FutureMetrics™ LLC
8 Airport Road
Bethel, ME 04217, USA

Advanced Biomass Upgrading Solutions for Decarbonizing Hard to Abate Sectors

- **Producing High Carbon Content Feedstocks**

  As an input to SAF production and iron ore refining

- **Producing Coal Substitution Solid Fuel**

  For heat and power generation

Overview of "Black" Pellets and the Process Characteristics of Torrefied and Steam Treated Pellet Fuels

Cost analysis normalized for energy output

Financial analysis, including sensitivity to changes in critical inputs

Conclusions on suitability and economic competitiveness

Produced by

FutureMetrics

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Acknowledgments and Disclaimers

This report would not be possible without the cooperation of the black pellet technology providers reviewed herein.

Airex, Andritz, Arbaflame, E3Carbon, TSI, Valmet, and Yilkins provided FutureMetrics with information and updates that enabled us to conduct our analysis and develop the opinions included in this report. The selection of participants for the more detailed analysis is based on their proven market presence and willingness to share data on their technology. We also include interesting technology case studies of E3Carbon, FICAP, and Rainbow Pellet.

Any reference to CAPEX for the respective installations is a high-level estimate by FutureMetrics, based on input from the participants and centered within the range of potential values. The reference capital expenditure (CAPEX) for a white pellet plant is calculated based on the real CAPEX costs of other projects of comparable size, with adjustments made for inflation. CAPEX for an individual project can vary significantly depending on specific scenarios. The stated CAPEX does not constitute offers from the technology providers. Each individual project needs to be calculated on its own merit. Throughout the report, the currency is US dollars unless otherwise specified.

The analysis in this report is by FutureMetrics and is based on normalized assumptions as outlined in the "General Assumptions for all Provider Sections" section.

FutureMetrics does not endorse any particular technology provider or project developer. Many other black pellet technology providers are not covered in this report. Their absence does not imply that those technologies or providers are inferior.

The opinions in this report are those of FutureMetrics.

Primary Authors: Laurenz Schmitd, and William Strauss, FutureMetrics

Additional content provided by:

Fahimeh Yazdan Panah, Wood Pellet Association of Canada

Note that all text referring to figures and tables are hyperlinks that when clicked take the reader to their locations in the document.

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Glossary

$/th	*$ of CAPEX per ton*hour*
$/ty	*$ of CAPEX/t of annual capacity*
5-HMF	5-Hydroxymethylfurfural
a.r	as received
ACFM	*Actual Cubic Feet per Minute*
BAC	*Biologically Activated Carbon*
BOD	*Biological Oxygen Demand*
BTU	*British Thermal Unit*
CAPEX	*Capital expense*
CCR Losses	*Convection, Conduction and Radiative Losses*
COD	*Chemical Oxygen Demand*
c_p	*Heat capacity (kJ/kg*°K)*
CV	*Calorific value*
Δ H	*Enthalpy change*
DNAe	*Digital Networked Automation (Valmet)*
EGSB	*Expanded Granular Sludge Bed (anearobic)*
EPC	Engineering, Procurement, Construction
EPS	Engineering, Procurement, Supervision
GHG	*Green House Gasses (primarily* CO_2 *and* CH_4*)*
GJ	*Gigajoule*
GOP	*Gross Operating Profit = Revenue – Cost (OPEX). In this model, it includes feedstock cost, OPEX, Loan Amortization, and Transportation. No SG&A or taxes. No Tariffs.*
h	*hour*
h_e	*Enthalpy (kJ/kg)*
HGI	*Hardgrove Grindability Index*
HHV	*Higher heating Value*
Kinuura	*Pellet port in Japan near Nagoya*
kW	*Kilowatt*
LHV	*Lower Heating value*
MBBR	*Moving Bed Biofilm Reactor (aerobic)*

