

Article

Environmental and Economic Assessment of Portable Systems: Production of Wood-Briquettes and Torrefied-Briquettes to Generate Heat and Electricity

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Abstract: This study assessed the environmental impacts and economic feasibility of generating heat using wood-briquettes (WBs), and heat and electricity using torrefied-wood-briquettes (TWBs). WBs and TWBs were manufactured from forest residues using portable systems and delivered to either residential consumers or power plants in the United States. An integrated cradle-to-grave life-cycle assessment (LCA) and techno-economic analysis (TEA) approach was used to quantify environmental impacts and minimum-selling prices (MSPs) of heat and electricity, respectively. Results illustrated that 82% and 59% of the cradle-to-grave global warming (GW) impact of producing heat resulted from the feedstock preparation in WBs and torrefaction in TWBs, respectively. About 46–54% of total cost in the production of heat were from labor and capital costs only. The GW impact of electricity production with TWBs was dominated by the torrefaction process (48% contribution). Capital cost (50%) was a major contributor to the total cost of electricity production using TWBs. The GW impacts of producing heat were 7–37 gCO₂eq/MJ for WBs, and 14–51 gCO₂eq/MJ for TWBs, whereas producing electricity using TWBs was 146–443 gCO₂eq/kWhe. MSPs of generating heat from WBs and TWBs were €1.09–€1.73 and €1.60–€2.26/MJ, respectively, whereas the MSP of electricity from TWBs was €20–€25/kWhe. Considering carbon and pile-burn credits, MSPs of heat and electricity were reduced by 60–90% compared to the base-case.

Keywords: bioenergy; torrefaction; life-cycle assessment; techno-economic analysis; environmental impacts; minimum selling price; forest residues; near-woods; portable system



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1. Introduction

The Sixth Assessment Report of the IPCC (Intergovernmental Panel on Climate Change) emphasized the urgency to reduce greenhouse gasses to mitigate climate change [1]. Fossil-based energy production often ignores the externalities costs borne by society such as greenhouse gas (GHG) induced climate change, air quality problems or air pollution, issues around fossil fuel extraction, production, and consumption [2,3]. Energy production from relatively low-cost fossil fuel sources continues to drive GHG emissions globally despite the widespread availability of plant-based biomass in various forms [2–6]. It has become increasingly imperative, with a growing global population, that alternative clean and sustainable energy sources are needed to be able to address environmental issues including climate change. Sustainable energy production from renewable resources can help mitigate GHG emissions and provide a mechanism for using underutilized forest resources such as forest residues and pulpwood. Progress has been made, but more understanding is

needed by integrating economic and environmental perspectives. In 2019, 12% of the total global primary energy consumption was derived from biomass, the highest percentage of all renewable energy resources [2]. The United States (U.S.) supplied 4.57 exajoules, 4.73% of its total primary energy consumption from biomass [2,5–7]. However, from a sustainability perspective, additional work is required, including identifying other low-carbon fuel sources and evaluating their effectiveness as fossil fuel alternatives. One underutilized resource, in the form of plant biomass, is forest residues that are widely available in many U.S. regions, especially in the Pacific Northwest. Forest residues can be found in different physical forms such as uncomminuted (non-merchantable logs, tops, branches) and comminuted (chips and ground biomass) [8]. However, the scattered nature of forest residues after harvest can make it cost-prohibitive to collect and transport this material [8–11]. Conversely, plant biomass has been used for thousands of years as an energy source and remains in wide use for simple heating and cooking in remote and rural areas [12–14]. This resource has been gaining more consideration as a renewable energy source over the past couple of decades because of growing environmental concerns from burning fossil fuels and its associated climate change impact [15]. In 2019, coal contributed to 60% of the U.S. total CO₂ emissions associated with the electrical power sector—approximately 973 million tons [7]. Part of this percentage pertains to coal's lower electrical conversion efficiency compared with natural gas, coal's primary replacement in new or refurbished power plants. Identifying alternative energy sources to coal is a major priority for many countries to reduce their country-level carbon footprint. Given that coal plants are still common in the U.S., alternative drop-in fuels have been investigated, including torrefied biomaterial [16–18].

The U.S. continues to assess many typical energy sources through research endeavors such as the Waste-to-Wisdom project to provide for societal needs while meeting sustainability goals (WTW: www.wastetowisdom.com (accessed on 15 June 2021)) [19]. The WTW project was centered on the Pacific Northwest because of its productive forestland, ongoing loss of its historical wood industry, air quality issues from forest fires, and a societal need to address the over-abundance of forest residues, especially in the Wildland Urban Interface (WUI) [19]. This research project was one of several projects that the U.S. Department of Agriculture (USDA) and the U.S. Department of Energy (DOE) funded to increase biomass use as an energy source [19]. This WTW study investigated woody biomass logistics, the processing of forest residues from near-woods or forests, distribution, and end-use. The investigation concentrated on various biomass processing systems of post-harvest forest residues as close as possible to the timber harvest operations, hence the term near-woods. In the West, wildfire suppression and timber harvesting have resulted in huge volumes of wood accumulation in the forest [20]. According to the 2016-billion-ton report reference scenario (that assumes low growth in biomass for energy and moderate growth in housing starts), about 84.5 million dry metric tons of forest residues (including biomass from clear-cutting harvesting and thinning operations) will be available in 2022 [21]. The WTW project identified a few logistics options, technologies, and processes that utilize these residues for high-value wood-based products that could help offset the forest restoration and fuel reduction treatments costs, while providing rural jobs [9,22,23].

Major biomass densification technologies include briquetting [24] and pelletization [25]. Densification technologies are used to overcome challenges from the high cost of utilizing forest residues, including excess hazardous fuel accumulation in forest lands, and offer an alternative to sustainably utilize this abundant resource as a solid bioenergy product. Densification improves feedstock quality by increasing the biomass volume density and energy density, allowing for easier and more efficient transportation and storage [8,26,27]. In addition, densification increases fuel shelf life and quality, where lower moisture prevents biomass degradation. Furthermore, increased density results in a longer and more efficient burn, and better combustion compared with wood logs [4,16,28,29]. Briquettes made from biomass can be used as fuel for wood furnaces and stoves and hot water boilers, substituting for conventional fuels (e.g., propane, cordwood, or heating oil) [24,30].

Many studies have assessed the technological performance, densification mechanisms, and end-product quality of this densified product [25,31,32]. Briquetting operations require less power or energy and are more flexible in terms of quality of input feedstock (size and moisture content) and can handle bark [24,33], which makes it an appropriate technology for handling forest residues, a less homogenous feedstock than sawdust (or grinding of biomass), primarily used in pellets. Thermal pretreatment such as torrefaction has been used to increase the energy content of the biomass. For example, pelletization and torrefaction can increase the energy density by 3–4 and 6–8 times compared to that of wood and sawdust ($2\text{--}3\text{ GJ/m}^3$) [34]. Further, torrefaction improves the storage and stability characteristics of biomass due to hydrophobicity, stability against microbial degradation, and chemical oxidation. A suite of literature [25,35,36] has provided the detailed benefits of densification and torrefaction compared to raw biomass, including traditional wood fuel. In addition to the improvement of quality and consistency of wood fuel, densification and torrefaction can also make the biomass fuel supply chain robust and resilient [8,37].

This work focuses on the novel biomass feedstock production and conversion logistics suggested to overcome the utilization barriers to forest residues [19]. These include processing and sorting forest residues (small-diameter trees and treetops) to increase biomass feedstock quality and yield. Portable technologies that can operate close to the biomass source and be transported to other nearby harvest sites were analyzed. This is the first integrated cradle-to-grave life-cycle assessment (LCA) and techno-economic analysis (TEA) study conducted to evaluate the environmental viability and economic feasibility of producing wood briquettes (WBs) and torrefied wood briquettes (TWBs) as end (final) products from forest residues in the western United States using integrated near-woods semi-mobile or portable technology. The environmental impacts were estimated using a cradle-to-grave LCA approach [38,39]. A discounted cash flow rate of return (DCFROR) model was used to estimate the economic feasibility and the financial performance of producing heat using WBs or TWBs, and electricity using TWBs [40]. The supply chain system was harmonized to match the LCA and financial assessments to cover logistics of forest residues, comminution (i.e., chipping), product manufacturing (i.e., densification), handling and delivery to customers, and product combustion to produce heat and/or electricity. A comprehensive uncertainty analysis was performed using the Monte Carlo simulation method to understand the influence of uncertainties in input data on the results. Further, a sensitivity analysis was carried out to quantify the impact of the most critical input parameters affecting environmental impacts and financial feasibility.

2. Materials and Methods

This research aimed to evaluate the environmental sustainability and economic feasibility of utilizing forest residues generated from commercial timber harvesting operations in the Pacific Northwest (PNW), United States (U.S.). Conversion of field-dried forest residues to WBs and TWBs using semi-mobile (portable) biomass densification technologies that can operate in remote forest areas and close to timber harvest sites were evaluated. The life cycle stages covered biomass feedstock procurement and transportation, solid biofuels manufacturing, transportation to the user, and the use (combustion) phase. Solid biofuels manufacturing operations consisted of feedstock preparation (chipping, screening, and drying) and biomass conversion (densification and/or torrefaction) processes. The techno-economic analysis (TEA) covered all costs incurred from feedstock preparation, logistics, biomass conversion into final products (WBs and TWBs), product transportation, and the use of heat or power generation from combusting the final products. Two alternative end-use options were investigated. These were (a) generating thermal energy from a domestic wood stove using WBs and TWBs for heating, and (b) generating electricity from a biomass-fired power plant using TWBs.

