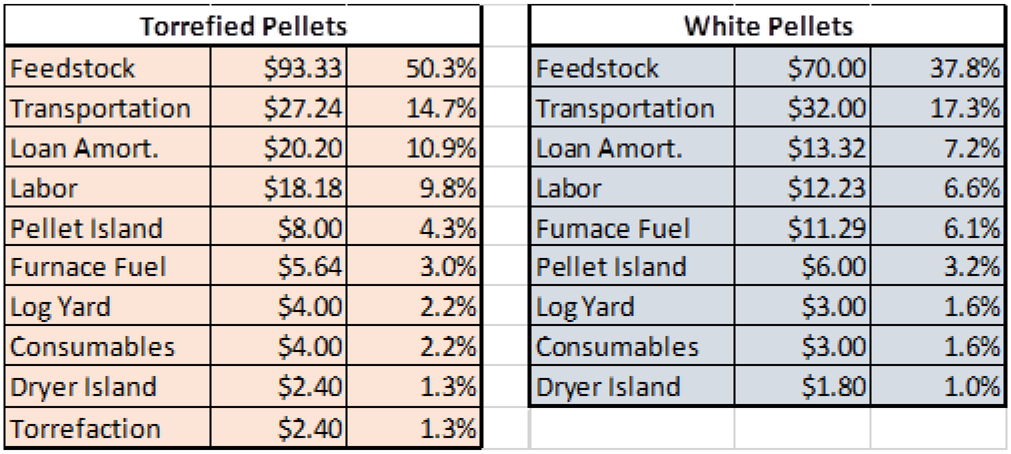
Sensitivity Analysis

The baseline assumptions for the sensitivity analysis were as follows.

Moisture content of green feedstock	50%
Final moisture of pellets	4%
Energy value of dry feedstock	19.06 GJ/t
Energy value of white pellets	18.3 GJ/t
Energy value of torrefied pellets	21.9 GJ/t
Mass loss due to torrefaction	25%
Energy loss due to torrefaction	10%
Evaporative load	3.37 GJ/t
(equal to 72% aggregate efficiency - dryer, burner, heat loss)	
Plant capacity (white pellets equivalent)	26.7 t/h
Aggregate headcount	35 white / 39 torr
Burdened aggregate labor rate	35 $/h
Feedstock cost at plant gate	70 $/o.d. t
Supplementary Furnace Fuel Cost	50 $/o.d. t
Electrical energy cost	60 $/MWh
Freight plant to port	11 $/t
Oversea shipping (Vancouver-Tokyo)	21 $/t
Est. Plant CAPEX white pellet plant	40 $M
Est. Plant CAPEX torrefaction pellet plant	46 $M
Sale price	$10.10/GJ ($185/t white pellets)

We ranked the cost contributors to the cost of pellets and performed a sensitivity analysis for the two topmost cost factors.

Table 34 shows a ranking of the OPEX cost factors in $/t output for torrefied pellets and white pellets at the baseline assumptions. The % figure shows the contribution of the OPEX cost factor to the total cost of the production. We focused our analysis on two variable pairs and compared the impact on the GOP.



Torrefied Pellets				White Pellets		
Feedstock	$93.33	50.3%		Feedstock	$70.00	37.8%
Transportation	$27.24	14.7%		Transportation	$32.00	17.3%
Loan Amort.	$20.20	10.9%		Loan Amort.	$13.32	7.2%
Labor	$18.18	9.8%		Labor	$12.23	6.6%
Pellet Island	$8.00	4.3%		Fumace Fuel	$11.29	6.1%
Furnace Fuel	$5.64	3.0%		Pellet Island	$6.00	3.2%
Log Yard	$4.00	2.2%		Log Yard	$3.00	1.6%
Consumables	$4.00	2.2%		Consumables	$3.00	1.6%
Dryer Island	$2.40	1.3%		Dryer Island	$1.80	1.0%
Torrefaction	$2.40	1.3%				

