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AN ENERGY ANALYSIS COMPARING
BIOMASS TORREFACTION IN DEPOTS TO WIND WITH NATURAL GAS
COMBUSTION FOR ELECTRICITY GENERATION

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ABSTRACT

AN ENERGY ANALYSIS COMPARING BIOMASS TORREFACTION IN DEPOTS TO WIND WITH NATURAL GAS COMBUSTION FOR ELECTRICITY GENERATION

Biomass torrefaction and wind power with natural gas are compared to decide which renewable energy system to adopt when both plant biomass and wind are available. The renewability of both systems was compared in terms of energy return on investment (EROI) by quantifying the fossil energy input and renewable energy output. On the basis of a functionally equivalent amount of electrical power (100 MWe) and heat (50 MWth), a breakeven wind velocity of 9.875 m/s resulted in both systems having the same the EROI. In regions with available biomass feedstock, facilities suitable for biomass power and wind velocities below 10 m/s, torrefaction is a more renewable approach. Conversely, regions with velocities greater than 10 m/s or little access to biomass sources and facilities, wind combined with natural gas is superior. Due to average wind speeds below 10 m/s and the wide availability of biomass in Michigan, the torrefaction bioenergy system outperforms the wind-natural gas system.

Keywords: torrefaction, biomass, wind energy, energy analysis

1 Introduction

Population growth and increased energy consumption have furthered U.S. reliance on fossil fuels to meet the growing demand for electric power. Negative environmental impacts associated with the extraction and combustion of fossil fuels has resulted in the U.S. EPA proposing a 30% reduction of carbon emissions from coal-fired power plants.[1-5] Given the large extent of U.S. shale gas reserves, this reduction favors another fossil fuel, natural gas, because its carbon emissions are less than coal. Instead of becoming reliant on yet another fossil fuel, renewable energy sources should be considered for making electrical power with lower environmental impacts.

Due to incentives and success in European countries, Michigan and other states with areas of high wind velocities have chosen wind power as a renewable solution.[6, 7] However, wind intermittency leads to oscillatory electricity generation,[8] creating the need for an additional energy source that can be dispatched to match generation and demand on the power grid.[9] Complementary power can be generated by combusting natural gas in gas turbine cycles, which are operated to counter wind intermittency.[6, 10] Though wind power generates renewable electricity, operating combustion turbines during intermittency consumes fossil energy. Therefore, a renewable source that provides dispatchable power is required to completely end reliance on fossil fuels.

Plant biomass, the fourth largest worldwide energy source, offers one such renewable pathway.[11] Though woody fuels are traditional feedstocks for the electrical power industry, several properties of raw wood are less desirable than coal, including: low energy density, poor grindability, hydrophilicity and tendency towards microbial degradation during storage.[12, 13] Conversely, thermally upgrading biomass by torrefaction (an anoxic heat treatment) creates a solid fuel product with similar properties to coal.[14-19] Further, combusting torrefied biomass in a traditional coal-fired facility has the potential to generate power on a consistent basis without the capital cost associated with additional infrastructure.

In terms of renewability, how torrefied biomass combustion compares to a combined wind-natural gas system is largely unexplored. A functionally equivalent comparison of these competing systems in terms of their renewable energy output has yet to be performed. Such a comparison must account for their fossil inputs, meaning that the natural gas used to stabilize intermittent wind energy must be included in the analysis. The inclusion of fossil fuels is not needed during torrefied biomass combustion, however, as this renewable solid fuel produces stable heat and power. For this study, the renewable energy return on fossil energy investment (EROI) was computed to indicate which system was more renewable in terms of energy use and generation. By quantifying the energy flow in each system and calculating the EROI, this study compares electrical power production from torrefied biomass to wind energy coupled with natural gas. This analysis fills a knowledge gap by improving a decision maker's ability to select amongst these systems for sustainable heat and power production.

1.1 Description of Torrefaction System

The torrefaction system under study uses a decentralized depot to produce dense, torrefied biomass for centralized combustion at a coal-fired power plant. This system, shown in Figure 1,

is accomplished by the cultivation, harvesting, chipping and drying of biomass prior to torrefaction and densification to create the desired end product. The dense, torrefied biomass is then transported to a mid-sized power plant, where it is combusted to create heat and power. As a means to make a functionally equivalent comparison, 100 MW_e and 50 MW_{th} were selected as power plant outputs.

Figure 1. Torrefaction process flow diagram.

It is important to note, the energy required to construct a torrefaction depot has been excluded from this comparison. When compared to the assumed 20-year lifetime of the facility, the fossil energy input needed to supply and transform plant biomass is negligible. The basis for this assumption is further discussed in Section 3.3, EROI.

1.2 Description of Wind and Natural Gas System

The second system includes both a wind farm and natural gas combined cycle to smooth oscillations of wind power production. A natural gas combined cycle (NGCC) plant was selected due to increased efficiency over traditional plants. In addition, fast startup time advantages a gas turbine system by quickly responding to changes in wind output.[9] The NGCC was assumed to be 47% efficient, which is a significant increase over steam cycles that have 35% efficiency. [20, 21] For cases in which process heat is required, natural gas can be combusted in a boiler with a 90% efficiency to solely produce heat, without electricity. Combining these two processes will generate a constant stream of electricity and heat, independent of wind velocity. Figure 2 is a manufacturing and operation diagram for wind turbines including the formation of metals, construction of parts, assembly and operation. The power obtained from the wind farm will be balanced by power from natural gas combustion when wind is intermittent to produce a total of 100 MW_e. Heat from the combined cycle is supplemented with additional heat from direct natural gas combustion, totaling 50 MW_{th}.