To have a benchmark “like for like” analysis, functional units were identified to have a consistent unit to calculate the cost and environmental impacts of the same operations: 1 MJ of useful heat produced at a wood stove and 1 kWh of electricity (kWh_e) generated

at a power plant. The primary data used in the LCA and TEA analyses came from the experimental studies performed in the U.S. Department of Energy-funded Biomass Research and Development Initiative research project: Waste-to-Wisdom (WTW) [19,41]. Secondary data such as the electricity supply, and materials and fuel inputs, transport, and waste disposal came from the DATASmart (US EI 2.2) database [42] and peer-reviewed literature.

2.1. System Boundary and Description

The biomass supply chain for the production of WBs and TWBs from forest residues is presented in Figure 1. The system boundary covering the whole life cycle was used in the analysis. In the base case, which is the near-forest (woods) operation scenario, the sorted and processed field-dried forest residues were transported to a nearby remote conversion site.

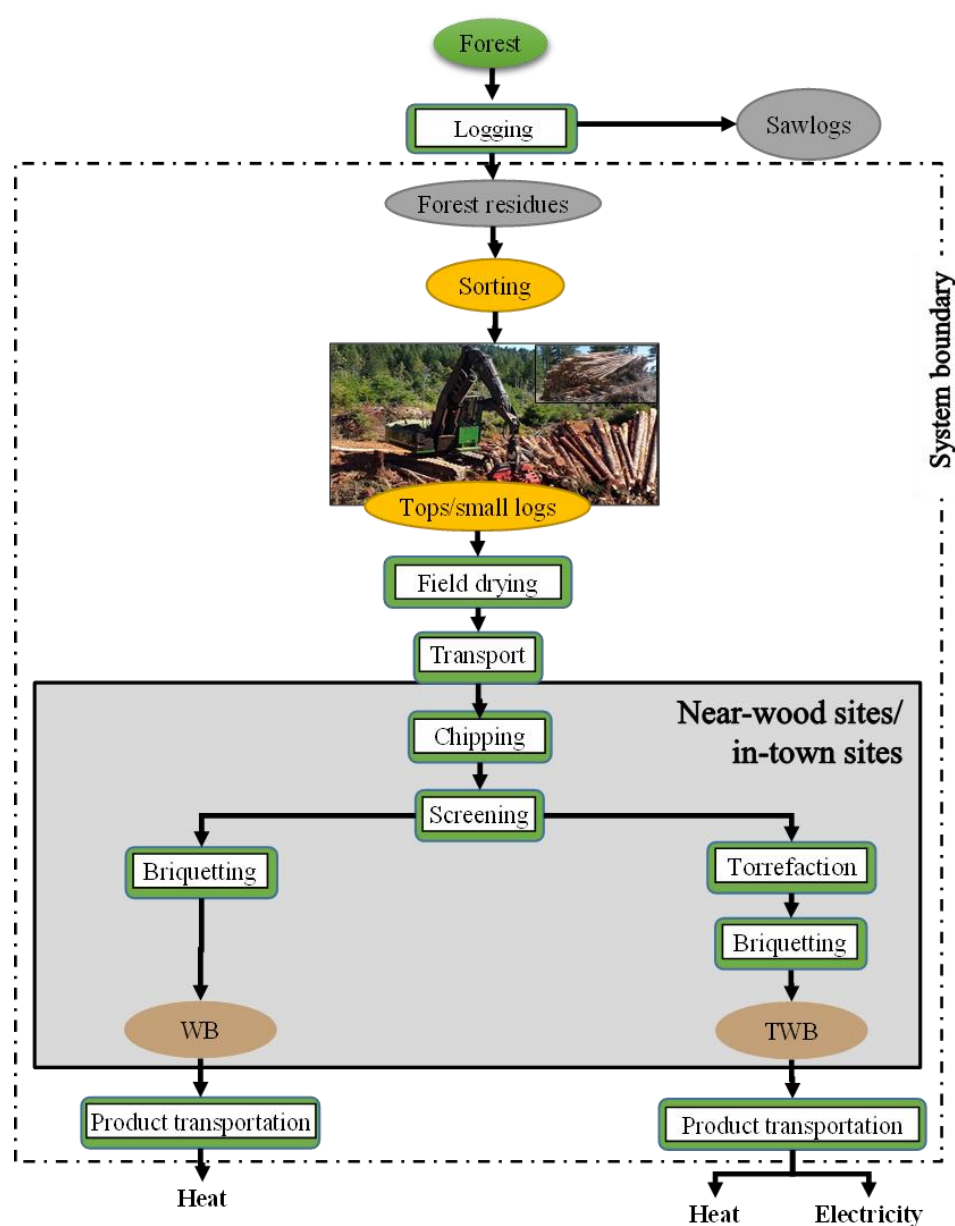


Figure 1. The system boundary of wood briquette (WB) and torrefied wood briquette (TWB) supply chains.

The feedstock preparation and woody biomass conversion were performed at the same site. The analyses looked at WB and TWB production in different locations: (a) near-forest site with a maximum of one-hour travel time for feedstock transportation from source to biomass conversion site, and (b) in-town operation with a maximum two to four-hour travel time for feedstock transportation from source to the biomass conversion site. Feedstock qualities (moisture and ash content and chipped or ground forest residues), and different power sources (wood gasifier-based generator, diesel generator, and grid), and biomass processing locations (in-town locations (used available grids) and near-forest locations (used a diesel or wood gasifier-based generator)). The torrefaction and briquetting systems were tested extensively by the Schatz Energy Research Center until high product quality was achieved. Performance data for biomass logistics and processing were collected and analyzed [43,44].

2.1.1. Biomass Feedstock Supply Chain

The logging residues, treetops, and pulp logs left at the site after commercial harvesting operations were sorted, collected, and delimbed at forest landing to minimize contamination and enhance biomass feedstock quality [45]. Biomass feedstock was hauled to a nearby manufacturing site, about 18 km away, using a mule-train (a truck with trailer of 25.9 tons maximum capacity) [46]. Forest logistics were modeled on timber harvest activities and biomass available in the western U.S. Forest residues were left in the forest to air-dry (for a few months after harvest, and the final moisture content (MC) (wet basis) reached around $20 \pm 3\%$) before collection [47]. Forest residues logistics LCA data and techno-economic analysis were based on the studies performed by Oneil et al. [46], Alanya-Rosenbaum and Bergman [48,49], and Sahoo et al. [40].

2.1.2. Product Manufacturing at Near-Woods Site

Sorted and processed forest residues were further processed at a nearby forest site to achieve the input criteria of the integrated biomass conversion technology used and produce high-quality solid biofuel. Feedstock preparation for the portable processing systems included chipping, screening, and drying. Woodchips were dried to about 6% MC for WBs and 9% MC for TWBs using a belt dryer. The feedstock used was a mix of common hardwood and softwood species sourced from logging operations in the western U.S. with an average higher heating value (HHV) of about 19 MJ/kg on a dry basis (db). In this study, a portable woody biomass gasifier with an engine generator was used to meet the electricity demand of the equipment used at the near-forest production site [50]. The dryer process heat requirement was assumed to be 5 MJ/kg water removed [51].

Figure 2 presents the flow diagram of the WB production system. The feedstock used in briquettes testing was a mix of coast redwood (*Sequoia sempervirens*), Douglas fir (*Pseudotsuga menziesii*), tanoak (*Lithocarpus densiflorus*), and mixed conifer species. Wood chips were densified into briquettes using RUF200 model briquetter [52]. The briquettes used a hydraulic system to drive the densification process. The RUF 200 had a mass throughput of 218 kg/h [49]. The dryer unit used at the WB supply chain was a propane-fueled belt dryer. Briquetting was performed without a binder [44,49].

Torrefaction test data came from a portable electrically-heated screw-type torrefaction unit with about a 600 kg/h torrefied chips output capacity [41,44]. Feedstocks were sourced from forest residues generated from logging operations of tanoak (*Notholithocarpus densiflorus*) used in pulp and paper production. Among various operating conditions tested, the optimized operating conditions for the torrefaction unit were defined as feedstock material with an MC lower than 11% (wet basis), a short residence time (10 min), and the reactor setpoint temperature between 400 °C and 425 °C [41,44].

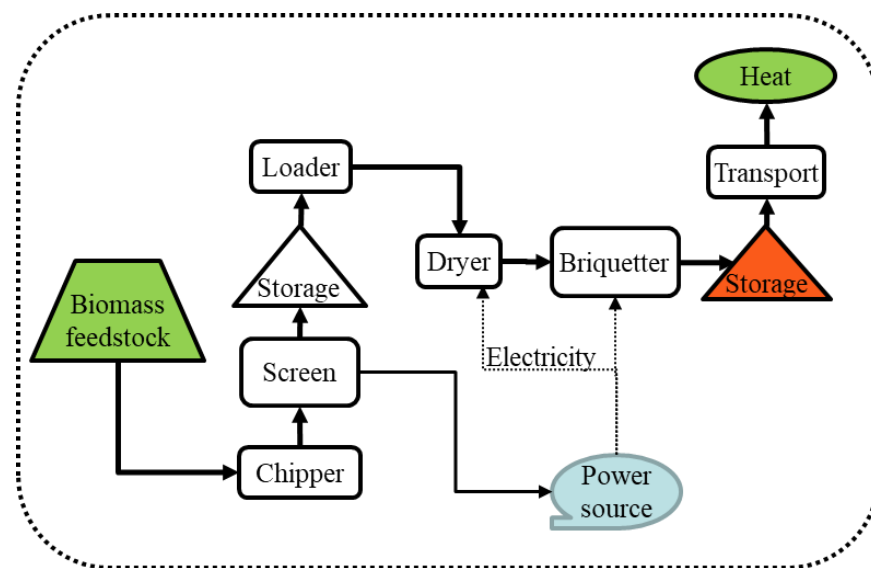


Figure 2. Forest landing to product 1—Process flow diagram of manufacturing of WBs at the near-wood site and delivered to customers in the city for heat generation.