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*
MTTF	*Mean Time To Failure*
MTTR	*Mean Time To Repair (or Maintain)*
MW	*Megawatt*
MWh	*Megawatt hours*
o.d.	*oven dry, 0% moisture content*
°K	*Degree Kelvin*
OPEX	*Operations expense*
p.a.	*per annum (per year)*
PAC	*Powdered Activated Carbon*
PAT	*Pelletization After Torrefaction*
PCI	*Pulverized Coal Injection*
RAFT	*Relative Air Flow Temperature*
SAF	Sustainable Aviation Fuel
SCADA	*Supervisory, Control And Data Acquisition*
SE, STBP	*Steam Explosion*
SG&A	*Sales, General & Administration*
SPC	*Statistical Process Control*
STBP	*Steam Treated Black Pellets*
STBP	Steam Treated Black Pellets
t, tonne(s)	*metric ton*
TAP `	*Torrefaction After Pelletization*
WIP	Work In Process (inventory)
WWTP `	*WasteWater Treatment plant*

Prolog

To meet their committed GHG emission targets, many countries have implemented policies that either phase out coal in power generation or impose penalties on CO_2 emissions to make switching from coal to renewable, bioresource-derived solid fuels more cost-effective.

The most common renewable energy sources, wind and solar PV, have a major limitation: they only generate power when the wind blows or the sun shines. In contrast, traditional power plants can be turned on or off based on demand.

Another opportunity to reduce carbon emissions lies in metallurgical technologies. In these, wind- or solar-generated hydrogen or electrical energy are fundamentally feasible as energy sources and reductants, but they are not yet economically viable. Converting biomass to high-carbon biochar appears to be a practical solution, as it would allow the use of already installed assets. This technology is still developing, as considerations for the use of upgraded biomass for power generation need to be factored in.

Sustainable Aviation Fuel

SAF is an energy dense hydrocarbon. Energy density is critical for aviation fuel. Aircraft that travel moderate distances or more will not be battery-electric driven. The energy density per kilogram of modern Li-ion batteries is about 0.25 kWh/kg. SAF is about 12.0 kWh/kg (nearly 50 times more energy per unit of weight). While battery efficiency per kg will likely improve in coming years, it is highly unlikely that we will see a 50x improvement! Furthermore, as SAF is consumed during flight, the aircraft gets lighter, resulting in lower fuel consumption per distance traveled. Batteries retain 100% of their weight from takeoff to landing[1].

By most accounts, SAF demand will grow from the current ~2-3 million metric tonnes per year to ~40 million tonnes per year in 2035 and, if net zero is to be reached for air travel by 2050, more than300 million tonnes per year[2]. The basis of the expected growth is government policies, carbon emissions regulations, airline net-zero commitments, and an evolution in consumer sensitivity to CO2 pollution. A key characteristic supporting the growth of the use of SAF is that it is a "drop-in" replacement for fossil fuel derived aviation fuel.

The current supply of SAF is less than 1% of the global aviation fuel demand. Even if actual future demand is significantly less than the forecasts, there is a massive opportunity for growth.

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[1] For example, a 3,000-mile flight would require about 30 tonnes of regular aviation fuel or SAF. Batteries with the same energy would weigh about1,500 tonnes. That is about 5 times the maximum takeoff weight of a Boeing 787 and leaves no room for passengers or cargo.
[2] S&P Global, IATA

Currently most SAF comes from used animal fats, used cooking oil, and waste with high lipids content that are converted via the HEFA process3. But those feedstocks are limited and cannot come close to satisfying the expected long-term demand.

The future supply of SAF will depend on biomass including the residues from the forest products industry4.

The optimal pathway for conversion of biomass to SAF is via the Fischer-Tropsch process. The higher the carbon content of the feedstock, the more efficient the conversion of feedstock to SAF is.

This report discusses the only pathway to high carbon content biomass: torrefaction. It includes a section on SAF.