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B

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C

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Figure 2. A. Wind turbine manufacturing diagram, B. Natural gas combined cycle process, showing the topping gas cycle over the bottoming vapor cycle, C. Direct combustion of natural gas for heat.

Similarly to the torrefaction process, the energy input to the construction of the wind turbines has also been ignored. Over the assumed 20-year lifetime of the turbine, the energy input to making the turbines is negligible in comparison to the energy generated.

2 Methods

2.1 Functional Unit Selection and Reference Flows

A reasonable scale for heat and power production was selected to compare both energy systems in a functionally equivalent manner. Surveying the literature revealed that several power plants are run as cogeneration systems, producing both heat and electrical work.[18, 22, 23] District heating facilities are examples of cogeneration delivering electricity and steam, via underground pipes, to the municipalities they serve. Though the scale of combined heat and power plants vary, a 100 MW_e and 50 MW_{th} plant is in the range of reasonable capacities and was thus chosen as the functional unit [24, 25]. Combustion of torrefied biomass and natural gas results in the production of heat and power while harvested energy from wind turbines only supplies electricity. Reference flows needed to meet the functional unit include the flow rates of torrefied biomass and natural gas in addition to wind velocity.

2.2 Mass and Energy Balance

Mass and energy balances were performed to formulate process models used to compare both systems. The energy required to complete each step in the torrefaction bioenergy system was computed on a functional unit basis. The same process was used for a wind farm, calculating energy output for various wind velocities and the natural gas required to meet the functional unit.

2.3 Energy Return on Investment

Upon selecting a functional unit in terms of heat and power produced, energy return on investment was chosen as the metric to compare renewable energy output to fossil energy input for each system. Equation 1 was used to calculate the EROI, where E_{out} represents the total renewable energy produced, which will be 100 MW_e and 50 MW_{th} for the torrefaction system. E_{out} will fluctuate for the wind and natural gas system, due to variance in wind velocities. E_{pre} represents the pre-combustion energy of the wind turbines or torrefaction facility equipment. Pre-combustion energy is a term used in life cycle assessments and refers to the fabrication energy that is needed to create facilities or equipment. Lastly, E_{fossil} totals the fossil energy input to produce E_{out} or meet the functional unit.

$$EROI = \frac{E_{out}}{E_{pre} + E_{fossil}} \quad \text{Eq. (1)}$$

2.4 System Analysis

2.4.1 Torrefaction Bioenergy System

Energy balances were performed for each of these system components using data and approaches from the literature. These data, including their sources, are presented in Table 2 of the results section 3.1.

Cultivation

The cultivation of a poplar plantation was studied to determine the energy inputs for growing the feedstock. Poplar was selected as it grows rapidly in the state of Michigan with minimal input. Energy inputs were assessed for planting, six years of growth and harvest at a hypothetical Michigan-based poplar plantation. Di Nasso et al.[26] and Manzone et al.[27] were used to identify the range of energy inputs during cultivation. Dr. Raymond Miller, the director of the Forest Biomass Innovation Center in Escanaba, Michigan, is an expert on conditions that support poplar cultivation in Michigan's Upper Peninsula.[28]

Both Di Nasso and Manzone recorded energy inputs for establishment, equipment operation, fertilization, mechanical weed control and land clearing. Unlike the sites considered by Di Nasso and Manzone, Michigan poplar plantations are not typically fertilized. Omitting fertilization and low average temperatures contribute to Michigan's low yield, 10 Mg/ha versus 11 Mg/ha and 15 Mg/ha yields reported by Di Nasso and Manzone.[29] In Michigan, the cultivation process requires planting, herbicide application, mechanical weed control, pesticide application and stump removal. Based upon this knowledge of Michigan management practices, the energy inputs from Manzone and Di Nasso were combined to mimic a Michigan poplar plantation.

Harvesting

Energy inputs can fluctuate depending upon equipment, harvesting strategy and targeted material size. Both Di Nasso and Manzone harvesting processes immediately chip the biomass. Instead, this assessment considers chipping after natural drying and transport to the torrefaction depot. Hamelinck et al. [30] describes a harvesting operation of whole-trees that involves cutting, hauling and piling at the roadside of the site. This operation requires 48 MJ of diesel per tonne of biomass harvested which is about half of the Di Nasso harvesting energy requirement.

Chipping

Upon arrival at the torrefaction depot, the biomass is chipped into particles with approximate dimensions of 2x1x0.5 cm by a Morbark® 40/36 Whole Tree MicroChipper.[31] Three chippers, each rated at 340 tonnes per day, are needed to meet the functional unit, though they are not run at full throughput simultaneously. During operation, an average of 2.25 tons of microchips are produced from one gallon of diesel fuel consumed.[31] The combined chipping and harvesting energies were higher than the energy input reported by Di Nasso. Higher energy requirements can be partially attributed to the smaller chip size produced from this chipper, as further reducing particle size is more energy intensive.

