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Torrefied plastic-fiber fuel pellets as a replacement for fossil fuels — a case study life cycle assessment for Green Bay, Wisconsin, USA

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Abstract

Purpose The commercial-scale production of torrefied plastic-fiber fuel pellets from waste plastics and waste fibers may offer a viable alternative to fossil fuel–based energy. In this study, the environmental impact of fuel pellets produced and consumed in Green Bay, Wisconsin, USA is evaluated and compared to the status quo of grid energy production from fossil fuels (i.e., coal or natural gas).

Methods A cradle-to-grave life cycle assessment was conducted using a functional unit of 1 kWh of energy produced using torrefied plastic-fiber fuel pellets versus production of energy from coal or natural gas. Regional data along with relevant manufacturing data was used to inform the inventory of the production of the torrefied fuel pellets, which are manufactured using waste fibers and waste plastics sourced from within 5 km of the torrefaction facility and consumed within 50 km of the facility. Since fuel pellets are produced from waste inputs and contain biogenic carbon sources, impacts were assessed with/without credit for biogenic carbon and with/without the burden of the torrefaction inputs.

Results and discussion The production of 1 kWh of energy using torrefied plastic-fiber fuel pellets was determined to produce between 0.303 and 0.757 kg CO_2 eq emissions due to combustion and between 0.062 and 1.105 kg CO_2 eq additional emissions as a result of the manufacturing process, with the ranges dependent upon the allocation method selected. Under a burden-free allocation due to waste materials used as inputs, along with a credit for biogenic carbon emissions, the system produces 0.365 kg CO_2 eq per 1 kWh of energy; however, under a full-burden allocation with no credit for biogenic carbon emissions, 1.862 kg CO_2 eq per 1 kWh of energy is produced. This highlights the differences between allocation scenarios and role of credits for biogenic carbon emissions when evaluating systems.

Conclusions The usage of torrefied plastic-fiber fuel pellets produced using waste plastics and fibers is a reasonable alternative to the status quo of waste disposal coupled with the production of grid energy from fossil fuels. In addition to the reduction in GHG emissions, the use of the process would also help to alleviate the environmental burden of waste plastics.

Keywords Torrefaction · GHG reduction · Fiber-Plastic waste · Coal replacement

1 Introduction

Global plastics production has been increasing at an unprecedented pace, having quadrupled over the past four decades to reach the current production of 460 million tons per year (OECD 2022; Cabernard et al. 2022), with the OECD estimating that plastic production and incineration contribute 3.4% of global emissions responsible for global climate change (OECD 2022). Although up to 9% of plastics are recycled, up to 22% of plastics are mismanaged; ending up in the environment, oceans, and landfills further contributing to environmental degradation (MacLeod et al. 2021; OECD 2022). Furthermore, even with a transition to plant-derived plastics (Sun et al. 2022), non-recyclable waste products are still likely to be produced (Filiciotto and Rothenberg 2021). These waste products may be the result of the underlying

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material properties, rendering them unable to be recycled; or due to composite layering rendering the recovery of recyclable materials to be cost and energy prohibitive (Kolapkar et al. 2022). While new techniques for plastic recycling are being developed (e.g., chemical recycling, thermal recycling, etc.), many attempts have been unsuccessful due to a combination of poor product quality and prohibitive economics (Tejaswini et al. 2022). However, one additional means of addressing waste plastics is through the application of non-traditional waste-to-energy processes wherein waste plastics are used to produce fuel pellets using a torrefaction production process. These fuel pellets may then be used as an alternative to fossil fuels.

In a typical waste-to-energy process, the primary objective of incineration is volume reduction and mineralization of the waste products (e.g., municipal solid waste) with the heat produced being used locally or for grid power production (Liamsanguan and Gheewala 2007; Sharma et al. 2020). In contrast, in a non-traditional waste-to-energy torrefaction process, energy production is the primary goal, and waste plastics along with waste fibers (e.g., paper, cardboard, and carton) or biomass are used as inputs to produce solid fuel pellets for later use (Xu et al. 2018; Kolapkar et al. 2022). While torrefaction is typically associated with biomass inputs (see Batidzirai et al. 2013; Brown 2015; Niu et al. 2019; Cahyanti et al. 2020), the use of purely biomass inputs has drawbacks which include logistical and economic challenges arising from the feedstock density, high moisture content, and wear of production equipment (Niu et al. 2019; Nunes 2020; Chen et al. 2021). Blending waste plastics with biomass, or waste fiber inputs, has been demonstrated to address some of these concerns and also has the advantage of increasing the calorific value of the resulting fuel pellets (Zinchik et al. 2018, 2020). As a result, the physical characteristics of torrefied plastic-fiber fuel pellets have been studied and documented (see Xu et al. 2018, 2020, 2021; Zinchik et al. 2020). However, the evaluation of the environmental impact of the use plastic-fiber fuel pellets has been limited to a pilot scale study in comparison to forest-derived woodchips (Kolapkar et al. 2022). This is despite the physical characteristics (e.g., lower moisture, higher calorific value) of the fuel pellets suggesting that they have applications as a replacement for fossil fuels, particularly in the context of coal-fired power plants.

