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Techno-Economic Evaluation of the Thermochemical Energy Valorization of Construction Waste and Algae Biomass: A Case Study for a Biomass Treatment Plant in Northern Greece

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Abstract: Biomass treatment for energy production is a promising way for achieving fossil fuel replacement and environmental relief. Thermochemical processes are a common way of processing biomass, but their potential economic benefits are not always clear to investors. In this work, three basic thermochemical processes (combustion, gasification, and pyrolysis) are examined in terms of their theoretical yields and their products, as well as their economic viability. The goal of this analysis was to look into the total amount of available biomass streams and compare business plans in terms of sustainability from a technical and economic perspective. The estimation of the fixed capital investment was based on ready−made solutions that are already available on the market. The analysis showed that the gasification unit has the optimum sustainability results since the total amount of gross income was EUR 0.13/kg of biomass while the treatment cost was estimated at EUR 0.09/kg of biomass. The internal rate of return of the investment was calculated at 9%, establishing a promising alternative solution to sustainable "green" energy production.

Keywords: techno−economic analysis; combustion; gasification; pyrolysis; biomass treatment; thermochemical treatment

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1. Introduction

The linear economy model can be described as a series of steps that include extracting resources from the environment, producing goods and services, consuming them, and finally disposing of the residues in a landfill. In recent years, it has become more and more obvious that this is not a sustainable economic concept. An alternative economy model described by a circle that utilizes the produced waste for the recovery of energy and materials has been promoted by the European Union (EU) during the last two decades. This has been advocated in a number of documents issued by the European Commission, such as the Roadmap to Resource Efficient Europe, the Ecodesign Directive, the circular economy package, and the EU directive on waste [1,2].

Waste biomass can play an important role in the circular economy model, as it contains valuable resources that can be recovered, including energy and other by−products. A number of resource recovery methods from biomass have been examined in the literature, leading to the production of energy and the recovery of by−products, as illustrated in Figure 1. Landfilling of biomass leads to the production of biogas, which is in some cases used for the production of electricity, while in other cases it is burnt to prevent its release into the atmosphere (methane is approximately 30 times more potent as a greenhouse gas than carbon dioxide). Moreover, a significant amount of methane escapes as onsite emissions, making landfilling a subpar resource recovery method [3]. Composting can be a very useful resource recovery method, mainly for biomass that has a relatively high moisture content and is not suitable for other forms of resource recovery [4]. Its use leads mostly to the recovery of nutrients in the form of compost, while some applications have been proposed for the recovery of the produced heat [5], though this is not a widespread application. Anaerobic digestion is typically used in the case of high moisture (liquid) biomass, leading to the recovery of biogas and by−products (in the form of anaerobic digestate) [6]. When dealing with low−moisture biomass, combustion, gasification, and pyrolysis are typically more suitable.