Drying

Prior to the transport of biomass from the harvesting site to the torrefaction depot, natural drying decreases the moisture content from 50 wt.% to 35 wt.%.[32] Further drying is needed for effective torrefaction. Reduced moisture avoids wasting heat that could be used to torrefy and increases the heating value of the torrefaction gas, as less water is present to absorb combustion energy. A rotary drum dryer, designed following Perry's Chemical Engineering Handbook, was selected to dry the biomass from a moisture content of 30 wt.% to 10 wt.%.[24]

To size the rotary dryer, Equation 2 was used in combination with the mass flow of raw biomass entering the dryer. The complete calculation can be found in the Supplemental Information.

$$v_B = \frac{\theta \dot{m}_B}{\rho_B f_s} \quad \text{Eq. (2)}$$

In this equation, θ is residence time, v_B is rotary dryer volume, $\dot{m}_B$ is biomass flow, f_s is the filled dryer fraction and ρ_B is biomass density. Drying residence time was selected to be 15 minutes, as this time dries material at low capital costs. A maximum fill capacity of 15% ensures efficient drying by good heat transfer. These inputs result in a dryer volume of 319 m³ that is 3 m in diameter, which exceeds Perry's L/D ratio for a single dryer. Therefore, three dryers with a diameter of 3 m and length of 15 m are operated in series.

Atmospheric air into the dryer was assumed to be 25°C and 50% relative humidity, which is the Michigan average.[33] Absolute humidity and partial pressure of water vapor were used to calculate the rate of evaporation by Equation C.2 shown in the Supplemental Information. Equation 3 is the mass balance for water, which includes biomass moisture and air's humidity.

$$\dot{m}_B(X_i - X_o) = \dot{m}_A(\omega_o - \omega_i) \quad \text{Eq. (3)}$$

The mass flow of air ($\dot{m}_A$) is solved by substituting known values for moisture content (X), absolute humidity of air (ω) and ($\dot{m}_B$) mass flow of biomass. Air-mass velocity was calculated to solve for the overall heat transfer coefficient as detailed in the Supplemental Information. The heat required to operate the dryer was found using Equation 4.

$$Q = UA_{HT}\Delta T \quad \text{Eq. (4)}$$

U is the overall heat transfer coefficient, A is the area of heat transfer in the dryer, ΔT is the mean temperature difference and Q is the total heat transferred to the material. In total, the heat required to reduce biomass moisture content from 30 wt.% to 10 wt.% is 1.16 MJ/s per dryer, or 72.8 kWh/tonne. Total heat required is 3.48 MW for three dryers operated in series, or 218.4 kWh/tonne

Electrical inputs for dryer rotation and air blowers were found from Bergman et al. who found that 25.6 kWh/tonne of biomass is needed to run a dryer slightly larger in size.[34] Hamelinck et al. reported a slightly lower value for the dryer electrical input, i.e. 20 kWh/tonne of biomass. Though Bergman's input is larger, it was used in this study as both air blower and motors were included. Comparatively, Kohl's study calculated a drying energy requirement of 3,000 kJ/kg of water evaporated.[35] Using Bergman's electricity input and Perry's methodology, the energy input is similar, though slightly higher, at 3,140 kJ/kg.

Torrefaction

Data compiled by a series of torrefaction trials using a pilot-scale torrefaction reactor were used for this assessment. Microchips from a Morbark Microchipper were selected as a feedstock because smaller chips torrefy more quickly than larger chips.[36] To maintain anoxic conditions in the torrefier, a nitrogen purge removes initial air and material enters through an air-lock. Torrefaction trials, conducted with a consistent residence time of 10 minutes, found the optimal torrefaction temperature of 263°C resulted in the highest energy yield (Figure 3) without significant mass loss. At 78% mass loss, the energy yield was approximately 80%, which is similar to Sermyagina's torrefaction study.[18] Energy yield was calculated by multiplying mass remaining by resulting material energy content.[37]

Figure 3. The energy yield of each torrefaction temperature at a residence time of 10 minutes. Energy yield is calculated by multiplying mass percentage remaining by heating value of resulting material. The optimum energy yield was found at a torrefaction temperature of 263°C.

To complete the mass balance, gas composition was assumed per a study by Bates et al. 2013, which modelled the volatiles production from willow during torrefaction. Solids yield and chemical composition of torrefaction off-gases, assuming poplar is similar to willow, were reported at various torrefaction temperatures.[38] Using the Bates model, an equation for the chemical reaction of this process was adapted for a torrefaction temperature of 263°C considering the composition of raw biomass, torrefied biomass and off-gas. The stoichiometric coefficients for biomass are found by ultimate analysis yielding raw and torrefied biomass empirical formulae: $C_{4.04}H_{5.8}O_{2.73}$ and $C_{4.84}H_{5.68}O_{2.41}$ respectively.[39]

Raw Biomass Torrefied Biomass Acetic Acid Water Formic Acid

Methanol Lactic Acid Furfural Hydroxyacetone Carbon Dioxide

Eq. (5)

Carbon Monoxide

The torrefaction reaction in Equation 5 was used to find the mass flow rate for each component by using the total throughput required to meet the functional unit. 41.9 tonnes/hr of biomass must enter the torrefier creating 9.6 tonnes/hr of off-gas, which will be combusted for torrefaction heat.[35]

The heat needed for torrefaction was estimated by determining the heat of reaction. Using the chemical reaction shown in Equation 5, Equation 6 was used to estimate the amount of energy required for the entire torrefaction reaction to take place.[40] In this equation, $\Delta \bar{h}$ is the change in

enthalpy, N_P is the moles of the product, N_R is the moles of reactant, and $\bar{h}_f$ is the heat of formation.

$$\bar{Q} = \sum N_P (\bar{h}_f + \Delta \bar{h}) - \sum N_R (\bar{h}_f + \Delta \bar{h}) \quad \text{Eq. (6)}$$

$\bar{Q}$ is the amount of heat required for the torrefaction reaction to occur per mole of reactant. This value reports heat only, and does not include the electrical inputs.