In this study, a cradle-to-grave life cycle assessment (LCA) is conducted to evaluate the environmental impacts of the energy produced using commercial-scale manufacture of torrefied plastic-fiber fuel pellets produced in Green Bay, Wisconsin, USA compared to the status quo of energy produced using fossil fuels. The regional grid energy mix, along with suppliers of waste plastics and waste fibers, and consumers of the fuel pellets is used to define the life cycle inventory. This study evaluates the environmental impact using the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) (Bare et al. 2012), with emphasis placed on greenhouse gas (GHG) emissions. Finally, insights into the use of fuel pellets in the context of plastics disposal and energy transitions are provided.

2 Methodology

2.1 Goal and scope definition

The goal of this study is to perform a cradle-to-grave assessment of energy produced using torrefied plastic-fiber fuel pellets manufactured and consumed in Green Bay, Wisconsin using the LCA methodology outlined in ISO 14040 (ISO 2006). This assessment uses a functional unit of one kilowatt hour (1 kWh) of energy and is based upon a *torrefied fuel pellets scenario* in which waste plastics and fibers are pelletized using torrefaction and used for power generation (Fig. 1). The cradle-to-grave system boundary includes the transport of waste inputs, manufacturing of fuel pellets, transport of fuel pellets, and use of the manufactured fuel pellets. This is in contrast to the current *status quo* in which energy is supplied via coal or natural gas. In order to protect the identity of potential suppliers and consumers of the fuel pellets, a pessimistic approach is taken using broad service areas for materials.

Presently, the waste materials used as inputs for the production of torrefied fuel pellets are disposed of in a sanitary landfill due to a lack of demand (i.e., waste fibers) or material composition (e.g., composite plastics). This suggests that in addition to their primary benefit as an energy source, the production of torrefied fuel pellets also offers waste management services. However, waste management services are not the primary objective of the system, which stands in contrast to other waste-to-energy systems, such as municipal solid waste incineration where energy is a secondary benefit following volume reduction and mineralization of waste (Liamsanguan and Gheewala 2007). Accordingly, the primary point of comparison for the status quo scenario (i.e., 1 kWh of energy from fossil fuels) is based solely upon energy production; although the impact of waste disposal is also calculated to fully contextualize the results.

Since the material inputs of these fuel pellets (i.e., waste fibers and waste plastics) are derived from waste products that would otherwise be landfilled, they may be considered burden-free (Olofsson and Börjesson 2018). However, the allocation of impacts in waste treatment and waste management processes is complicated (Heijungs and Guinée 2007), and may be subject to bias on the part of the practitioners (Pryshlakivsky and Searcy 2021). As such, to fully interrogate the possible impacts of the fuel pellets, four attribution approaches are considered wherein waste inputs are/are not burden-free, and biogenic carbon is/is not

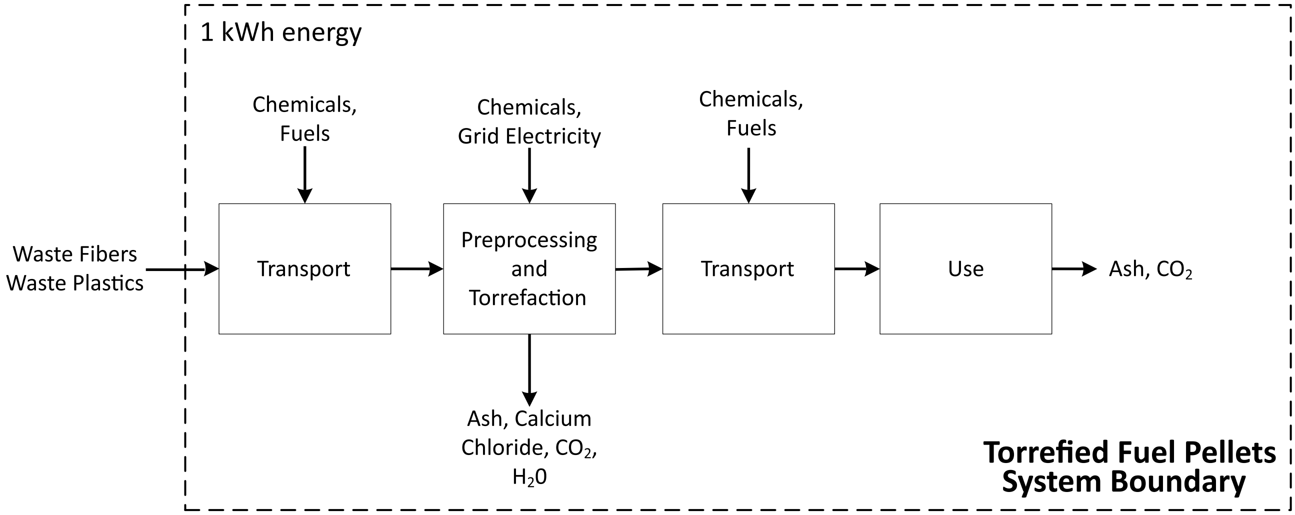

Fig. 1 System boundary with a functional unit of 1 kWh of energy produced by the combustion of the torrefied fuel pellets