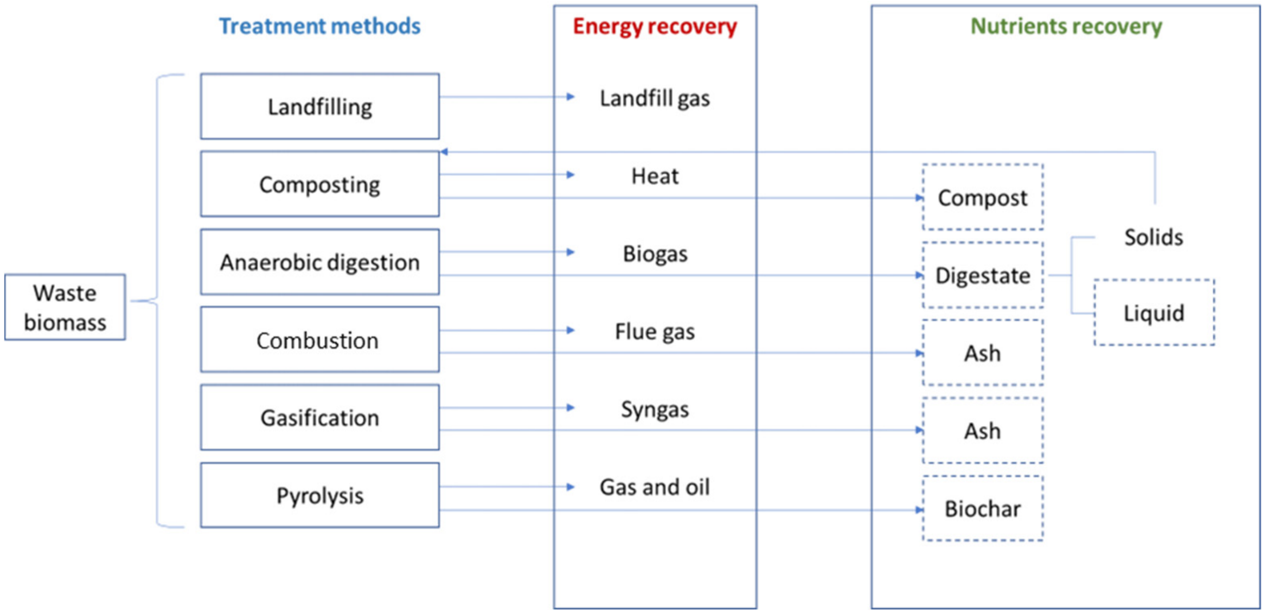

Figure 1. Most prominent resource recovery methods from waste biomass.

Combustion units have widespread use and applicability since this technique is a very common waste treatment method in countries of Northern Europe, such as Finland and Denmark [7]. The electric efficiency of these units is close to or above 80% (of lower heating value), with the highest capital cost typically occurring from the combined heat and power production unit (CHP) [8].

In order to initiate the combustion of biomass, its temperature must exceed a certain point (ignition temperature), which is different for each type of combustible biomass. Biomass during combustion goes through three different stages, which are overlapping and occur simultaneously. These stages are the drying, devolatilization, and burning of solid carbon [9]. Several challenges can occur using this biomass treatment method related to the biomass characteristics (moisture, minor constituents, etc.) [10]. The biomass chamber parameters need to be designed according to the biomass characteristics as well as the ash and gas emissions composition [11,12].

The gasification process converts a solid/liquid organic residue into a gas phase ("syngas") and, in some cases, a solid fraction ("char"). In this process, the biomass is heated in the presence of limited amounts of oxygen in order to release maximum amounts of gases such as CO and H_2. The oxygen requirements can be provided to the system either in the form of pure O_2 or as air [13]. The most widely used medium is air due to its low cost; however, using pure oxygen instead of air can increase the calorific value of the produced gas up to four times due to the absence of nitrogen in the gas phase [14]. Worldwide, several gasification plants are operating or are under construction with most of them dedicated to electricity production [15].

Pyrolysis is a thermochemical process for biomass degradation in the absence of oxygen which provides three different products (biochar, bio−oil, and fuel gas products) [16]. During this process, a large number of reactions take place, but it is mainly accepted that pyrolysis consists of three main stages (biomass drying, primary decomposition, and secondary decomposition reactions) [17,18]. This process can be sustainable and economically feasible only with the upgrading of the bio−-oil to a pure and stable product [19]. Depending on the rate of thermochemical treatment and the residence time, the process is characterized as fast or slow. Slow pyrolysis can increase the yield of biochar produced whereas fast pyrolysis leads to an increase in bio−oil production [20].

This work provides a case study of a potential biomass thermochemical treatment unit constructed in Greece, implementing combustion, gasification, or pyrolysis. The study took into account the mass and energy balances of the different processes considering the biomass characteristics. Equipment cost (Cp) and bioenergy efficiency were estimated for each process in order to assess the business plans during the lifetime of the investment. This analysis could be a guide for decision−making for biomass treatment in coastal regions of Europe since the subsidy percentage used is common throughout the EU [21]. Moreover, the present study investigates the energy production from a waste stream (algal biomass) that is not commonly used for energy recovery and constitutes a typical biomass solid effluent in coastal regions. The aim of this paper is to offer readers a general perspective of thermochemical processes and to evaluate the energy potential of construction and algal biomass (AB), considering their economic feasibility.

2. Materials and Methods

2.1. Feed Material and Pretreatment

The analysis was carried out with the implementation of three different substrates to evaluate the sustainability of the proposed processes. The quantitative characteristics of the final substrate mixture were based on full−scale data of an enterprise that manages construction waste in the region of Northern Greece. The feed material mixture consisted of woody biomass (WB) (branches, wood, tree trunks, and wooden pallets), construction materials (CM) (plastic, pipes, wires, and nylon), and AB (coastal seaweed). According to the data provided by the enterprise, the amounts of WB, CM, and AB to be managed were 30,000, 10,000, and 20,000 t/y, respectively. According to these quantities, the feed material consisted of the aforementioned substrates with a ratio of WB/CM/AB equal to 3/1/2. Several samples of the three different types of substrates were pretreated in order to evaluate the feed's main characteristics. The scope of this process was to calculate the specific elements (C, N, O, and H) and the moisture and ash content in order to estimate the substrate's biomass empirical formula and calorific value from each process reaction. The pretreatment included the initial shredding by a pilot scale shredder (CRUSHERS Monorotor, M4230-700, BLik, Milly-la-Forêt, France) and the subsequent pulping into 1×1 mm pieces by a hand-held crusher (IKA A11 Basic Griding mill—Gemini BV, IKA, Staufen, Germany). After the pretreatment steps, the samples were analyzed. Apart from the aforementioned substrates, the enterprise also manages excavation and demolition waste which are both used as inert materials and were out of the scope of this analysis.