For TWB manufacturing, torrefaction gas (torgas) was used to supplement heat to the dryer. Because of its low heat content, torgas was augmented with propane to initiate and maintain optimum combustion (Figure 3). The torrefaction unit had additional units such as condensation and filtration to remove contaminants from the torgas generated. Condensate (bio-oil) and tar generated at the torrefaction process were disposed to the municipal sewage system. Bio-oil was neutralized using NaOH before disposal. The torrefied wood chips generated were compressed into briquettes after the torrefaction process [44,48].

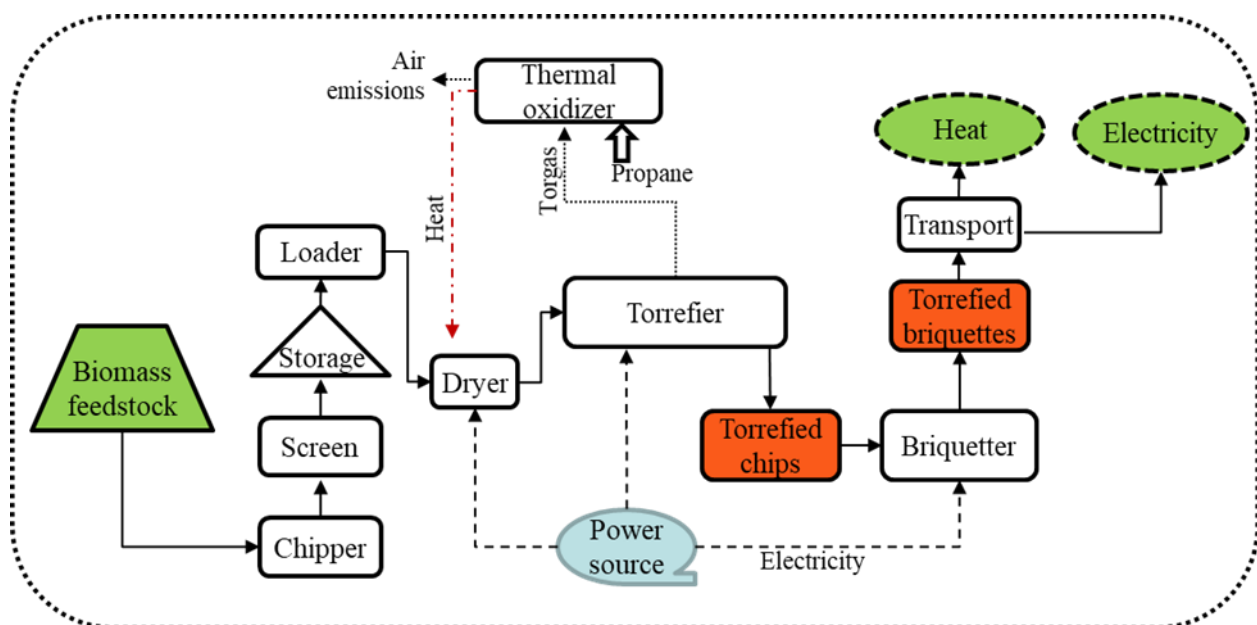


Figure 3. Forest landing to product 2—Process flow diagram of torrefied wood briquette (TWBs): manufacturing of TWBs at the near-woods site and delivery to the customers in the city for heat and electricity generation.

The properties of the solid biofuels manufactured from processed forest residues are presented in Table 1. The produced briquettes were about 63 mm × 150 mm × 109 mm (W × L × H) (adopted from [48,49,53,54]).

Table 1. Properties of wood briquette (WB) and torrefied wood briquette (TWB) products.

	Wood Briquette (WB)	Torrefied Wood Briquette (TWB)
Packing density, kg/m ³	861.67	1005
Moisture content (wet basis), %	6.13	0.6
Energy density (HHV) ^a , MJ/kg, db ^b	17.78	23.0
Ash content (%), db	-	2.5
Volatile matter (%), db	81	71
Durability (%) DU	96	93

^a Higher heating value. ^b Dry basis.

2.1.3. Scenario Analysis

Alternative scenarios (Table 2) for the production of WBs and TWBs were evaluated to identify the most viable process configuration. For this, the environmental impact of using an on-site diesel generator to operate portable systems was investigated as an alternative to the woody biomass gasifier. Another consideration was given to the operation's location. An in-town operation with access to grid electricity instead of a near-woods operation was investigated, where forest residues are transported to town to be processed. For these scenarios, two different transport distances, 2 h and 4 h, were considered based on the logistics analysis and harvest sites located in the region [46]. Other cases investigated were the use of feedstock with higher MC and accounting for the potential environmental benefits of the avoided pile and burn operations.

Table 2. Description of the scenarios evaluated.

Scenarios	Description	
	Manufacturing of WBs and TWBs	End Use ^a
Case 1 (Base case)	near-woods operation with woody biomass gasifier power (gasifier was used to power the equipment)	Heat/ electricity
Case 2	near-woods operation with diesel power (diesel generator was used to power the equipment)	Heat/ electricity
Case 3	in-town operation (2 h travel distance) with grid power (residues were hauled to 2 h travel distance, and grid electricity was used to power the equipment)	Heat
Case 4	in-town operation (4 h travel distance) with grid power (residues were hauled to 4 h travel distance, and grid electricity was used to power the equipment)	Heat
Case 5	50% MC feedstock, near-woods operation with wood gasifier power (input residue MC was 50% instead of air-dried residue)	Heat/ electricity
Case 6	near-woods operation with wood gasifier power with pile and burn credit	Heat/ electricity

^a WBs were used to generate heat only. However, TWBs were used to generate both heat and electricity.

2.2. LCA Method

This LCA study was completed following the ISO 14040/14044 standards [38,39]. SimaPro version 9 LCA software was used for modeling and impact assessment [55]. The LCA analysis identified the cradle to grave environmental impacts associated with the production of WBs and TWBs. Two functional units used were one MJ of heat generated at a wood stove and one kWh of electricity generated at a power plant. Table 3 summarizes the process data and assumptions used in modeling the WB and TWB supply chains.

Table 3. Data summary for modeling the wood briquette (WB) and torrefied wood briquette (TWB) supply chains.

	Parameter	Unit	Value	Reference
Feedstock procurement	Moisture content (wb) ¹ of air-dried forest residues	%	20	[46]
	Diesel for sorting, processing, loading	L/bdt ²	2.109	
	Lubricant for sorting, processing, loading	L/bdt	0.038	
	Hauling distance	km/bdt	18	
Chipping	Diesel use	L/bdt	0.5461	[46]
	Lubricant use	L/bdt	0.0098	
Screening	Diesel use	L/bdt	1.5939	
	Lubricant use	L/bdt	0.0287	
Drying	Heat required	MJ/kg water	5	[51,53]
	Electricity	kWh/bdt	7.14	
Briquetting	Electricity	kWh/bdt	33.79	Operational data
Torrefaction and briquetting	Mass yield	%	69	[44,53]
	Energy yield	%	81	
	Lubricants	mL/MJ TWB	0.002	
	Electricity	kWh/MJ TWB	0.023	
	NaOH	gr/MJ TWB	0.667	
	Bio-oil	L/MJ TWB	0.011	
	Torgas	m ³ /MJ TWB	0.043	
Packaging	Low-density polyethylene	kg/kg packed product	0.7	[53]
Grinding	Electricity, WB	Wh/kg (wb)	323	[44]
	Electricity, TWB	Wh/kg (wb)	123	

¹ wet basis. ² bdt: bone-dry ton.

Torgas captured was used in the TWB manufacturing system dryer. Torgas combustion required about 0.026 L of propane per liter of torgas combusted. The use phase was modeled using literature data and tests performed as a part of the WTW project and presented in Alanya-Rosenbaum and Bergman [53]. Energy allocation was used for the torrefaction process to allocate the burden between the torgas and torrefied chips. The biogenic carbon content of the wood was taken into consideration while accounting for the carbon emissions from the wood fuel combustion. The CO₂ emitted was assumed to be biogenic by considering that the biogenic carbon entering the product system is removed from the natural environment. The volatile organic compound (VOC) emissions from wood during the field-drying and at the drying process were accounted for in this study. About 80% of the VOC emitted was assumed to occur during the air-drying. The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) v2.1 was used in this study [56]. TRACI is a mid-point level impact assessment model developed by the U.S. Environmental Protection Agency and is specifically representative of U.S. conditions.