counted towards GHG emissions since it is derived from a renewable resource (i.e., cellulosic fibers). The four possible scenarios for the torrefied fuel pellets are the following:

1. *Full burden,* in which the full burden associated with the production of the waste inputs is included, and no credit is applied for the waste fibers.
2. *Full burden with renewable credit,* in which the full burden associated with the production of the waste inputs is included, but a renewable resource credit is applied for the waste fibers for the biogenic carbon.
3. *Burden-free,* in which the cradle-to-gate burdens of the waste inputs are not considered, but no renewable resource credit is applied.
4. *Burden-free with renewable credit,* in which waste inputs are considered burden-free since they would otherwise be landfilled, and a renewable resource credit is applied to the waste fibers due to the biogenic carbon source.

In determining the renewable resource credit, the same assumption as the Renewable Fuel Standard, namely that the consumption of fuels with a biomass component is assumed to be carbon neutral due to carbon sequestration during regrowth of biomass when compared to fossil fuels (Environmental Protection Agency 2007).

This study was conducted using openLCA version 1.11.0 (GreenDelta 2022) and TRACI version 2.1. National Energy Technology Laboratory (NETL) mod (Bare et al. 2012) was used to calculate the environmental impacts. In addition to primary data and inputs acquired from literature sources, the study used the Federal LCA Commons/US Electricity Baseline (Cooney et al. 2019) and U.S. Life Cycle Inventory Database (National Renewable Energy Laboratory 2012) databases, through the Federal LCA Commons (Kahn et al. 2022).

2.2 Pellet production using integrated torrefaction-extrusion

The complete manufacturing process is elucidated in detail in Kolapkar et al. (2022); however, the process can be summarized as follows. Pellet production begins with receiving in which manufacturing waste plastic, along with mixed paper and wood-fiber waste is delivered to the tipping floor from local manufacturing facilities (Fig. 2). The waste plastic is presumed to be a mix of Low-density Polyethylene (LDPE), Linear Low-Density Polyethylene (LLDPE), High-density Polyethylene (HDPE), Polypropylene (PP), and other thermoplastics such as Polyethylene Terephthalate (PET). This mixture is consistent with the waste plastic stream in the pilot-scale study (Kolapkar et al. 2022) and for this study, a mix of 9.86% LDPE, 25.17% LLDPE, 25.59% HDPE, 20.63% PP, and 18.75% PET was used. At full production scale, the precise ratio of plastics may change but is expected to remain consistent with the national average for the USA (American Chemistry Council 2022; Electronic Supplementary information 1, Table S8). Polyvinyl Chloride (PVC) is excluded from the waste plastics mix delivered for use in the manufacture of torrefied fuel pellets. The mixed paper and wood-fiber waste that is delivered is also presumed to consist primarily of paper, cardboard, carton materials, yad waste, agricultural residues, and other biogenic cardboard materials designated to go to a landfill.

Following the delivery of waste feedstocks, materials are retrieved using a wheeled loader and introduced to an infeed belt which delivers them to a three-stage shredder which renders them to about 3 mm in size. Following shredding, a