Quantifying the heat required follows the Bates et al. study.[14] The right-hand side of Equation 5, after the torrefied biomass term, represents components of the torrefaction gas. A theoretical combustion model was created using a stoichiometric amount of air and the coefficients in Equation 5. CO_2 , H_2O and N_2 were the products that remained following combustion. Balancing this chemical reaction yielded the reaction shown in Equation 7.

Finally, the motor required to operate the auger consumes a significant amount of electricity due to the amount of biomass processed. Bergman et al. reported 1,200 kW of electrical work consumed by an auger reactor of similar size.[34]

Grinding

Grinding is performed after torrefaction to take advantage of lower grinding costs associated with increased biomass friability.[15, 41] In addition, the grindability of a torrefied, friable material increases the dispersion of biomass particles for better combustion in boilers [42]. Quantifying the amount of energy required for the grinding process is dependent upon the hardness of the material. Phanphanich and Mani fit Equation 8 for the grinding energy required (E_g) based upon the torrefaction temperature (T). This equation was used to calculate the grinding energy required (kWh/ton) following torrefaction at 263°C.[43]

$$E_g = -0.756T + 260.0 \quad \text{Eq. (8)}$$

Using Equation 8, power input, shown in Table 2, was found for grinding torrefied chips to an average particle size of 0.24 mm.

Densification

A prototype briquetting system was used to model densification. This briquetter produces puck-shaped densified material by a simple piston-cylinder device, shown in Figure 4.

Figure 4. Model of the prototype briquetting system

Testing was conducted at a range of pressures, recording the length of compression. Volume was determined by multiplying the compression length by the surface area of the piston. Briquette volume was divided by the mass yielding specific volume. A P-v diagram was created and a polynomial equation (Equation 9) was fit to the results.

$$P = 6 \times 10^{11} v^2 - 2 \times 10^9 v + 1 \times 10^6 \quad \text{Eq. (9)}$$

Equation 9 was integrated (Equation 10) to compute the boundary work, or the energy required to operate the briquetter. W_b represents the boundary work, P is the pressure applied and v is the specific volume.

$$W_b = - \int_{v_1}^{v_2} P dv \quad \text{Eq. (10)}$$

By completing the integration in Equation 10, this unit requires 209 kJ per kg of densified biomass. Hamelinck reports 34 kWh/tonne for briquetting,[30] or 122.4 kJ/kg which is 70% less than the energy required by the experimental briquetting system. This difference may be attributed to the small particle size prior to briquetting, requiring more energy to bind material to make a stable briquette.

Transportation

Following harvesting, the biomass has a high moisture content and low bulk density, which increases the cost of transportation. To reduce cost, the torrefaction depot should be closer to the harvesting sites than the power plant.[44] A total transportation distance of 100 miles was considered; logs were hauled 35 miles to the depot [44] and torrefied briquettes were transported 65 miles to the power plant. The gas mileage for transport was assumed to be 5 miles/gallon.[45] The fuel required for the empty truck fleet to return to the depot or harvesting site was included in the energy analysis.

2.4.2 Wind and Natural Gas System

Energy Input

The material extraction, construction of parts and assembly of a 3.0 MW, onshore wind turbine was considered to compare the wind system directly to the torrefaction bioenergy system. Vestas published a life-cycle assessment (LCA) for the V90-3.0MW turbine, which was selected for this assessment.[46] The LCA reports an onshore turbine requires 4,304 MWh/turbine of electricity for material extraction, construction and assembly in Denmark.[46] This value was used for wind

turbines manufactured in the U.S., as it was assumed that Denmark and the U.S. have similar infrastructures.

Turbine Energy Output

Vestas' LCA was conducted for a Denmark wind farm with average wind velocities of 15 m/s.[46] Wind data used for a Michigan-based analysis was collected from a remote Enviro-weather station in Fremont, Michigan.[33] This location is close to Lake Michigan where the wind velocities are higher than most inland areas. This station records wind velocities at a height of 3 meters, but the Vestas turbine stands at a height of 105 m, experiencing higher wind velocities.[46] The Enviro-weather data was converted to wind velocities at 105 m using Equation 11, where WS_{105} is wind velocity at 105 m and WS_3 is wind velocity at 3 meters. [47-49]

$$WS_{105} = WS_3 * \frac{105^{1/7}}{3} \quad \text{Eq. (11)}$$

Three years of the wind data (2012-14) was collected and evaluated. Over the three-year period, the average wind speed was 8.1 m/s. A histogram of daily wind velocities for 2012-14 is shown in Figure 5.

Figure 5. Histogram of Fremont, MI wind velocity, at 105 m, over a three-year period

Wind Farm Selection

One hundred Vestas V90-3.0 MW turbines with the specifications shown in Table 1 compose the wind farm used for comparison to the torrefaction bioenergy system. This large wind farm is consistent with some wind farm sizes from the literature [51] and will be capable of producing 100 MW_e to meet the functional unit.