2.2. Analytical Techniques

The measurement of total organic carbon (TOC) was carried out using the TOC−VWS and Solid Module SSM-5000A apparatus (Shimadzu, Kyoto, Japan). Total nitrogen was measured through a Micro−Kjeldahl apparatus (VELP SCIENTIFICA, UDK 129, Usmate, Italy) by the conversion of the organic nitrogen to ammonium salt in the presence of K_2SO_4 and HgO/H_2SO_4 [22]. Moisture was determined by weighing an amount of fresh sample before and after drying at 105 °C overnight, while ash was determined by measuring the weight difference of the dried samples after burning at 550 °C for 45 min [22].

2.3. Description of the Proposed Processes

Regarding the biomass combustion unit, it was assumed that the plant equipment includes a biomass crusher and a main biomass combustion chamber, as well as a combined heat and power system for energy production. The thermal energy produced could potentially be used to cover the thermal requirements of the unit, which has not been included in this analysis. The cogeneration unit includes an electricity and heat production unit and facilities for receiving, storing, and preparing fuel.

Biomass combustion as well as electricity production were carried out in the main unit of the plant. The unit was considered to be installed next to the existing biomass storage structures, and the composition of the feed was assumed to remain constant during the whole operation period. Small changes in the feed lead to different system productivity; nevertheless, the annual biomass amount was assumed to be constant as well as the total annual energy production.

A prototype unit from an American supplier was selected for the evaluation of the gasification process, which included a biomass drying system, a gasification unit, and a CHP unit. A biomass crusher was considered in the analysis for biomass shredding. A solid organic residue fraction (biochar) is obtained from the gasification chamber, which can be further exploited for soil amendment [23] or as material in building constructions [24]. This type of biochar tends to have a higher surface area and a more porous structure compared to biochar produced by other processes (such as pyrolysis). This fact may occur due to the high process temperatures with a limited supply of oxygen. This type of biochar can also be used in animal feed to reduce the occurrence of digestive problems [25]. This analysis describes the construction of a 6.05 MW_e unit. The characteristics of the plant construction site remain the same as those mentioned in the assessment of the biomass combustion plant. Furthermore, this supplier markets a prefabricated treatment system with a maximum productivity of 200 kW. Thus, the 'two—-thirds' rule was used to calculate the C_p for the process.

For the design and analysis of the pyrolysis unit, a unit installed in the Pieria region, Greece, was chosen as a model. This unit includes a mechanical separation unit, a crusher, a thermal converter in the absence of oxygen (main pyrolysis unit) with simultaneous production of gas fuel, heat, and biochar, a thermal oxidizer for pyrolysis gas burning, heat recovery, and a superheated steam production boiler, a waste gas cleaning unit, and a CHP unit with a steam turbine electric generator. This unit has been built for a capacity of 125 tonnes per day of municipal solid waste.

The steps of the processes examined in this work are summarized in Figure 2.

The equipment size for each unit was estimated through the coefficient yields of each piece of equipment and the mass and energy balances of the processes. A figure of 9% equipment downtime for maintenance and repairs was considered. The total Cp was then estimated through the two—thirds rule [26,27]. The fixed capital investment (FCI) for each process was calculated through the total Cp according to Table 1. The individual costs for each FCI element were calculated through the equations in Table 1 according to the methodology by Peters et al. [26]. This method is capable of a preliminary estimation with a confidence of ±30%.

The operational costs, such as waste treatment (C_{wt}) and energy requirements, were estimated for each process, and different treatment costs were implemented for the analysis depending on the waste characteristics. The total treatment cost (TTC) was calculated through Equation (1):

$$TTC = 1.481\ C_{ol} + 1.235\ C_{wt} + 0.143\ FCI + 0.082\ C_p \quad (1)$$

where C_{ol} refers to the labor cost.

A lifetime of 15 years was assumed for the equipment, and 30 years was assumed for the erected buildings. The total operational cost can be divided again into direct costs connected with the production process and other costs such as the depreciation of the equipment and buildings, taxes and insurance, direct work, etc.