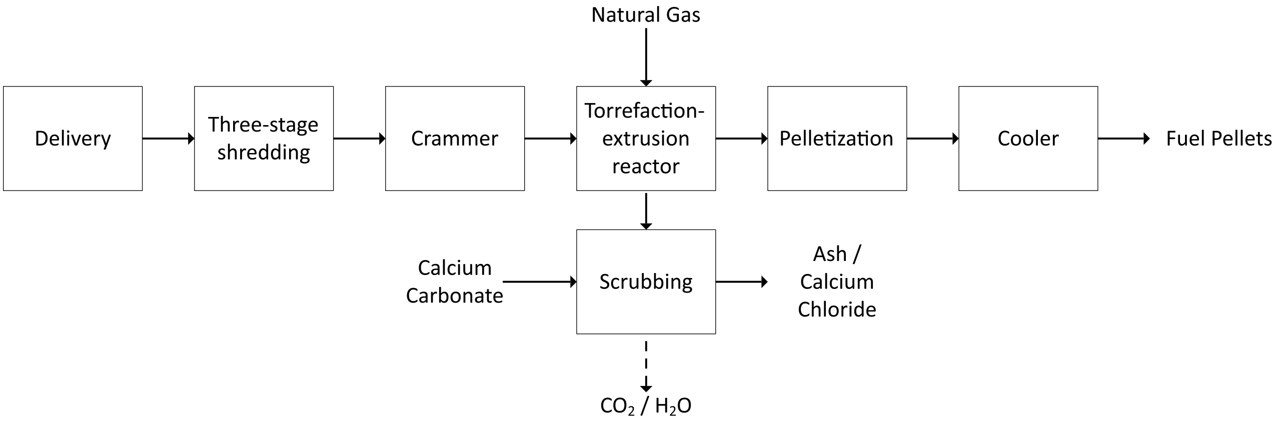

Fig. 2 Simplified overview of the integrated torrefaction-extrusion process, note that grid energy is used to power the manufacturing equipment

bottom hopper introduces the material to a bucket elevator which carries it to a distributor, which in turn delivers the material to an airlocked crammer. The crammer contains a heating jacket which maintains a temperature between 180 and 220 °C, allowing for the drying of the incoming material stream and softening of the plastics. The resulting paste-like material also helps to ensure lubrication of the crammer, assuming a minimum mix of 10–15% plastic. The crammer in turn directs the material to the torrefaction-extrusion reactor where it is mixed, heated, torrefied, and extruded, producing 1.27 cm (0.5 in) rods that are then cut into pellets. Cut pellets fall via gravity into a pellet collector which directs them to a bucket elevator, which in turn leads them to a cooler which reduces their temperature to 20 °C, prior to delivery to the conveyor and ultimately to storage.

Within the torrefaction-extrusion reactor, the material is heated to 350 °C to ensure that torrefaction occurs, but the extruded rod needs to be between 160 and 180 °C prior to cutting to ensure pellet consistency. This is performed using a mineral oil–based system for heating/cooling. Heating to operating temperatures occurs during system startup via natural gas; however, once stable reactor temperatures are achieved, the mineral oil system stabilizes system temperatures and acts as a cooling system. Waste heat is removed via an oil-to-water heat exchanger. Up to 48 MMBtu of natural gas is used as an energy source for start-up, although the commercial facility is designed with a heat management system to recapture as much heat/energy from the torrefaction process as possible for reuse. Full system shut-down for maintenance is planned 2–4 times/year.

Depending upon the composition of the waste plastic-fiber mix used, during the torrefaction process chlorine may be released as hydrochloric acid, necessitating scrubbing of the gasses (Xu et al. 2018, 2020). Scrubbing is accomplished using dry sorbent injection (DSI) wherein gas clean-up is performed using calcium carbonate, prior to redirection to the heat management system. Recapture of heat from the gasses allows a reduction in the overall energy input (i.e., natural gas usage) needed to run the commercial scale system. In addition, the heat management system will eliminate any traces of furnace and dioxins.

2.3 Regional description

Green Bay, located in Brown County, Wisconsin, USA was selected for the site of the initial commercial scale facility due proximity of potential suppliers of waste feedstocks along with potential consumers of the torrefied plastic-fiber fuel pellets produced. Green Bay is located on the shore of Lake Michigan and has a lake port along with railroad and interstate connectivity, resulting in a number of manufacturing facilities being located in the city. Wisconsin Public Service is the primary supplier of electricity in the state and has an energy mix of about 74.79% fossil fuels, 14.61% nuclear, and 10.60% renewables (see Electronic Supplementary information 1, Table S1; U.S. Energy Information Administration 2022).

The fuel pellet manufacturing facility will be located in the industrial center of Green Bay, and there are a number of suppliers of waste plastics and fibers within 5 km of the facility. Based upon a 50 km radius service area, there are more than 50 potential consumers consisting of a mix of cement manufacturers, power generation facilities, and paper mills. Waste disposal is served by the Brown County South Landfill which opened in 2022 with leachate collected for treatment in a wastewater treatment facility and is located approximately 40 km from the manufacturing facility.

2.4 Life cycle inventory

2.4.1 Manufacturing materials transport

The primary inputs for the torrefaction process are waste plastics and waste fibers as separate streams from local manufacturers within 5 km of the manufacturing facility. These waste materials and off-cuts are presumed to have no commercial value and would otherwise be disposed of in a sanctuary landfill. Previous studies have characterized the plastics as LDPE, LLDPE, HDPE, PP, and PET (Kolapkar et al. 2022), and an input mix of 9.86% LDPE, 25.17% LLDPE, 25.59% HDPE, 20.63% PP, and 18.75% PET is used based upon the national manufacturing mix (American Chemistry Council 2022; Electronic Supplementary information 1, Table S8). Waste fibers consist of paper, cardboard, and carton (Kolapkar et al. 2022), allowing containerboard to be used as a general proxy for the fibers. Waste plastics and fibers are delivered to the tipping floor via a municipal solid waste transfer trailer pulled by a short-haul tractor unit. The transfer trailer is presumed to have a capacity of about 76.45 m^3 (100 yd^3) and waste plastic and fibers are typically densified via fine-shredding, compaction, and/or baling prior to transportation. This allows for 20.18 t and 22.69 t of waste plastics and fibers, respectively, to be transported per load based upon typical densities of waste products (Environmental Protection Agency 1997).