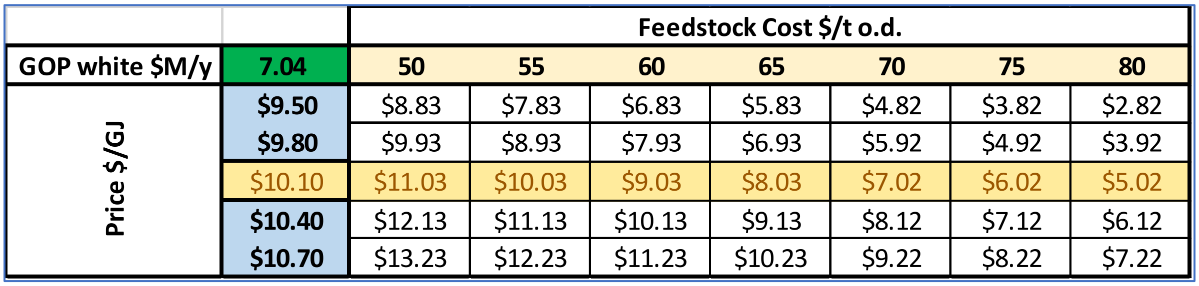
Table 34: OPEX Cost factor ranking

We did not perform an energy loss vs. profit impact pairing as the energy loss would require a change of process parameters and would require some complex iterations.

The first pair is feedstock cost vs. price per GJ.

The second pair is transportation cost vs. price per GJ

We did not perform a sensitivity analysis on CAPEX or Labor as the delta between the two scenarios is not sufficiently different to yield useful insights.



		Feedstock Cost $/t o.d.						
GOP white $M/y	**7.04**	**50**	**55**	**60**	**65**	**70**	**75**	**80**
Price $/GJ	**$9.50**	$8.83	$7.83	$6.83	$5.83	$4.82	$3.82	$2.82
	$9.80	$9.93	$8.93	$7.93	$6.93	$5.92	$4.92	$3.92
	$10.10	$11.03	$10.03	$9.03	$8.03	$7.02	$6.02	$5.02
	$10.40	$12.13	$11.13	$10.13	$9.13	$8.12	$7.12	$6.12
	$10.70	$13.23	$12.23	$11.23	$10.23	$9.22	$8.22	$7.22

Table 35: Sensitivity of white pellets feedstock vs. $/GJ

The green highlighted number represents the annual GOP in $M for white pellets under the baseline conditions. The feedstock cost is varied from $50/t o.d. to $80/t o.d. The price per GJ is CIF Vancouver-Tokyo. The light orange row reflects the GOP at $10.10/GJ.

		Feedstock Cost $/t o.d.						
GOP torr $M/y	**6.04**	**50**	**55**	**60**	**65**	**70**	**75**	**80**
Price $/GJ	**$9.50**	$8.05	$7.05	$6.05	$5.05	$4.05	$3.05	$2.04
	$9.80	$9.04	$8.04	$7.04	$6.04	$5.04	$4.04	$3.03
	$10.10	$10.03	$9.03	$8.03	$7.03	$6.03	$5.03	$4.02
	$10.40	$11.02	$10.02	$9.02	$8.02	$7.02	$6.02	$5.01
	$10.70	$12.01	$11.01	$10.01	$9.01	$8.01	$7.01	$6.00

Table 36: Sensitivity of torrefied pellets feedstock vs. $/GJ

The orange highlighted number represents the annual GOP in $M for torrefied pellets under the baseline conditions. The feedstock cost is varied from $50/t o.d. to $80/t o.d. The price per GJ is CIF Vancouver-Tokyo. The light orange row reflects the baseline conditions at $10.10/GJ. The light green shaded cells show the situations where torrefied pellets are more profitable than baseline white pellets. The cells left white are close to parity with white pellets profit for baseline conditions.

		Feedstock Cost $/t o.d.						
GOP torr/white	**% delta**	**50**	**55**	**60**	**65**	**70**	**75**	**80**
Price $/GJ	**$9.50**	-26.99%	-29.69%	-32.98%	-37.09%	-42.38%	-49.43%	-59.28%
	$9.80	-18.02%	-19.81%	-22.01%	-24.76%	-28.29%	-32.99%	-39.57%
	$10.10	-9.04%	-9.94%	-11.04%	-12.42%	-14.19%	-16.55%	-19.85%
	$10.40	-0.06%	-0.07%	-0.08%	-0.09%	-0.10%	-0.11%	-0.14%
	$10.70	8.91%	9.80%	10.89%	12.25%	14.00%	16.32%	19.58%

Table 37: Sensitivity of GOP delta

The GOP delta is between torrefied pellets and white pellets under baseline conditions. For the given set of circumstances, a price premium of $.30/GJ for torrefied pellet would establish GOP parity. For higher premiums, torrefied pellets have an advantage. Comparing white pellets profit under baseline conditions and torrefied pellets at a lower price per GJ is unrealistic.

