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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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HIGHLIGHTS

- A torrefaction bioenergy system is compared to wind with natural gas combustion in terms of heat and power production.
- Torrefaction has a larger EROI for a functional unit of 100 MW_e and 50 MW_{th}.
- Biomass rich areas benefit from torrefaction if average wind speeds are less than 9 m/s.
- Consistent wind velocities exceeding 10 m/s advantage a wind-natural gas energy system.

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ABSTRACT

Biomass torrefaction and wind power with natural gas are compared to determine 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 MW_e) and heat (50 MW_{th}), a breakeven wind velocity of 9.875 m/s resulted in both systems having the same EROI. In regions with available biomass feedstock, facilities suitable for biomass power and wind velocities below 9 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.

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

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[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 Fig. 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.

It is important to note, the energy required to construct a torrefaction depot has been excluded from this comparison. Over the 20-year lifetime of the facility, the fossil energy input needed to construct the facility is negligible when compared to the energy needed to supply and torrefy the plant biomass. 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. Fig. 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}.

Similarly to the torrefaction process, the energy input for construction of the wind turbine facility has also been ignored. Over the assumed 20-year lifetime of the turbine, the energy input for making the turbine facility 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 that were used to compare both systems. The energy

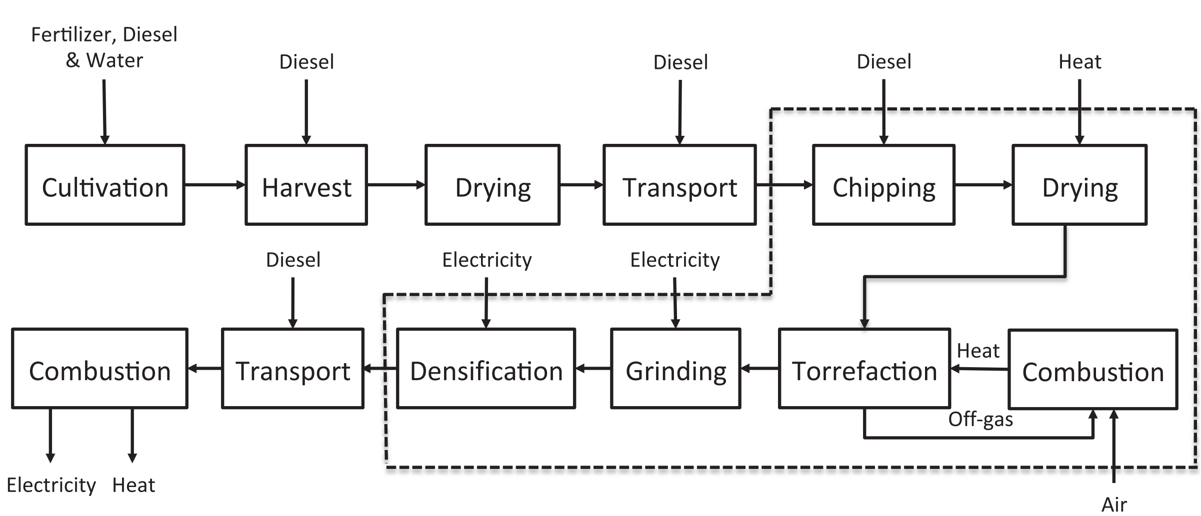

Fig. 1. Torrefaction process flow diagram.