2.4.2 Fuel pellet manufacturing

After the materials are delivered to the tipping floor, a total of four, wheeled loaders are used to introduce materials to the manufacturing infeed belt in a ratio of 60% waste fibers to 40% waste plastics (Kolapkar et al. 2022). The loaders consume approximately 4.69 L/h of diesel based upon the average of five loaders evaluated by Frey et al. (2010) for a total consumption of 157,584 L across four wheeled loaders with 8400 h of operation per year.

Upon system startup, natural gas is required to bring the system to operating temperatures (Table 1), after which waste heat from the torrefaction process is used to maintain the operating temperature. The torrefaction process results in a mass loss of the input materials with total carbon going from 48.0 to 42.1% (Klinger et al. 2015), with the 5.9% difference presumed to be emitted as carbon dioxide. Following torrefaction, the total carbon content of the fuel pellet increases to approximately 57% (Klinger et al. 2015; Xu et al. 2018). Ash produced during the torrefaction process, along with any other solid wastes, is disposed of in a sanctuary landfill approximately 40 km from the production facility via a trailer pulled by a short-haul tractor unit.

During torrefaction, the chlorine component of the waste plastics is released and requires scrubbing via DSI using calcium carbonate. While the chlorine percentage can range from 0 to 5% of the waste plastics by weight, 3% is the typical percentage. Sorbent usage was calculated based upon the quantity needed to neutralize the hydrochloric acid produced as part of the torrefaction process when calcium carbonate ($CaCO_3$) is used as the neutralizing compound via the reaction $CaCO_3 + HCl \rightarrow CaCl_2 + H_2O + CO_2$ (Electronic Supplementary information 1, Table S4). Following neutralization by calcium carbonate, calcium chloride ($CaCl_2$) is produced as a solid, with water vapor and carbon dioxide vented to the atmosphere. The process presumes a typical DSI efficiency of 99% for hydrochloric acid (Hemmer et al. 2002). The quantity of calcium chloride produced was determined based upon the mass balanced ratio of remaining solids to inputs (Electronic Supplementary information 1, Table S4).

2.4.3 Fuel pellet transport

Following manufacturing, torrefied plastic-fiber fuel pellets are stored in a silo until they are to be delivered to a consumer via a trailer pulled by a short-haul tractor unit. The trailer is presumed to have a capacity of 22.69 t and will be delivered within the 50 km service area of the production facility.

Table 1 Manufacturing inputs and outputs used in the analysis, see Electronic Supplementary information 1, Table S1 for full calculations

	Process	Item	
Input	*Wheeled Loaders, Four*	Diesel	157,584 L/yr
	Manufacturing	Mixed waste fibers	857,14.2 t/yr
		Mixed waste plastic	571,42.8 t/yr
		Calcium carbonate	4705.7 t/yr
		Mineral oil	860.2 L/yr
		Grid electricity	64.0 kWh/t
		Natural gas	0.6 MJ/t
Output	*Manufactured goods*	Torrefied plastic-fiber fuel pellets	100,000 t/yr
	Solid waste	Ash	7142.8 t/yr
		Contaminated mineral oil	860.2 L/yr
		Calcium chloride	5218.2 t/yr
	Emissions to atmosphere	Carbon dioxide	10,142.8 t/yr

2.4.4 Fuel pellet use

While fuel pellets can be co-fired with coal for higher efficiency than fuel pellets alone (Lako et al. 2015), we assume that pellets will be the only combustion source. Assuming the process and input mix outlined above torrefied fuel pellets have a calculated heat of 31.04 MJ/kg (Electronic Supplementary information 1, Table S3); however, manufactured fuel pellets from pilot studies have been shown to have a slightly higher heat of 31.4 MJ/kg when combusted (Gug et al. 2015; Xu et al. 2018; Kolapkar et al. 2022). Due to the low moisture content of the torrefied pellets (Kolapkar et al. 2022), the generating efficiency is presumed to be comparable to biomass power plants using paper as a feedstock and is set at a typical value of 32% (Lako et al. 2015), resulting in energy production of 2.76 kWh/kg. Mass balance calculations result in CO_2 emissions of 2.09 kg, or 0.84 kg if a renewable credit is applied due to the biogenic carbon origins of the waste fibers. Finally, previous studies have indicated only trace emissions of byproducts (e.g., particular matter, NO_x, SO_2, etc.) when considering the functional unit (Xu et al. 2018).