2.3. TEA Method

A discounted cash-flow rate of return (DCFROR) model was used to perform the techno-economic analysis of producing heat using WBs or TWBs, and electricity using TWBs [11,40,57,58]. The minimum selling price (MSP) of heat included the costs of forest residues harvesting and their logistics, manufacturing WBs or TWBs, and transportation of

WBs or TWBs from production site to end consumer where WBs or TWBs were burned in a furnace to produce heat. Similarly, the MSP of electricity production by a power plant using TWBs included the cost of forest residues harvesting and their logistics, TWB production, transportation of TWBs from production site to power plant, and the burning of TWBs to produce electricity. The project assumed an inflation rate of 2% for both costs and revenue, an income tax rate of 40%, and a declining depreciation rate of 200% on the asset's value [11,40,58].

Detailed descriptions of capital and operating costs (Table 4) for WB and TWB systems are mentioned in Sahoo et al. [40] and in the supporting document (Table S3). The capital and operating costs of the biomass power plant were mentioned in the technical report [59]. Capital and operational costs were normalized to 2019 U.S. dollars using the Chemical Engineering Plant Cost Index (CEPCI).

Table 4. Capital and operating costs in WB, TWB, and electricity production systems.

	WB System ¹	TWB System ¹	Power Plant (PP) ²
Plant capacity (ODMT/year)	2657	2035	-
Plant capacity (MW)	-	-	10
Capital cost (\$)	315,000–390,000	810,000–960,000	42,645,000
Feedstock cost (\$/ODMT)	14.5–34.3	26.4–50.2	242.0
Operational cost (\$/year)	208,963–397,582	261,358–474,943	2,670,941
Product transport (\$/DOMT)	0–15.2	0–14.21	-
Project life (years)	10.0	10.0	20.0
Discount rate (nominal, before finance and tax)	16.5%	16.5%	12.0%
Debt-to-equity ratio	60/40	60/40	80/20

¹ The annual production capacities of WB and TWB systems were about 3000 and 4000 oven-dry tons [40]. The capital costs, operational costs, feedstocks costs, and product transport costs are provided in the supporting document (Table S3). ² Power plant electrical capacity was assumed to be 10 MW_e, and the total biomass input was estimated to be 34,235 dry tons/year considering the power plant ran 365 days and 24 h per day, and 85% of plant utilization. The electrical efficiency (net electrical energy generated divided by the total energy released by the fuel consumed) was assumed to be 34.1% [60,61].

2.4. Uncertainty Analysis

Monte Carlo simulation was performed to estimate the impact of input data uncertainty on the LCIA and TEA results. LCA and TEA models were run for 10,000 iterations to generate the results and perform statistical analysis including estimating the 95% confidence interval. For LCA, standard deviation from primary data was used where available; otherwise, the pedigree matrix algorithm available in SimaPro software was used. For TEA, the Monte Carlo simulation was conducted in Excel using Palisade's @Risk 8 add-in software. The TEA model for the base case scenario was simulated using 10,000 simulations to produce the probability distribution of MSPs. The distributions of major inputs data are mentioned in the supporting document (Table S4).

3. Results

This study quantified several environmental impacts including GW impacts. However, the results section presents only the cradle-to-grave GW impacts. The supporting document shows the estimated values of eleven environmental impacts (Tables S4–S6) of generating heat and electricity from forest residues.

3.1. Life Cycle Environmental and Economic Impacts

This section presents the environmental and techno-economic analysis results for the base case scenario investigated, namely 1 MJ useful heat generated at a wood stove using WBs (WB_{heat}) and TWBs (TWB_{heat}), and 1 kWh generated from TWBs at a powerplant ($TWB_{electricity}$). Figure 4 shows the contribution of different life-cycle stages to the total GW impact and costs per 1 MJ useful heat generated at a wood stove using WBs (Figure 4a,b) and TWBs (Figure 4c,d) for the base case (Case 1). The total GW impact per 1 MJ useful heat generated at a wood stove using WBs and TWBs was about 9 and 16 g CO₂eq, respectively.

Feedstock preparation was responsible most of the GW impact for the WB_{heat} supply chain at 82% contribution. Conversely, the briquetting stage at 1% had a minor contribution to the resulting GW impact. The total cost (annual capital and operating costs) per 1 MJ of the useful heat using WBs and TWBs were about 1.09€ and 1.60€, respectively. For the WB_{heat} supply chain, the operating costs were dominated by the labor cost, about a 26% contribution, followed by feedstock production and handling costs (18%). The contribution of the capital cost was also notable, at about 18%. For the TWB_{heat} supply chain, the torrefaction process contributed most of the GW impact at 59% followed by feedstock preparation at 30%. The drying process was the major contributor to GW impact at the feedstock preparation stage. The rest of the stages had a relatively small contribution to the overall GW impact for both supply chains.

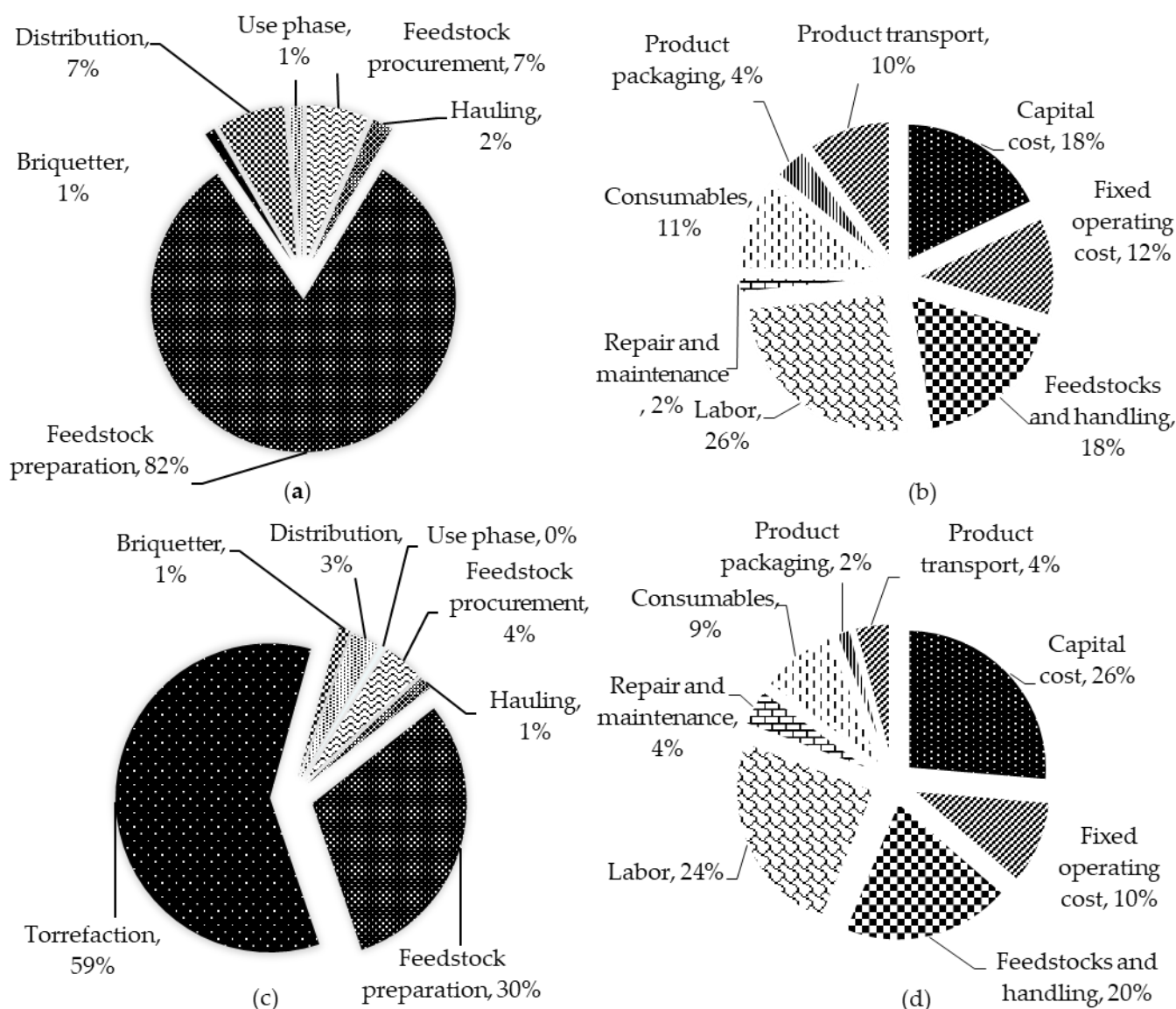


Figure 4. Contribution of various unit processes or inputs to the (a) overall global warming impact, and (b) cost of 1 MJ of useful heat produced from wood briquette; (c) overall global warming impact, and (d) cost of 1 MJ of useful heat produced from torrefied wood briquette.

Contribution analysis showed similar results for the TWB supply chain, where most of the total cost, €0.81 per MJ heat generated, was due to capital assets and labor. Capital cost constituted the major portion of the total cost with a 24% contribution. The contribution analysis showed the highest contributions were associated with the torrefaction process

(Figure 5a). Among the stages covered, torrefaction constituted the maximum portion (48%) of the total GW impact of 167.8 gCO₂eq, followed by feedstock preparation (24%).