Table 1. Vestas V90-3.0 MW wind turbine specifications[46]

Specification	Value
Rated power	3.0 MW
Cut-in wind velocity	3.5 m/s
Rated wind velocity	15 m/s
Cut-out wind velocity	25 m/s
Rotor Diameter	90 m
Blade Length	44 m

Power Output Calculations

In order to meet the functional unit selected for this analysis, 33% of the maximum rated power would have to be achieved. To calculate the power produced from a turbine, Betz's Law was used, shown in Equation 12.[52] ρ_A is the air density (kg/m^3), A_T is the rotor swept area (m^2) and $\bar{v}$ is the wind velocity (m/s).

$$P = 0.5 * \rho_A * A_T * \bar{v}^3 \quad \text{Eq. (12)}$$

Betz's limit of turbine efficiency is commonly below 35%.[53] Based upon Vestas rated power and rated wind velocity in comparison to the ideal power, 13.1 MW, the V90 turbine has a turbine efficiency of 23%. Therefore the power output of the turbine is calculated using Equation 13.

$$P = 0.5 * \rho_A * A_T * \bar{v}^3 * 0.23 \quad \text{Eq. (13)}$$

In the three years of selected data, the wind farm met the 100 MW functional unit for 316 days. High wind velocities (>10 m/s) produce an excess of 100 MW_e. The grid cannot accommodate fluctuation and intermittency of wind power, forcing wind farms to curb output to demand.[6, 54, 55] Energy storage is not favorable as few technologies have been successfully implemented and are often cost prohibitive.[56] Only 100 MW of wind power is accepted, regardless of surplus production.

When the wind farm provides 100 MW_e, natural gas is combusted at 90% efficiency for process heat. Natural gas, with a heating value of 34.31MJ/m³, is delivered at 1.62 m³/s producing 50 MW_{th}. Lower wind speeds require that natural gas be burned in a combined cycle facility to supplement 100 MWe. Additional heat will be produced by direct combustion to supplement 50 MW_{th}.

3 Results

3.1 Torrefaction Bioenergy System Results

Table 2. Energy inputs to each process of the torrefaction bioenergy system. The calculated or assumed values for this assessment are found in the column on the far right; these values are compared to literature sources.

		Literature Sources		
Cultivation	Units	Di Nasso	Manzone	Michigan
Yield	Mg ha ⁻¹ yr ⁻¹	16.4	15.0	10.0
Establishment	GJ ha ⁻¹ yr ⁻¹	1.22	0.75	0.75
Harrowing/Plowing or Mechanical Weed Control	GJ ha ⁻¹ yr ⁻¹	0.34	0.84	0.84
Tractor and Truck	GJ ha ⁻¹ yr ⁻¹	0.48	--	--
Urea Application	GJ ha ⁻¹ yr ⁻¹	--	5.59	--
N Fertilization	GJ ha ⁻¹ yr ⁻¹	1.31	--	--
Mineral Fertilization	GJ ha ⁻¹ yr ⁻¹	--	2.90	--
Pesticide Application	GJ ha ⁻¹ yr ⁻¹	--	0.33	0.33
Interrow Cultivation	GJ ha ⁻¹ yr ⁻¹	--	0.71	0.71
Harvesting	GJ ha ⁻¹ yr ⁻¹	1.32	--	--
Harvest and Transport	GJ ha ⁻¹ yr ⁻¹	--	3.72	--
Land Clearing	GJ ha ⁻¹ yr ⁻¹	0.52	0.33	0.52
Total	GJ ha ⁻¹ yr ⁻¹	5.2	15.2	3.15
Total (Functional Unit Basis)	MW			4.18
Harvesting	Units	Di Nasso	Hamelinck	Michigan
Total Energy Input	MJ diesel tonne ⁻¹	--	48.0	48.0
Total Energy Input	GJ ha ⁻¹ yr ⁻¹	--	0.77	0.77
Total Energy + Chipping	GJ ha ⁻¹ yr ⁻¹	1.32	--	--
Total	GJ ha ⁻¹ yr ⁻¹	1.32	0.77	0.77
Total (Functional Unit Basis)	MW			1.59
Chipping	Units	Di Nasso	Morbark	Michigan
Production Rate	tonne gal diesel ⁻¹	--	2.25	--
Total Energy Input	GJ hr ⁻¹	3.96	3.17	3.17
Total (Functional Unit Basis)	MW			0.88
Drying	Units	Bergman	Hamelinck	Michigan
Heat	GJ tonne ⁻¹	--	2.50	2.40

	water			
Electrical Input	kWh tonne ⁻¹	25.6	20.0	25.6
Total (Functional Unit Basis)	MW			4.71
Torrefaction	Units	Bergman	Hamelinck	Michigan
Auger Motor	kWh tonne ⁻¹	19.1	19.9	19.1
Heat Required	MW	--	--	10.34
Energy Recovered	MW	--	--	-10.92
Total (Functional Unit Basis)	MW			0.22
Grinding	Units		Phanphanich	Michigan
Electrical Work	kWh ton ⁻¹		71.0	61.2
Total (Functional Unit Basis)	MW			2.04
Densification	Units		Hamelinck	Michigan
Boundary Work	kJ kg ⁻¹		144	209
Total (Functional Unit Basis)	MW		--	1.94
Transportation	Units		Hamelinck	Michigan
Harvesting Site to Depot (35 miles)	km		--	56.35
Depot to Power Plant (65 miles)	km		--	104.65
Fuel Efficiency	miles gallon ⁻¹		--	5.00
Heating Value of Diesel	MJ kg ⁻¹		42.0	42.0
Diesel Energy Input	MJ km ⁻¹		18.10	16.90
Total (Functional Unit Basis)	MW			0.98
Total Energy Required	MW			16.54
Energy No Off-Gas Combustion	MW			27.46

As observed in Table 2, cultivation and drying are the most energy intensive steps in the torrefaction system, requiring more than 4 MW of energy to meet the functional unit. Although the torrefaction energy input is the lowest of all processes in the system, without torrefier gas combustion and recycle of heat across the reactor, it would be the largest. By taking advantage of the energy content of the off-gas, less natural gas and therefore, energy input is required to torrefy raw material. In this particular process, over 10 MW of energy is recovered through off-gas combustion. This drastic reduction in energy improves the EROI of the torrefaction system from 5.5 to 9. An EROI one and a half times that of the system without off-gas combustion benefits the torrefaction system greatly when compared to the wind system.