Power Generation

Since conventional coal plants often have many years of economically useful life, power generators can offer a carbon-beneficial solution to the intermittency and variability of wind and solar energy by replacing coal with a solid fuel made from refined and upgraded renewable biomass. Biomass derived from forest residues (such as branches and parts of the harvest that are unsuitable for lumber or pulp), as well as sawmill residuals and specific agricultural residues, including empty fruit bunches (EFBs) that are by-product of the palm oil sector, are sources of feedstock for producing pellet fuel.

Research continues into EFBs and other bioresources, such as straw, grasses, bagasse, corn stover, and agricultural waste streams. While the inherent heating value would be sufficient, the mineral content of these biomass sources, especially alkali metals and chlorides, poses some challenges because of a lower ash melting point and potential increases in fouling, and corrosion of heat exchangers.

Since woody biomass is the simplest to use as a coal substitute, we will focus on it. An exception might be EFBs, which have attracted significant interest. Removing some alkali metals and chlorides could create a valuable opportunity to turn waste into a resource. The lower cost of the feedstock might balance the extra processing costs.

We base our analysis on the assumption that biomass is sourced strictly in line with sustainability criteria or is a byproduct of agricultural production. The key condition for sustainability is that the harvest/removal rate is lower than the regrowth rate. Under these conditions, ligno-cellulosic biomass is carbon-neutral when used as fuel or as a reductant for iron ore refining.

Using wood chips directly is generally impractical. Wood chips have a low volumetric energy density, which results in high transportation costs. They also act as a substrate for fungal growth and can biodegrade quickly, potentially causing self-heating when stored in piles. However, the primary issue is that wood chips

[3] See HERE for a discussion of SAF production using the HEFA process.
[4] For a discussion of how the forest products industry can provide a perpetual supply of sustainably sourced biomass, see this webinar by Dr. Strauss sponsored by the Advanced Woody Biomass Alliance on YouTube HERE.

cannot be used in pulverized coal (PC) power boilers because coal grinders are not suitable for milling the chips. The solution is to use dried, densified, and finely milled wood fiber, usually in pellet form.

"White" pellets, which are dried, milled, and compressed wood fibers, have a significantly higher volumetric energy density than wood chips. The particles they consist of are small enough to allow co-firing with coal without costly modifications to the fuel delivery system, up to approximately 10-15%. They can also be used as a 100% substitute, but this requires modifications to the burners, fuel preparation, and conveyance systems, potentially leading to a derating of the power plant. White pellets can only be used in a pulverized coal injection burner if their particle size is already small. They cannot be ground finer than the particle size established by the hammer mills at the pellet production factory.

The biggest economic challenge of using white pellets is the need for dry storage, since the pellets fall apart and swell when exposed to water, making them unusable. If a power generator wants to use them, it must invest heavily in dry storage facilities. This is especially difficult for power plants with a lower capacity factor.

Fortunately, thermal treatment options that produce so-called "black" pellets provide water resistance, boost volumetric energy density even more, enhance durability during transport and handling, and influence the grindability of the product.

For some utility-scale pulverized coal (PC) power plants, black pellets might be the most cost-effective way to replace coal with a solid fuel that provides the benefits of carbon neutrality and works well with their fuel handling and combustion systems.

There are two fundamentally different industrial methods to enhance ligno-cellulosic fibers, making them water-resistant, grindable, and increasing their energy density.

- Torrefaction, which is a thermal treatment in an oxygen-depleted ambient
- High-pressure steam treatment, followed by rapid explosive decompression (often called "steam explosion" pellets, referred to in this report as SE). Other names for the same technology are:
  - STBP — Steam Treated Black Pellets
  - Vapeur Craquage — Steam Cracking
  - SE — Steam Expanded

In the cases of thermochemical conversion and steam treatment, some of the woody biomass, mainly hemicellulose, breaks down and releases volatile reaction compounds. At the severity used to produce power generation pellets, torrefaction results in a loss of mass and energy, typically 25-30% in mass and 12-15% in energy. The lost energy in torrefaction is reclaimed from the torrefaction gases through combustion and used to dry the green feedstock.