		Aggregate transportation cost $/t						
GOP white $M/y	**7.04**	**15**	**20**	**25**	**35**	**35**	**40**	**45**
Price $/GJ	**$9.50**	$8.23	$7.23	$6.23	$4.23	$4.23	$3.23	$2.23
	$9.80	$9.33	$8.33	$7.33	$5.33	$5.33	$4.33	$3.33
	$10.10	$10.43	$9.43	$8.43	$6.43	$6.43	$5.43	$4.43
	$10.40	$11.53	$10.53	$9.53	$7.53	$7.53	$6.53	$5.53
	$10.70	$12.63	$11.63	$10.63	$8.63	$8.63	$7.63	$6.63

Table 38: Sensitivity of white pellets Transportation cost vs. $/GJ

The green highlighted number in Table 38 represents the annual GOP in $M for white pellets under the baseline conditions. The transportation cost is varied from $15/t to $45/t. The price per GJ is CIF Vancouver-Tokyo. The light orange row shows the GOP based on $10.10/GJ.

		Aggregate transportation cost $/t						
GOP torr $M/y	**6.06**	**15**	**20**	**25**	**30**	**35**	**40**	**45**
Price $/GJ	**$9.50**	$6.24	$5.60	$4.96	$4.32	$3.68	$3.05	$2.41
	$9.80	$7.23	$6.59	$5.95	$5.31	$4.67	$4.04	$3.40
	$10.10	$8.22	$7.58	$6.94	$6.30	$5.67	$5.03	$4.39
	$10.40	$9.21	$8.57	$7.93	$7.29	$6.66	$6.02	$5.38
	$10.70	$10.20	$9.56	$8.92	$8.28	$7.65	$7.01	$6.37

Table 39: Sensitivity of torrefied pellets Transportation cost vs. $/GJ

The orange highlighted number represents the annual GOP in $M for torrefied pellets under the baseline conditions. The transportation cost is varied from $15/t to $45/t. The price per GJ is CIF Vancouver-Tokyo. The light orange cell indicates the baseline price at $10.10/GJ. The light green shaded cells show the conditions where torrefied pellets are more profitable than white pellets at $10.10/GJ. The advantage of torrefied pellets of higher gravimetric density and higher energy density diminishes at lower transportation cost.

		Aggregate transportation cost $/t						
GOP torr/white	**% delta**	**15**	**20**	**25**	**30**	**35**	**40**	**45**
Price $/GJ	**$9.50**	-40.18%	-40.60%	-41.13%	-32.73%	-42.67%	-43.87%	-45.62%
	$9.80	-30.69%	-30.11%	-29.39%	-17.33%	-27.27%	-25.63%	-23.25%
	$10.10	-21.20%	-19.61%	-17.64%	-1.93%	-11.87%	-7.39%	-0.88%
	$10.40	-11.71%	-9.11%	-5.90%	13.47%	3.53%	10.86%	21.49%
	$10.70	-2.22%	1.38%	5.84%	28.87%	18.93%	29.10%	43.86%

Table 40: Sensitivity of GOP delta

The GOP delta is between torrefied pellets and white pellets at $10.10/GJ. For higher transportation cost the GOP declines, but less so for torrefied pellets. At $45/t of white pellets, the torrefied pellets have almost GOP parity. Comparing white pellets profit at baseline conditions and torrefied pellets at a lower price per GJ is unrealistic.

Summary and Conclusions

We compared the techno-economic perspective between white pellets and several torrefaction technologies. We looked only at anaerobic torrefaction of woody biomass, not any other forms of thermal treatment or other feedstocks. We used a baseline of 19.06 GJ/t o.d. feedstock uniformly for all comparisons; this is a conservative number. The report is not diving deep into material research or into fundamental thermodynamics. Instead, it looks at the practical technology aspects, the safety aspects, and the various processes' economics. We recommend performing a thorough analysis with technology providers once the specific variables for a project are known. If deeper fundamental insights are desired, Chen et al. [12] wrote an excellent synopsis of torrefaction in 2015.