3.2 Wind and Natural Gas System

To calculate the amount of natural gas needed for supplementation on days where wind velocities were lower than 10 m/s, the total power produced from the wind farm was subtracted from the functional unit, 100 MW. Table 3 shows the average wind velocity required to produce

100 MW_e is 10 m/s. Wind velocities below 10 m/s require natural gas to supplement the system power output. A natural gas flow rate of 22,300 m³/hr is required to produce 100 MW_e from a 47% efficient NGCC plant. The associated process heat created at this efficiency totals 48.9 MW, meaning additional natural gas provides the remaining heat to reach the functional unit.

Table 3. Heat and power production requirements based upon wind velocity. The second column indicates the amount of electricity needed from natural gas to meet the 100 MW functional unit. The third column is the resulting heat produced by creating power from natural gas. The last column lists the additional heat needed to meet the 50 MW functional unit by the direct combustion of natural gas in a separate furnace.

Wind Velocity (m/s)	MW Required from NGCC	MW _{th} Produced	MW of Extra Heat Required
<3.5	100	48.9	1.1
4	93.5	45.8	4.2
5	87.3	42.7	7.3
6	78.1	38.2	11.8
7	65.2	31.9	18.1
8	48.1	23.6	26.4
9	20.4	12.8	37.2
≥10	0	0	50

Table 3 shows the power and heat required to meet the functional unit at various wind velocities. An average wind velocity of 8 m/s requires 48.1 MW_e from the NGCC facility, which co-produces 23.6 MW_{th}. An additional 26.4 MW_{th} is produced by combustion of natural gas in a furnace. When 100 MW of power is produced from the wind farm, 50 MW_{th} is needed by the combustion of natural gas revealing that higher wind velocities reduce natural gas consumption.

3.3 EROI

The mass and energy balances were used to calculate the EROI for each system. First, pre-combustion energy was found in the literature. Wide variances in equipment and plant capacity lead to a variance in pre-combustion energy. Kaliyan et al. calculated the GHG emissions of a torrefaction process through combustion at a power plant. The power plant construction contributed 0.06 g of CO₂ / MJ of energy produced, [57] which is very small (0.37%) when compared to upstream and combustion GHG emissions, totaling 15.83 g CO₂/ MJ. Emissions from torrefaction facility construction are likely less than power plant construction emissions. Since GHG emissions are minute in comparison, it is assumed that the energy input follows the same trend. The pre-combustion energy required to construct a torrefaction depot is negligible when compared to the fossil energy input needed to supply and transform plant biomass over the 20-year lifetime of the facility. The EROI of the torrefaction system equals the amount of renewable energy output, 150 MW, over the fossil energy required, 16.54 MW, resulting in a value of 9.07.

The EROI of the wind and natural gas system was first calculated using the average wind velocity of 8.1 m/s. A pre-combustion value of 4,304 MWh/turbine, reported by Vestas, must

also be added to the calculation.[46] These values were carried over a 20-year lifetime of the wind turbines. Since the pre-combustion energy for torrefaction was ignored, the pre-combustion energy of the turbine construction facilities and natural gas combined cycle plant were also assumed negligible. Therefore, the EROI for a wind farm of 100 turbines with natural gas supplementation, at the average wind velocity of 8.1 m/s, is 0.73 (Table 4). This number is less than 1.0 because the renewable power produced from the wind farm is less than the fossil energy required to meet the functional unit.

Table 4. EROI calculations for multiple cases, varying wind velocities and process heat requirements

Case	Wind Velocity (m/s)	MW Required from NGCC	MW _{th} Produced	Extra MW _{th} Required	EROI
1	8.1	46	22.6	27.4	0.73
2	10	0	0	50	2
3	8.1	46	22.6	0	1.23
4	10	0	0	0	16,667

The EROI was calculated for three other scenarios and shown in Table 4. Case 2 is the best-case since the EROI is 2 with wind velocities at 10 m/s, producing 100 MW_e. Case 3 does not take into consideration the process heat requirement making the EROI for the average wind velocity 1.27. Case 4 considers a wind velocity of 10 m/s without 50 MW_{th}, resulting in an EROI is 16,667. This EROI is large because the energy input to make a turbine is insignificant in comparison to the energy output over a 20-year lifetime. However, the last two scenarios provide an unfair comparison because without heat, the comparison ignores energy co-produced during electricity generation.

4 Discussion

Although the torrefaction system performs significantly better in terms of EROI when 100 MWe and 50 MW_{th} are produced, there are many factors that could alter the results of this comparison. The effectiveness of the torrefaction system itself is sensitive to multiple factors. The most impactful factor investigated in this study is the raw material's moisture content. Moisture content impacts the energy required for torrefaction and hauling costs for transportation to the depot as previously determined by Chai and Saffron.[58] Briefly, high biomass moisture contents justify more severe torrefaction processing conditions because more combustible off-gas is produced for process heat. Assuming a reasonable range of field conditions, torrefied biomass production costs can vary by about 10% when these sensitivities are considered. Even when increasing the energy input by 10%, a relatively high EROI of 8.26 results for the torrefaction process.