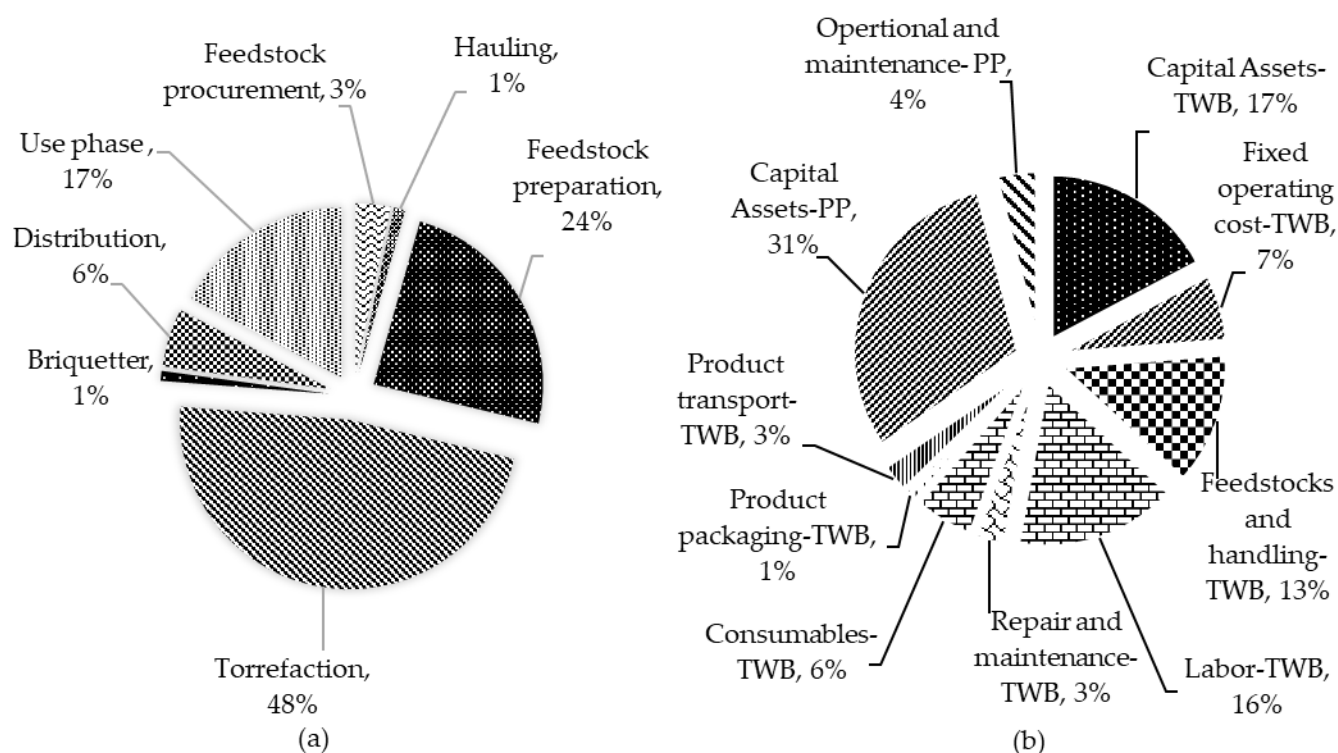


Figure 5. Contribution of processes or inputs to the (a) overall global warming potential, and (b) cost of 1 kWh generated from torrefied wood briquettes (TWBs) in the power plant (PP).

The use phase also had a notable contribution, about 17%, due to the feedstock grinding (pulverizing) into a fine powder that occurs at a power plant. The total annual cost of producing 1 kWh from TWBs was about €19.66. The contribution analysis revealed that only 16% of the total cost resulted from feedstocks, i.e., both forest residues and TWB logistics. Capital costs (for TWB processing system (17%) and power plant (31%)) constituted about 48% of the total cost of electricity production.

3.2. LCA and TEA Analysis of Different Scenarios

The results of the cradle-to-grave life cycle analysis of the alternative system configurations for three base cases are presented in Table 5. Among the heat generation from WB cases, high moisture content (Case 5) had the highest GW impact at 36.8 gCO₂eq. The contribution of the feedstock preparation stage in Case 5 was about 95% resulting from the higher fuel requirement for drying, whereas Case 2, at 50.8 gCO₂eq, was the worst scenario for the TWB_{heat} system. The torrefaction process runs on electricity, therefore the use of diesel power in Case 2 increased the GW impact contribution of the torrefaction process from 59% to 72%. Similarly, the use of diesel power in Case 2 was observed to be the least favorable among the scenarios investigated for the $TWB_{electricity}$ case. The avoided pile and burn credits resulted in about 25%, 16%, and 13% decline in the resulting GW impact of WB_{heat} , TWB_{heat} , and $TWB_{electricity}$ supply chains.

Table 5. Comparison of processes' contributions to overall global warming impact per 1 MJ of useful heat produced for residential consumers and per 1 kWhe generated at a power plant *.

1 MJ Heat from Wood Briquette (WB_{heat})									
	Feedstock Procurement	Hauling	Feedstock Preparation	Briquetter	Distribution	Use Phase	Pile and Burn	Total (g CO ₂ eq/MJ)	
Case 1	7%	2%	82%	1%	7%	1%	-	9.3	
Case 2	5%	2%	65%	23%	5%	1%	-	12.6	
Case 3	6%	9%	71%	12%	1%	1%	-	11.0	
Case 4	5%	18%	64%	11%	1%	1%	-	12.3	
Case 5	2%	1%	95%	0%	2%	0%	-	36.8	
Case 6	7%	2%	82%	1%	7%	1%	−25%	7.0	
1 MJ Heat from Torrefied Wood Briquette (TWB_{heat})									
	Feedstock Procurement	Hauling	Feedstock Preparation	Torrefaction	Briquetter	Distribution	Use Phase	Pile and Burn	Total (g CO ₂ eq/MJ)
Case 1	4%	1%	30%	59%	1%	3%	0%	-	16.5
Case 2	1%	0%	14%	72%	11%	1%	0%	-	50.8
Case 3	2%	3%	20%	66%	8%	0%	0%	-	31.5
Case 4	2%	8%	19%	64%	7%	0%	0%	-	32.9
Case 5	2%	1%	55%	34%	7%	1%	0%	-	37.1
Case 6	4%	1%	30%	59%	1%	3%	0%	−16%	13.9
1 kWhe from TWB ($TWB_{electricity}$)									
	Feedstock Procurement	Hauling	Feedstock Preparation	Torrefaction	Briquetter	Distribution	Use Phase	Pile and Burn	Total (g CO ₂ eq/kWh)
Case 1	3%	1%	24%	48%	1%	6%	17%	-	166.8
Case 2	1%	0%	13%	66%	10%	2%	7%	-	443.0
Case 5	2%	1%	50%	30%	6%	3%	9%	-	332.7
Case 6	4%	1%	28%	54%	1%	6%	20%	−13%	145.7

* Case 1: near-woods operation with wood biomass gasifier power; Case 2: near-woods operation with diesel power; Case 3: in-town operation (2 h travel distance) with grid power; Case 4: in-town operation (4 h travel distance) with grid power; Case 5: 50% MC feedstock, near-woods operation with wood gasifier power; Case 6: near-woods operation with wood gasifier power with pile and burn credit.

Figure 6 shows the MSPs of 1 MJ of useful heat generated using WBs in various scenarios considered in this study. Without considering incentives, MSPs varied between €1.0 and €1.7. The MSP of WB_{heat} was lowest in Case 1, in which WBs were manufactured at near-forest sites using gasifier-based generators and then transported to in-town customers. In-town manufacturing of WB scenarios to generate heat had uniformly higher MSPs irrespective of the power sources. Due to the heat requirement to dry feedstocks, the higher the moisture content of feedstock, the larger was the MSP of WB_{heat} . The results illustrated that longer forest residue transport distances, high-moisture content feedstocks, and the use of a diesel genset adversely affected the MSP of WB_{heat} . When considering financial incentives such as a pile burn credit (\$17/ODMT) and carbon credits (\$131.16/ton CO₂e), the MSP of WB_{heat} was negative, i.e., the economic benefits outweighed the total cost [40].