2.4.5 Status quo scenario

The status quo scenario is for 1 kWh of grid energy produced using coal or natural gas. However, in order to fully contextualize the results, the impact of disposing of waste fibers and plastics is also calculated. Presently, waste fibers and plastics disposed of in a sanitary landfill within 40 km of their production facility. Under this status quo scenario, 0.31 kg of waste fibers, and 0.21 kg of mixed waste plastic fibers are disposed of in the sanitary landfill. The weights of the waste fibers and waste plastics were calculated based upon the total waste material necessary to produce torrefied fuel pellets capable of producing 1 kWh of energy assuming 32% efficiency (Electronic Supplementary information 1, Table S1; Lako et al. 2015). The waste plastics compositions are the same as for fuel pellet production (see Sect. 2.4.1); however, upon delivery to the sanitary landfill the inorganic carbon contained in the waste plastics is presumed to be sequestered (Lee et al. 2017). As with waste plastics, waste fibers are the same composition as fuel pellet production and upon landfilling, emit 0.051 kg CH_4 and 0.365 kg CO_2 per 1 kg of waste fibers (Demetrious and Crossin 2019).

2.5 Impact assessment

Impact assessment is conducted using TRACI with the NETL mod to ensure compatibility with the Federal LCA Commons data architecture (Edelen et al. 2019). While the full scope of impact categories is considered as part of the assessment, emphasis is placed upon the global warming potential of the GHG emissions since these are the highest impact category for fossil fuels. In order to ensure that the full impact of the system is explored, the torrefied plastic-fiber fuel pellets are considered all across all four possible scenarios with regard to the burden of material inputs and renewable credit for biogenic carbon.

3 Results and discussion

Under the burden-free assumption for waste material inputs suggested by Olofsson and Börjesson (2018), torrefied plastic-fiber fuel pellets could serve as a direct replacement for coal as an energy source; with GHG emissions reduced by 28.10%, which improves to 67.97% when a credit is also applied for biogenic carbon sources (Table 2). When the burden associated with the manufacturing of waste inputs is included, coal has a lower environmental impact than torrefied fuel pellets. Likewise, torrefied fuel pellets only

Table 2 Comparison of the TRACI assessment of torrefied plastic-fiber fuel pellets vs. the status quo with a functional unit of 1 kWh of energy

		Status quo		**Torrefied plastic-fiber fuel pellets**			
TRACI 2.1 (NETL mod)		*Coal*	*Natural gas*	*Burden free, Renewable credit*	*Burden free*	*Full burden, Renewable credit*	*Full burden*
Acidification	kg SO2 eq	2.88E-03	7.91E-04	1.15E-04	1.15E-04	3.11E-03	3.11E-03
Eutrophication	kg N eq	9.15E-05	5.87E-05	5.61E-06	5.61E-06	2.55E-04	2.55E-04
Freshwater ecotoxicity	CTUeco	3.96E-01	1.91E-01	4.19E-01	4.19E-01	5.07E-01	5.07E-01
Global warming	kg CO_2 eq	1.14E+00	5.50E-01	3.65E-01	8.20E-01	1.41E+00	1.86E+00
Human health — cancer	CTUcancer	8.97E-10	6.60E-11	1.02E-09	1.02E-09	1.61E-09	1.61E-09
Human health — non-cancer	CTUnoncancer	1.54E-07	5.44E-09	1.64E-07	1.64E-07	2.15E-07	2.15E-07
Human health — particulate matter	PM 2.5 eq	5.74E-04	2.31E-05	8.19E-06	8.19E-06	2.11E-04	2.11E-04
Ozone depletion	kg CFC-11 eq	2.44E-08	4.70E-10	3.65E-10	3.65E-10	3.19E-08	3.19E-08
Smog formation	kg O3 eq	3.79E-02	2.64E-02	2.65E-03	2.65E-03	2.11E-01	2.11E-01

outperform natural gas when the waste plastic and waste fibers are considered to be burden free, and a credit for biogenic carbon is applied, at which point they the produce 33.61% lower GHG emissions than natural gas. When considering the sources of GHG emissions across the various scenarios (Fig. 3), the majority of the emissions are due to the combustion of the relevant fuel source, followed by the production of fibers when considering the full burden of inputs for torrefied plastic-fiber fuel pellets. Since combustion of the torrefied fuel pellets results in CO_2 emissions to the atmosphere, hotspot analysis using the 10% inclusion/exclusion threshold (Pelton and Smith 2015) is highly influenced by the selection of the attribution approach, although shorter transportation distances and the use of renewable energy sources for manufacturing would help to reduce GHG emissions.

To fully contextualize this full burden scenario, it is necessary to consider the secondary waste disposal services offered by the torrefied fuel pellets since the status quo scenario of energy production via fossil fuels suggests that the waste fibers and waste plastics would otherwise be disposed of in a sanitary landfill. When 0.518 kg of waste required to produce torrefied plastic-fiber fuel pellets capable of producing 1 kWh of energy is disposed of, a total of 1.729 kg CO_2 eq GHG emissions is produced (Electronic Supplementary information 1, Table S2).