In section 3.3 of the results section, various cases were considered when comparing the EROI of both systems. Alternative cases have been considered for the wind system by varying heat requirements, shown by the curved lines in Figure 8. The two straight lines represent the EROI of the torrefaction systems.

Figure 8. Comparison of EROI values to wind velocity with varying amounts of heat required

Figure 8 shows that a heat requirement of 10 MW_{th} or less is necessary for the EROI with average wind velocity to exceed the torrefaction system. The EROI for the torrefaction system is larger than wind-natural gas when 50 MW_{th} is included in the calculation. Conversely, the EROI for the wind and natural gas system increases dramatically as the heat requirement is reduced. However, this comparison is not made on an equivalent basis without the inclusion of heat. Two breakeven points are apparent from Figure 8. With wind velocities higher than 9.875 m/s and 10 MW_{th} required, a wind farm has the same EROI as torrefaction when considering 50 MW_{th}. Also, at a wind velocity of 9.25 m/s and a heat requirement of 10 MW_{th}, the EROI is comparable to a torrefaction system without heat production.

When the biomass moisture content sensitivity is taken into consideration, the breakeven points change slightly. A 10% increase in the energy required for torrefied biomass production reduces the EROI to 8.26 when 50 MW of heat production is included. An average wind velocity of 9.6 m/s must be sustained to have a comparable EROI to the torrefaction system even with the increase in energy input.

Figure 9. Comparison of EROI to varying heat requirements.

In addition to wind speed, EROI is also a function of the heat requirement, as shown in Figure 9. As expected, the EROI of the torrefaction system increases as the heat requirement increases. Conversely, all of the wind systems are disadvantaged with larger heat requirements because increasing amounts of natural gas are combusted. Similar to the conclusions of other wind studies a consistently high wind velocity is required to make the investment of a wind farm economically feasible from an energy benefit and economic perspective.[59] As revealed in Figure 9, a wind speed approaching 10 m/s must be sustained to have a larger EROI than the torrefaction system. However, only between 0 and 10 MW is the EROI larger than the torrefaction system. Higher wind velocities will show the same result as the 10 m/s curve because the electrical portion of the functional unit is met with larger wind speed, but the heat requirement is met with natural gas. This chart also confirms that when heat is removed from the functional unit, the torrefaction system has a larger EROI than the wind system when Michigan's average wind velocity is considered.

Though this comparison provides a view of energy inputs and outputs, many factors can impact the energy return of both systems. The largest impact is the availability of resources. Wind systems experience a wide range of variability that is difficult to capture and quantify. This variation occurs over time periods of an hour, day, and season. Any wind velocity change impacts power output and the resulting heat and power required from the NGCC plant.

Of the three years of data evaluated, the average annual wind velocity only varied by 0.2 m/s at the specified location. Though the average wind velocity was consistent, seasonal or hourly variations were not analyzed. This approach places a greater value on the system's gross renewable electricity output and does not capture the impact and efficiency losses from cycling the NGCC plant to match wind energy output. Like wind systems, biomass availability is also impacted by seasonal changes and other conditions that affect biomass growth or harvesting. Without the ability to predict growth changes and quantify seasonal swings, these sensitivities were not included in the energy analysis of the torrefaction system. Regions that are impacted by seasonal variation in renewable sources should investigate the potential of integrating wind

power and power generation from torrefied biomass in a synergistic way to maximize EROI. Future analyses should include the aforementioned variations and consider integrating wind systems and torrefied biomass facilities to create a superior system that is less vulnerable to resource availability.

5 Conclusions

This energy analysis compares a torrefaction system to a wind farm supplemented with natural gas. Using the EROI for comparison, results indicate that a torrefaction system provides a larger energy return for a functional unit of 100 MW_e and 50 MW_{th}. This is largely due to the addition of process heat from torrefied biomass combustion. Wind velocities also have a significant impact on EROI. With wind velocities averaging in the range of 7-8 m/s and a wind farm of 100 turbines, the wind and natural gas system must rely on natural gas to meet the 100 MW power requirements. Although the EROI metric for this assessment supports the torrefaction system, the average wind velocity is location dependent and the market for thermal energy should be considered.

The wind system EROI improves when wind velocities above 10 m/s are sustained. When a wind velocity of 10 m/s is sustained and when only 10 MW of process heat is required, the EROI is comparable to the torrefaction system. Therefore, an area that averages higher wind velocities (10 m/s) would greatly benefit from harvesting this available energy. If in that surrounding area, the woody biomass sources are insignificant, natural gas can still be used to meet any heat requirements. Conversely, if the surrounding area had available biomass or could support energy crop plantations, direct raw biomass combustion can provide process heat. Such a scheme produces needed heat and power from renewable sources.