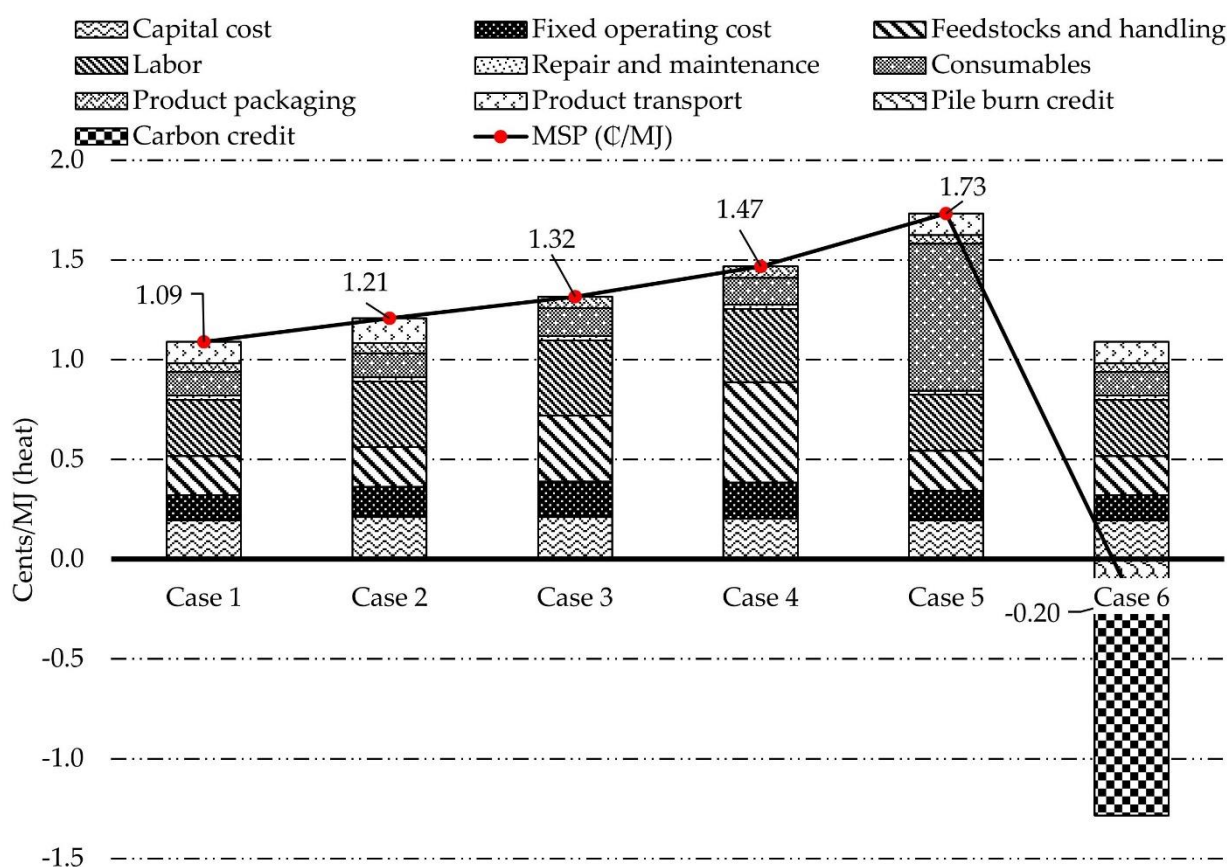


Figure 6. Comparison of minimum selling price (MSP) per 1 MJ of heat generated using wood briquettes and contributions of various cost inputs to MSP in six cases. Case 1: near-woods operation with wood biomass gasifier power; Case 2: near-woods operation with diesel power; Case 3: in-town operation (2 h travel distance) with grid power; Case 4: in-town operation (4 h travel distance) with grid power; Case 5: 50% moisture content feedstock, near-woods operation with wood gasifier power; Case 6: near-woods operation with wood gasifier power with pile and burn credit.

Figure 7 shows the TWB_{heat} 's MSP and contribution of cost components for six scenarios. The MSPs of TWB_{heat} varied between €1.6 and 2.3/MJ without considering credits such as pile burn and carbon credits. There was a large increase in the MSP of TWB_{heat} in Case 2 due to an increase in the use of diesel in the diesel generator to power the TWB portable system. In contrast to the WB system, higher moisture content of feedstocks did not have much impact on the MSP of TWB_{heat} due to the use of torgas (as a by-product of the torrefaction process) as a source of heat to dry feedstocks. In-town production of TWBs had both higher consumable cost (especially electricity compared to near-forest operations with a gasifier-based generator) and feedstock transport cost. Like the WB_{heat}

system, the MSP of TWB_{heat} was reduced substantially (~90%) when considering pile burn and carbon credits.

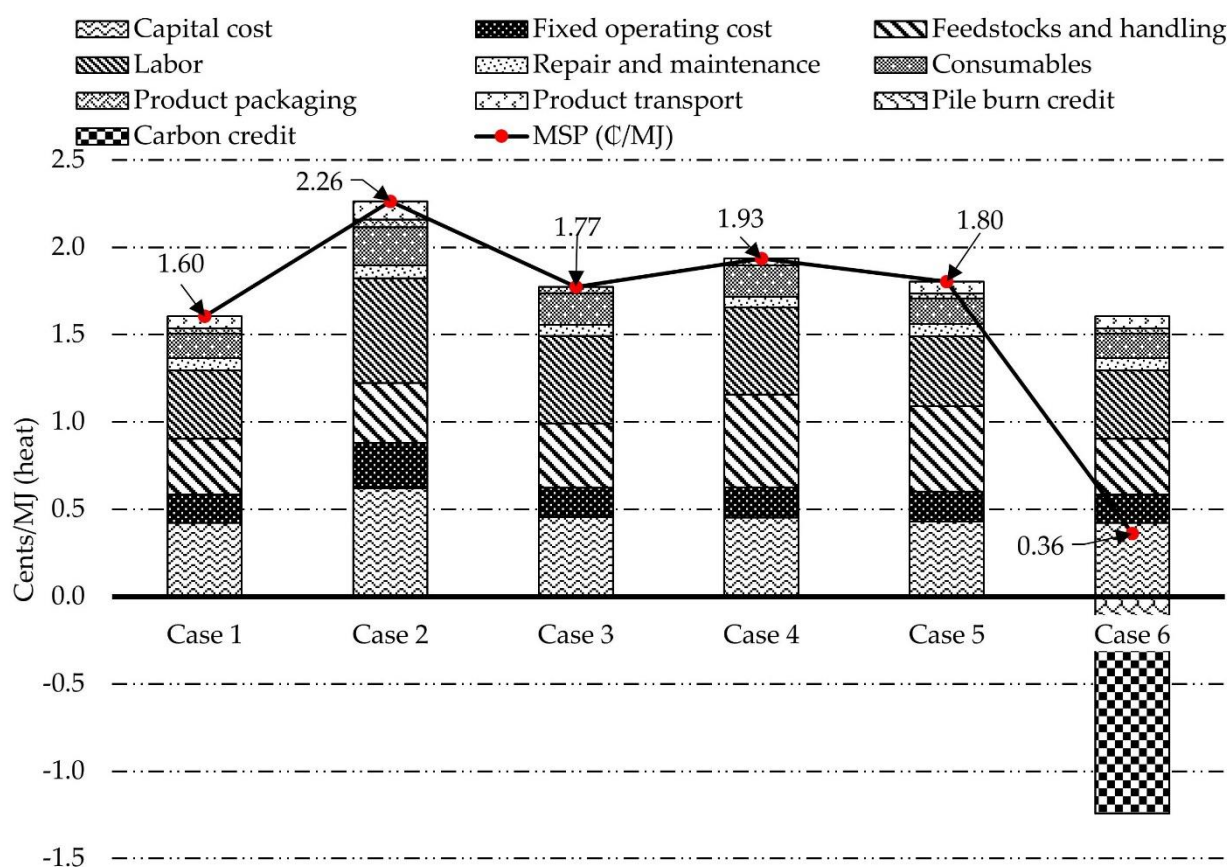


Figure 7. Comparison of minimum selling price (MSP) per 1 MJ of heat generated using torrefied wood briquettes and contributions of various costs inputs to MSP in six cases. Case 1: near-woods operation with wood biomass gasifier power; Case 2: near-woods operation with diesel power; Case 3: in-town operation (2 h travel distance) with grid power; Case 4: in-town operation (4 h travel distance) with grid power; Case 5: 50% moisture content b feedstock, near-woods operation with wood gasifier power; Case 6: near-woods operation with wood gasifier power with pile and burn credit.

Figure 8 shows the MSPs of electricity produced using TWBs and the contribution of cost inputs for each scenario. Without considering credits, the MSPs of electricity varied between \$0.20 and \$0.25/kWh. Input feedstocks in the power plant, i.e., TWBs, was one of the major costs that contributed 62–71% towards the MSP of electricity. The MSPs of the electricity produced using TWBs were much higher than the current market price (average electricity price in the US for residential, commercial, and industrial were ~\$0.14, \$0.11, and \$0.07/kWh in 2020). However, considering the credits (pile burn and carbon), the MSP of electricity produced with TWBs was reduced to \$0.10/kWh and thus within the market price.