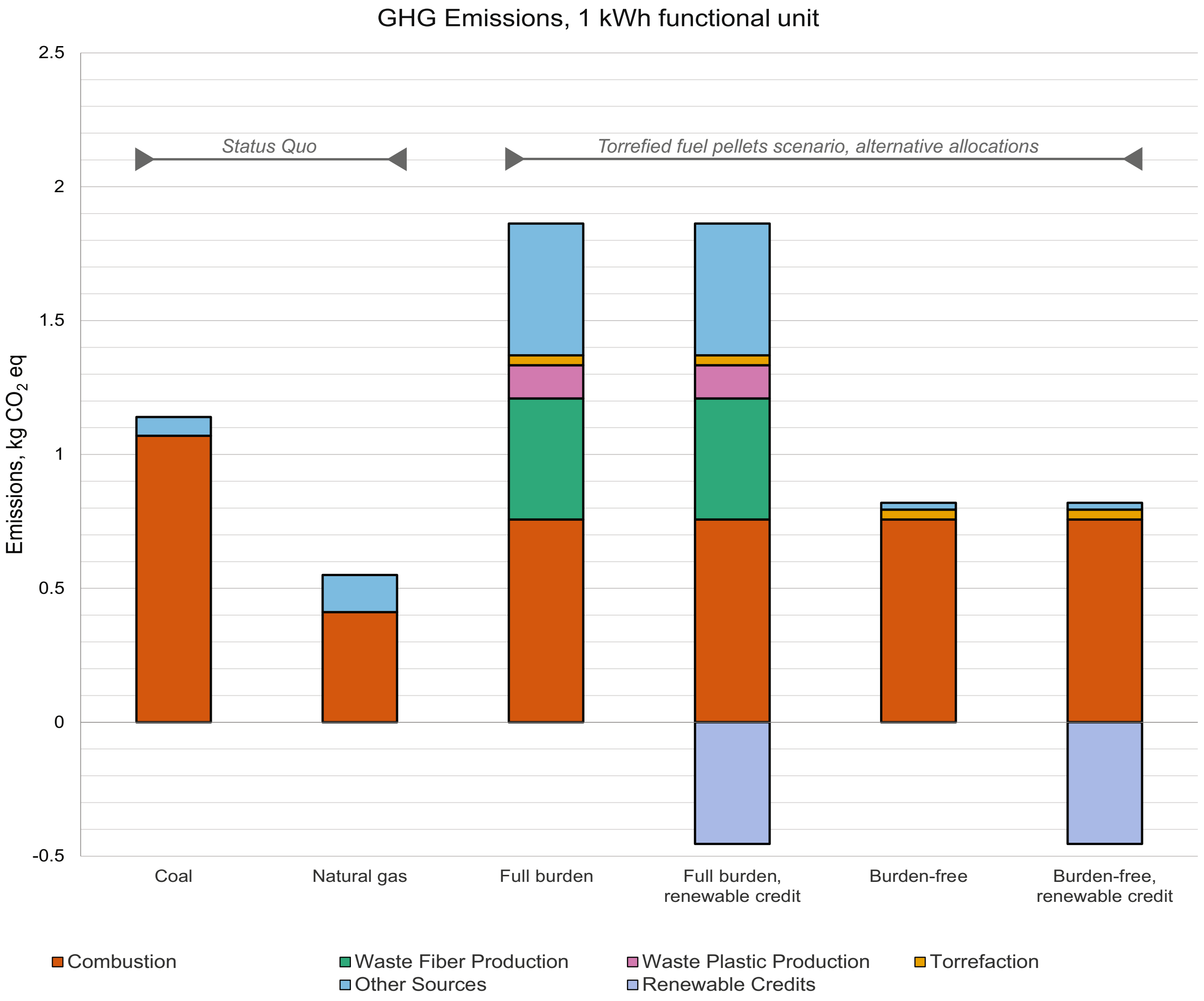

Fig. 3 Comparison of greenhouse gas (GHG) emissions for a 1 kWh functional unit when comparing energy production using torrefied plastic-fiber fuel pellets, versus the current status quo energy production fossil fuels and disposal of waste plastics and waste fibers (see Electronic Supplementary information 1, Table S2 for underlying values) The category "Other Sources" encompassing processes such as transportation of materials and the production of fossil fuel sources, while "full burden" presumes that the burden of waste materials is by the torrefied fuel pellets

Much of this is due to the disposal of the waste fibers, due to the breakdown of fibers producing GHG emissions upon landfilling (Demetrious and Crossin 2019), although the carbon contained in the waste plastics is sequestered (Lee et al. 2017). Thus, when accounting for avoided waste disposal, torrefied fuel pellets have a lower environmental burden than energy production from coal or natural gas.