SE usually causes a 10-14% mass loss and a 5-8% energy loss, conserving more of the biomass's original energy content. The nature of SE's mass and energy loss is different from torrefaction; more condensable and marketable compounds are generated, such as furfural, 5-HMF, and acetic acid.

For both technologies, we model a severity limited to achieving water resistance and improved grindability.

This assumption does not apply to biomass upgrades for metallurgical purposes, SAF, soil improvement, or gasification. For these purposes, a higher severity level should be selected, which can produce up to 70-80+% fixed carbon.

This report will summarize and discuss the offerings of some industry-leading companies in these sectors. We will compare technical and economic parameters under comparable conditions. In all cases, the black pellet products are considered suitable as a direct coal replacement, requiring no dry storage and only modest modifications to the burner and pulverizer systems. We cover the COD (chemical oxygen demand) of runoff from pellets stored in the open in a special section of this report. This is an issue that cannot be ignored.

We expanded the report to discuss several options for using more severe levels of torrefaction/pyrolysis to obtain biomass-derived reductants for metallurgical purposes, including a cost estimate.

Both torrefaction and SE can produce upgraded pellets for power generation. As shown in the main body of this report, this FutureMetrics analysis finds that torrefaction's ability to create a product with higher carbon content than SE has unique value.

Highly torrefied or pyrolyzed biomass can replace part of the fossil carbon used as a reductant in the CO_2-intensive steelmaking process or serve as biochar in soil improvement or for SAF production for which high fixed carbon from torrefied/carbonized pellets is an advantage. The report also indicates that SE may offer a somewhat lower cost than torrefaction for producing a coal substitute for power generation. This is because SE involves co-generating marketable biochemicals, such as furfural or 5-HMF, which provide a decent net profit contribution. The byproducts of torrefaction are mostly used as fuel for drying the feedstock and at higher severities, energy for export.

We will discuss the continuous steam treatment process, like those offered by Valmet and Andritz, and compare that to the batch process, such as the one provided by Arbaflame.

We analyzed torrefaction solutions provided by Airex, Andritz, TSI, and Yilkins, including their offered services.

We offer comments on safety, process robustness, equipment capability, project management and operational and economic perspectives, thereby assisting in strategic decision-making.

We only examined technologies that densify the product before pelletization to reduce transportation costs and potential throughput constraints of pulverizers. However, that limitation should not be the only consideration used to produce high-carbon-content reductants for the metallurgical industry.

Even for upgrading existing white pellet plants to black pellets, TAP (torrefaction after pelletization) may offer an alternative path and should not be disregarded. TAP also offers higher hydrophobicity of the product compared to PAT.

We examined the technologies from a high-level techno-economic perspective, including safety factors, operational considerations such as maintenance and equipment uptime, and the companies' likely ability to provide spare parts and services as needed worldwide and quickly.

Inputs from users of the analyzed technologies and providers were included when quantified data was available.

The comparisons are made with the same cost assumptions for feedstock, labor, external energy cost, and financing, but for different moisture contents (MC) of the end-products (based on the technology provider's input).

This report can help narrow the search, save time and money, select the most reliable technology, and reduce the risk of unexpected results.

Before approving and pursuing a black pellet plant project, it should be modeled with project-specific actual inputs and risk analyzed to make the best decision and set accurate expectations.

FutureMetrics is well-qualified to assist in specific project due diligence.

We provide guidance on the factors and process steps to consider when setting objective specifications for a project, finding a cost-effective solution, and managing the project to reduce change orders, prevent dead ends, and complete the project on time and within budget.

From an operational perspective, we suggest ways to maximize asset utilization by lengthening MTTF (Mean Time To Failure) and shortening MTTR (Mean Time To Repair). We emphasize the importance of having sufficient resources to operate safely and maintain good housekeeping.