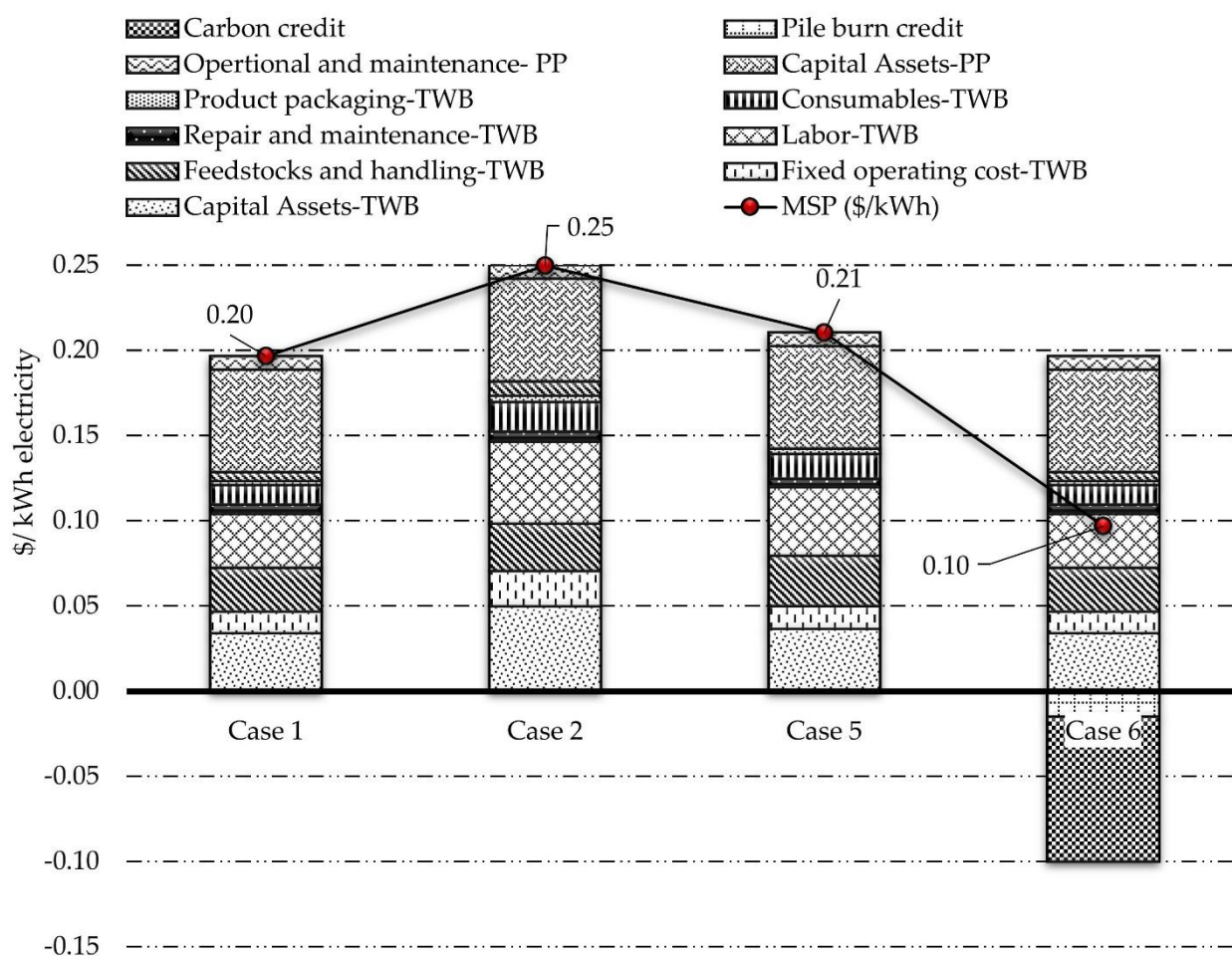


Figure 8. Comparison of minimum selling price (MSP) per 1 kWh electricity generated using torrefied wood briquettes (TWBs) in power plant (PP), and contributions of various costs inputs to MSP (only for electricity values).

3.3. Results of Uncertainty Analysis of the Base Case

Figure 9 shows the probability distribution of GW impact for three base cases. The 95% confidence interval for WB_{heat} and TWB_{heat} was found to lie between 8.9 and 9.6 g CO₂eq, and 14.6 and 18.7 g CO₂eq, respectively.

Torrefied wood briquette scenarios showed a slightly higher coefficient of variation. The 95% confidence interval for $TWB_{electricity}$ was between 148 and 187 gCO₂eq. Key parameters that influenced the GW impact at WB_{heat} in the supply chain was the dryer propane consumption [53,54]. In the TWB cases, propane used to supplement torgas combustion influenced the results most, where electricity use at the power plant for grinding (pulverizing) was another key parameter for the $TWB_{electricity}$ system.

Figure 10a,b shows the probabilistic distribution of MSPs of heat produced with WBs and TWBs, respectively. The 95% confidence interval for MSPs of WB_{heat} and TWB_{heat} were 0.7¢–1.35¢/MJ and 1.2¢–1.9¢/MJ, respectively. The MSP histograms for WB_{heat} and TWB_{heat} were skewed towards the left and right, respectively. The 95% confidence interval of MSP of electricity generated from TWB varied between 21.3¢ and 22.7¢/kWh.

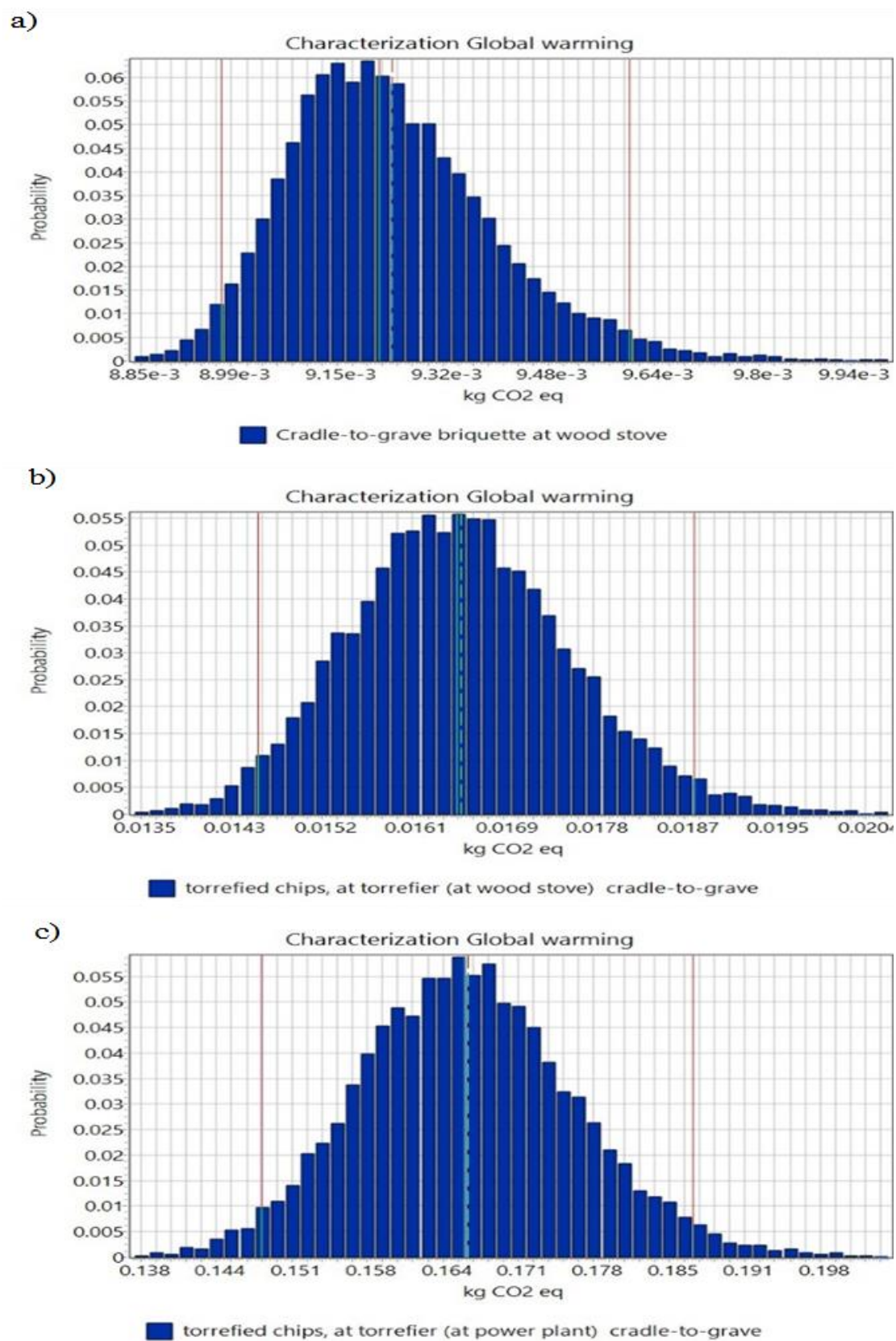


Figure 9. Probability distribution of GW impact for heat from (a) wood briquettes, and (b) torrefied wood briquettes (TWBs), and (c) electricity production from TWBs.