3.1 Sensitivity analysis

Sensitivity analysis was performed by computing the theoretical heat when adjusting the ratio of waste fibers to waste plastics based upon the potential manufacturing ratios of 50–50, 60–40, 70–30, and 80–20 (fibers to plastic ratio). Adjusting the ratio of waste fibers to waste plastics impacts the calorific value of the manufactured fuel pellets with the overall heat content declining as the percentage of fiber increases. Likewise, during the torrefaction process, gasses are released that contain a small energy potential, or around 9% when 30% of the original mass is converted to gas (Xu et al. 2018; Kolapkar et al. 2022). As a result, there is a slight increase in total heat to 33.61 MJ/kg with a 50–50 ratio, this decreases to 28.48 and 25.92 with a 70–30 and 80–20 ratio, respectively (Electronic Supplementary information 1, Table S3).

As expected, increasing the percentage of fibers results in an increase in the total GHG emissions due to the reduction in the heat content of the pellets and in turn increases the fuel required to produce 1 kWh of energy (Table 3; Electronic Supplementary information 2). However, even under the full burden scenario with no renewable credit applied, the GHG emissions are still lower than under the status quo of disposal plus energy production using fossil fuels. Moreover, with a renewable credit applied and/or under the assumption that the waste fibers and waste plastics are burden-free, there is a dramatic reduction in GHG emissions.

4 Conclusions

While waste plastics landfilling may contribute to carbon capture (Lee et al. 2017), the extent of environmental degradation due to improperly managed plastic waste (MacLeod et al. 2021) suggests that the use of waste plastics as a torrefaction input may present a viable resource management scheme. Under such a scheme, the resulting fuel pellets may be capable of occupying an unusual place within the broader energy transition due to their lower GHG emissions when compared to fossil fuel sources. While the ultimate goal is the elimination of fossil fuels in favor of renewables (Solomon and Krishna 2011), the transition to fully renewables can be supported by less carbon intensive energy sources (e.g., replacement of coal with natural gas) (Wilson and Staffell 2018). However, this is predicated upon the fuel pellets acting displacing the use of fossil fuels as opposed to acting as a supplemental energy source on a one-to-one basis (Zink et al. 2016), a possible scenario that is typically not explored in LCAs of energy systems (Rajagopal and Plevin 2013; Yang 2016).

It is important to highlight the degree to which the results of this study vary based upon the selection of burden allocation, credit for biogenic carbon, and treatment of waste materials. When accounting for the full burden of waste material inputs under the 1 kWh functional unit, torrefied plastic-fiber fuel pellets have a greater environmental impact than energy production from coal or natural gas. However, when the environmental burden of disposing of the waste plastic and waste fiber inputs for the torrefied fuel pellets is added to energy production via coal or natural gas, the fossil fuel energy sources have a higher environmental impact. This offers support for the treatment of waste inputs as burden free as suggested by Olofsson and Börjesson (2018), although the calculation and inclusion of waste materials may offer greater transparency into a product's lifecycle.

Ultimately, this case study of torrefied plastic-fiber fuel pellets produced and consumed in Green Bay, Wisconsin suggests that they may be lower impact option when

Table 3 GHG emissions (kg CO_2 eq) during the production of 1 kWh of energy under various fiber percentages, with the percent change from the baseline 60–40 ratio of waste fiber to waste plastic inputs

Torrefied fuel pellets, Alternative allocations	**GHG emissions (kg CO_2 eq)**				**Percent change from baseline (60% fiber)**		
	Fiber percentage				*Fiber percentage*		
	50%	60%	70%	80%	50%	70%	80%
Full burden	1.73E+00	1.86E+00	2.02E+00	2.20E+00	−7.10%	8.34%	18.33%
Full burden, Renewable Credit	1.38E+00	1.41E+00	1.44E+00	1.48E+00	−1.95%	2.27%	4.98%
Burden free	7.60E-01	8.20E-01	8.90E-01	9.74E-01	−7.31%	8.59%	18.87%
Burden free, Renewable credit	4.10E-01	3.65E-01	3.12E-01	2.49E-01	12.27%	−14.52%	−31.91%

compared to the status quo with energy production from fossil fuels. Additionally, the torrefaction process suggests a practical use for waste plastics and waste fibers that would otherwise be disposed of in a sanitary landfill. While the results of this case study indicate that torrefied plastic-fiber fuel pellets represent a viable alternative to fossil fuels (see Fig. 3, Table 3), the sensitivity of the results to the assumptions made (i.e., full burden vs. burden free, renewable credit vs. none) serves as a reminder that proper attribution of the impacts associated with process inputs is an important aspect of the LCA methodology.

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Data availability Author calculations and life cycle inventory are included in the supplemental data. Third-party data sets used in calculations are available through the Federal LCA Commons with the values used listed as part of Electronic Supplementary information, Table S1. Outputs from openLCA calculations are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no conflict of interests.

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