There are several common differences between white pellets and pellets made from torrefied biomass.

- All torrefaction processes result in mass loss and energy loss from the dry feedstock mass, while white pellets do not suffer an energy or mass loss.
- Pellets or briquettes from torrefied biomass are generally water-resistant, have a higher gravimetric and volumetric energy density, and are easier to grind and pulverize than white pellets.
- Transportation and storage costs for pellets from torrefied biomass are lower due to the higher energy density and no dry storage requirement.
- Pellets or briquettes from torrefied biomass show little biodegradation and CV loss over time compared to untreated biomass

Our evaluations found that the companies developing torrefaction technologies have addressed several issues that plagued the process in earlier years. Some of the critical issues were quality consistency of the output, product properties, safety concerns, and predictable uptime of the equipment. Between 25-54% of the dry mass is converted into volatile compounds that can polymerize and condensate on surfaces. It is paramount to either dilute the torrefaction gasses to minimize deposits and potential flare-ups or keep the time between generation and destruction of the gasses very short and the surfaces hot. We found that technologies to address these issues have matured to commercial readiness. Processes that purge the volatiles and steam strip the torrefied biomass with high volume inert gas leave fewer residual volatiles with the product. These products have less odor and less propensity to self-heat or to release flammable gasses upon warming up during storage or transport.

While the biomass product properties are significantly enhanced to result in a better-suited fuel for power generation, the mass losses in all reviewed cases result in a higher cost per GJ. As there is currently no secondary value stream from the torrefaction gasses, the market value of a GJ from torrefied matter would have to be higher than from white pellets to establish profit parity.

All studied technologies use the energy contained in the torrefaction gasses to offset much or all of the fuel needed for drying the feedstock and reclaim some of the lost value that way. We noticed that some came in at lower CAPEX assumptions than others; we could not drill deeper as we could not visit any site (due to COVID-19 travel bans), nor were all companies willing to share high granularity information. We recommend taking the CAPEX figures as useful guidance, yet in need of project-specific examination.

For possible use of torrefied pellets as a coal substitute for power generation, the best approach would minimize the torrefaction mass loss to achieve water resistance and the minimum desired grindability. The transportation cost savings from higher energy densification do not justify the higher mass and energy loss. The goal would have to be to minimize the inevitable mass and energy loss and avoid the need for costly binders. If the torrefaction process degrades too much lignin, the pellets/briquettes' durability will suffer to the point where the addition of a binder is needed. Depending on the chosen binder, the water-resistance of the product could be affected (Table 2).

We concluded that pellets or briquettes made from torrefied biomass must obtain a higher GJ price than white pellets to attract investors. If sold at the same price in $/GJ as white pellets, the GOP% for torrefied pellets is between 10 – 18%, while it is 16 – 19% for white pellets under the same conditions. Because of the added value attributes of torrefied pellets, it should be possible to convince the off-takers to pay a higher price to save significant CAPEX for conversion and OPEX for not needing dry storage. Developers may also want to look at a comparison with other thermal treatments such as hydrothermal or steam treatments; in both cases, secondary value streams could be realized that would take the energy loss disadvantage away. Some technology developers have stated that they want to look into secondary value streams from the torrefaction gasses, but none had any concrete plans at this time.

As biomass substitute for coal is just as much a commodity as coal itself, buyers will insist on supply assurance and multiple sources. Developers and owners/operators of torrefaction plants could accelerate the market acceptance by collaboration and mutual second sourcing and backing to alleviate the perceived risk of supply chain instability. Consequently, it is likely that thermally treated biomass to be used as fuel without requiring expensive modifications at power plants will meet with increased interest as the pressure for CO_2 and GHG reduction is rising worldwide.

We further want to point out that competing technologies that offer similar product properties offset the profit impact from mass and energy loss with a secondary revenue stream from biochemicals gained from converting the volatilized biomass.

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Stuart Paskett, VP Business Development	CEG
Isabel Santos, Chief Marketing Officer	ADF
Joris Spaan, Business Development	Yilkins

Appendix

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