This analysis was conducted for a region in which biomass was a better asset for energy production when compared to wind velocities averaging in the 7-8 m/s range. For locations in which biomass is available and the wind velocities are low, torrefaction is a renewable solution. Michigan has access to a large amount of biomass, including poplar. Also, with the large amount of coal-fired generating stations in the state, there are many opportunities available for torrefied biomass combustion in power plants. However, in other areas characterized by high wind velocities in excess of 10 m/s or low biomass availability, wind power would significantly offset the power required from fossil fuels. Taking into consideration biomass accessibility and wind velocity is essential for the sustainability of the renewable system. Although this work highlights local resource consideration, environmental impacts and cost must also be considered for both systems before implementation. In regard to the environmental impacts, a carbon footprint analysis would expand the results of this study by tracking the renewability of each system beyond the energy inputs and outputs. Tracking emissions from product creation to disposal will expand the scope of the comparison to include the entire life cycle of each system. Additionally, a comparison of capital and operating costs is essential to inform stakeholders of the economic feasibility of each renewable system. Further study should also evaluate other biomass sources that are readily available outside of the Midwest, such as corn stover, grasses or other agricultural wastes. In areas where solar energy is abundant, a similar type of energy analysis should be conducted to compare electrical power from torrefied biomass and solar technologies.

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6 Glossary

EROI – Energy Return On Investment

MW – Megawatt

MW_e – Megawatt electrical

MW_{th}– Megawatt thermal

Natural Gas Combined Cycle – An electric power generation process that uses both a gas turbine and a steam turbine to create power using waste heat, therefore, increasing plant efficiency

Precombustion Energy – The resource acquisition energy or in other terms, the fabrication energy that is needed to create a facility or a piece of equipment

Torrefaction – A thermal process that heats a material in an oxygen-free environment to a temperature between 200 and 300°C

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8 Appendices

A. Co-generation Calculation

Utilization Factor = 0.7

$$\frac{W_{e\ net} + Q_p}{\dot{m} \cdot HHV} \quad \text{Eq. (A.1)}$$

$$W_{e\ net} = 100\ MW$$

$$Q_p = 50\ MW$$

$$HHV = 23.1 \frac{MJ}{kg}$$

B. Mass Flow Calculation

Power Plant Capacity = 100 MW

Total Electrical Generation = 876,000 MWh/year

Higher Heating Value (HHV) of Torrefied Material = 23.1 MJ/kg

$$\text{Electrical Work: } 3.15 \times 10^9 \frac{MJ}{year}$$

$$\frac{876,000,000\ kWh}{year} * \frac{1\ J}{2.778 \times 10^{-7}\ kWh} * \frac{1\ MJ}{10^6\ J} \quad \text{Eq. (B.1)}$$

Thermal Efficiency = 32%

Thermal Efficiency Equation:

$$\eta_{TH} = \frac{W_e}{\dot{m} \cdot HHV} \quad \text{Eq. (B.2)}$$

$$\text{Mass Flow: } \dot{m} = 187,500 \frac{tonnes}{year}$$

C. Dryer Unit Calculations

Density of Raw Biomass = 250 kg/m³

Mass Flow of Biomass = 797 kg/min

Volume of Rotary Dryer (v_B) = 319 m³

$$v_B = \frac{\dot{m}_B \theta}{f_s \rho_B} \quad \text{Eq. (C.1)}$$

Number of Dryers = 3

Dimensions: D= 3 m L= 15

L/D Ratio = 5

Initial Moisture Content of Biomass = 0.3 kg H₂O/kg biomass

Final Moisture Content of Biomass = 0.1 kg H₂O/kg biomass

Rate of Evaporation ($\dot{m}_{rem}$) = $48.3 \frac{\text{kg H}_2\text{O}}{\text{min}}$

$$\dot{m}_{rem} = \dot{m}_{raw} * \frac{1 \text{ kg Dry}}{1.1 \text{ kg Wet}} * \frac{MC_i - MC_f}{1 \text{ kg Dry}} \quad \text{Eq. (C.2)}$$

Mass of Air ($\dot{m}_A$) = $29.33 \frac{\text{kg}}{\text{s}}$

$$\dot{m}_A = \left[\frac{\dot{m}_B (X_i - X_o)}{(\omega_o - \omega_i)} \rho_A \right] = \frac{4.43 \frac{\text{kg}}{\text{s}} * (0.3 - 0.1)}{(0.049 - 0.012) \frac{\text{kg}}{\text{m}^3}} \quad \text{Eq. (C.3)}$$

Air Mass Velocity (G) = $4.15 \frac{\text{kg}}{\text{s m}^2}$

$$G = \frac{\dot{m}_A}{A} = \frac{29.33 \frac{\text{kg}}{\text{s}}}{\pi (1.5 \text{ m})^2} \quad \text{Eq. (C.4)}$$

Overall Heat Transfer Coefficient (U) = $155.7 \frac{\text{J}}{\text{s m}^2 \text{K}}$

$$U = 60G^{0.67} = 60 * 4.15^{0.67} \quad \text{Eq. (C.5)}$$

Area of Heat Transfer (A_{HT}) = 17.43 m^2

$$A_{Fill} = [\pi (1.5 \text{ m})^2 * 15\%] = 1.06 \text{ m}^2 \quad \text{Eq. (C.6)}$$

$$D_{Fill} = \sqrt{\frac{1.06 \text{ m}^2}{\pi}} = 1.16 \text{ m} \quad \text{Eq. (C.7)}$$

$$A_{HT} = D_{Fill} * L = 1.16 \text{ m} * 15 \text{ m} \quad \text{Eq. (C.8)}$$

Total heat required (Q) = $1.16 \frac{\text{MW}}{\text{dryer}}$

$$Q = UA_{HT} \Delta T = 155.7 \frac{\text{J}}{\text{s m}^2 \text{K}} * 17.43 \text{ m}^2 * (428.15 \text{ K}) \quad \text{Eq. (C.9)}$$