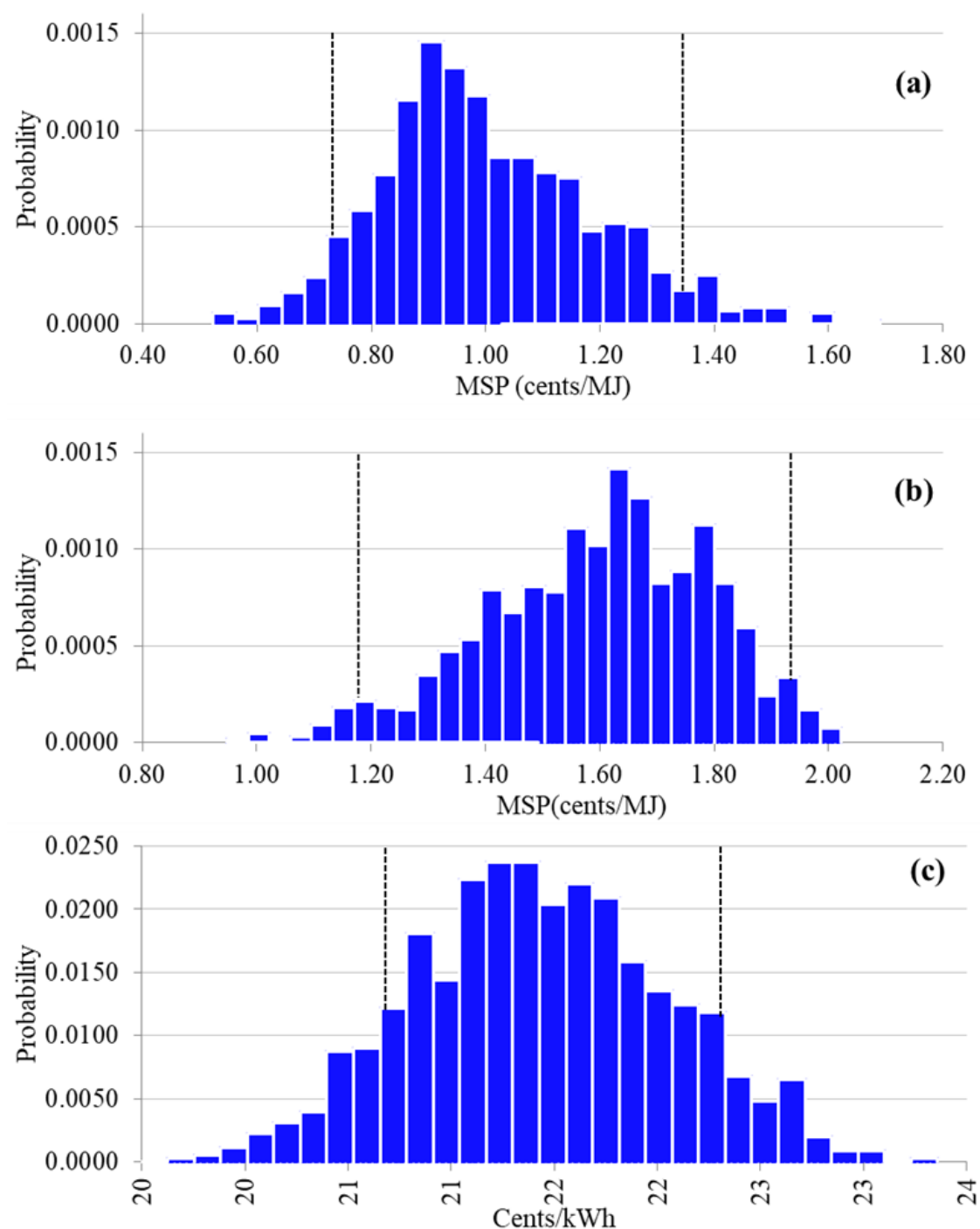


Figure 10. Probability distribution of the minimum selling price for heat from wood briquettes (a), and torrefied wood briquettes (TWBs) (b), and electricity production from TWBs (c) calculated with Monte Carlo analysis.

4. Discussion

Utilizing forest residues for useful energy products instead of piling and burning offers landowners an opportunity to generate low-carbon products at reasonable prices. Near-wood portable systems can be logistically challenging because of the small scales, as was done for the WTW project, although implementing many of these integrated systems jointly could offset this issue but has not been fully explored. The results from this study suggest that the substitution of fossil-based alternatives with WBs and TWBs for heat and TWBs for electricity generation offer a GHG mitigation strategy along with lower costs. One caveat is that the following results do not consider the externalities of using forest residues to avoid

piling and burning unless explicitly stated. Incorporating these benefits improved both the environmental and economic sustainability perspective of the three systems studied, WB_{heat} , TWB_{heat} , and $TWB_{electricity}$. The total GW impact resulting from heat production from a furnace fuelled with 100% propane is about 94 g CO₂eq/MJ [53]. Burning WBs and TWBs in a wood stove for heat generation resulted in 9.3 and 16.5 g CO₂eq/MJ, respectively, which is a substantial decrease in the overall GW impact. For the electricity generation case, the GW impact of coal-based electricity is about 0.99 kg CO₂eq/kWh, while it is about 0.17 kg CO₂eq/kWh when TWBs are burned for power generation. The generation of useful heat from burning WBs and TWBs is not only environmentally better than its fossil alternatives but also economically competitive. The estimated MSPs of useful heat (€1–2/MJ) with WBs and TWBs were lower (at 95% confidence interval) than the current market price of alternatives such as propane (€3.3/MJ). Further, the inclusion of various available credits such as carbon credits and pile and burn credits reduce the MSP of heat drastically and are much lower than the market price of fossil alternatives.

Not unexpectedly for GW impact, torrefaction, and drying processes at the torrefaction supply chains, had a high contribution. This was mainly due to low torgas energy content, in addition to the electricity-intensive torrefaction system used for the thermochemical conversion process. Alternative portable systems using fuel instead of electricity for heat during torrefaction could lower the GHG emissions profile, especially if better quality torgas could be produced or synthesis gas from an integrated biochar system could be utilized [62–65]. In the torrefaction system investigated, bio-oil was separated from torgas by condensation, which decreased the energy content of the torgas. This caused a high propane supplement requirement for ignition and steady burn. There was also an additional burden due to the disposal of bio-oil generated. Even though bio-oil may be used to generate high-value chemicals, it was not investigated as part of this project and had to be disposed of safely. The use of a more efficient combustion system would likely lead to effective use of the torgas generated and decrease the propane supplement used. One major issue is force drying of the feedstock. The forced drying process at the WB_{heat} supply chain was the major contributor to the total GW impact, due to propane use. Specifically, the case with high MC wood chip input had the worst environmental performance because of the additional force drying required. Therefore, it will be better to leave the forest residues for a certain period of time to dry [47]. Near-wood operation is a feasible option as long as the MC of the wood chips is decreased by air (field) drying. Another option is to optimize the system for processing feedstock with lower MC, which would result in lower MC in the torgas and thus higher energy content in the torgas. While torgas was used to supplement the drying process in these systems, the remaining torgas was combusted using propane supplement. This resulted in an increased environmental burden in the torrefaction process. Scenario analysis showed that near-woods biomass using a gasifier genset had better environmental performance compared with the in-town operation alternative. The environmental performance of the torrefied briquette supply chain can be increased by optimizing the amount of propane used for torgas combustion or using torgas or synthesis gas for heat during torrefaction instead of electricity. A large portion of the total cost of heat from either WBs or TWBs was labor and capital investment. Thus, the cost of generating heat from WBs and TWBs or electricity from TWBs can be reduced if multiple portable systems are operated with a small crew. Further, increasing the productivity of the WB and TWB systems, such as increasing the daily working hours, working days in a year, capacity, etc., can further reduce the cost. However, the local conditions such as fire restrictions, weather, and geography may affect the overall cost of producing heat and electricity.

The moisture content of the feedstock was observed to be an important parameter. The high MC input scenario caused a notable increase in GW impacts as well as costs for all cases, due to the propane used for force drying. Air-drying the feedstock before processing is necessary to achieve an environmentally and economically viable system.

5. Conclusions

This study quantified the cradle-to-grave environmental impacts and financial performance of heat (WB_{heat} , TWB_{heat}) and electricity ($TWB_{electricity}$) production from densified wood-products such as wood briquettes (WBs) and torrefied wood briquettes (TWBs) processed from forest residues using a portable system in a near-forest setup. Heat production from WBs and TWBs were studied for six scenarios, whereas electricity production using TWBs was analyzed for four different scenarios, including locations of processing densified briquettes and the feedstocks' moisture contents. Uncertainty of results due to variability in the inputs were analyzed using Monte Carlo simulation.

The results showed that the utilization of forest residues to make densified products (WBs and TWBs) and burn them to produce heat was environmentally better and economical compared to its fossil-based alternative such as propane. The total cradle-to-grave GW impacts of heat generated by burning forest residues as WBs and TWBs were 10–37 and 17–51 gCO₂eq/MJ of heat, respectively. The MSPs of heat generated from forest residues as produced as WBs and TWBs were €1.09–€1.73 and €1.6–€2.26 per MJ of heat, respectively. However, the cradle-to-grave GW impacts and MSPs of electricity production from forest residues as TWBs were 167–443 g CO₂ eq/kWh (Table 5) and \$0.2–\$0.25/kWh (Figure 8), respectively. The cradle-to-grave GW impacts and MSPs of heat production from forest residues as WBs and TWBs were significantly (95% confidence) lower than their fossil alternatives such as propane. Although electricity production from TWBs had lower GW impact compared to fossil-alternatives, the former had higher MSP or production costs than the later. However, considering credits such as pile burn and monetization of lower carbon, the MSP of heat and electricity production was reduced substantially. The scenario analysis showed that lower GW impacts and MSP of heat and electricity generation can be achieved by using lower moisture forest residues and production of WBs and TWBs at near-forest setups. Overall, it can be concluded that utilizing forest residues to make WBs and TWBs with portable systems and using them to make heat as well as electricity are economical and provide much lower carbon footprints.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/fuels2030020/s1>, Figure S1: Mass balances of studied cases for heat generation from wood briquettes (WBs), Figure S2: Mass balances of studied cases for heat generation from torrefied wood briquettes (TWBs), Figure S3: Mass balances of studied cases for electricity from torrefied wood briquettes (TWBs), Table S1: Cradle-to-gate input–output flow analysis for one bone-dry metric ton of wood chips, Table S2: Input–output flows of non-torrefied briquette (NTB) and torrefied briquette (TOB) production and use, Table S3: Capital costs and operating costs of WB and TWB production systems for six scenarios, Table S4: Summary of inputs for TEA study with uncertainty distributions, Table S5: Environmental impacts of 1 MJ of heat generated for domestic heating from WBs, Table S6: Environmental impacts of 1 MJ of heat generated for domestic heating from TWBs, Table S7: Environmental impacts of 1 kWh generated at coal-fired power plant from TWBs.

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