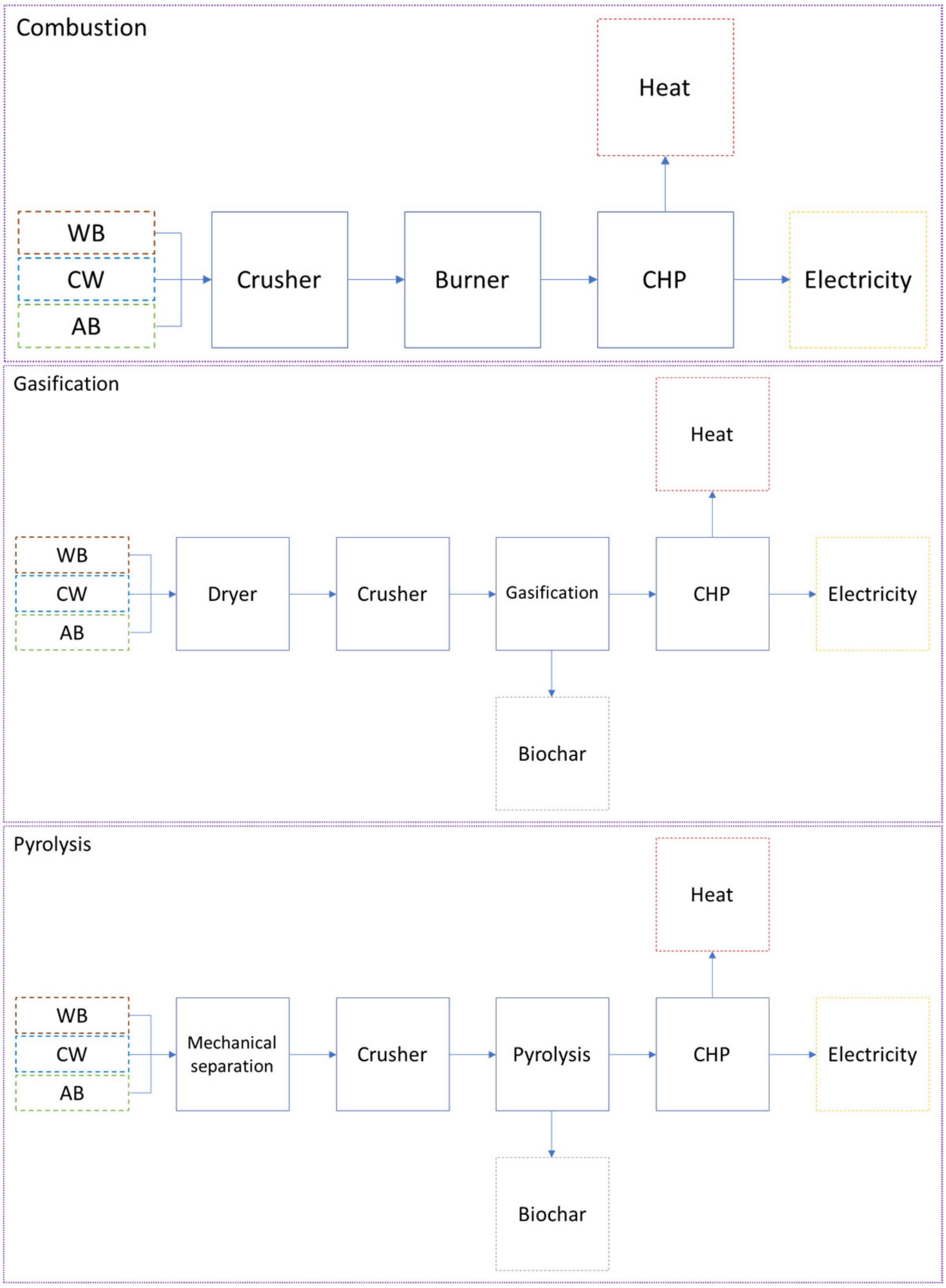

Figure 2. Main steps of the three thermochemical processes examined in this work.

For the investment plan estimation for the installation and operation of the proposed units, it was considered that 25% of the FCI could be covered by the investor's own funds, while 40% could be covered by subsidies according to the development law of Greece 3299/2004. The remaining percentage could be covered by a loan with an interest rate of 8% that must be repaid in the first three years of unit operation. Subsequently, working capital (14% × FCI) must be calculated in the total cash flows, which will be returned to the investor at the end of the life of the unit. Income tax was assumed to be 20% on business profits.

Table 1. Equations used for the economic evaluation of the processes.

Fixed Capital Investment (EUR)	Direct Cost (EUR)	Onsite	Purchased equipment	C_p
			Equipment installation	0.06 FCI
			Automatic control and instruments	0.02 FCI
			Piping	0.04 FCI
			Electrical equipment	0.02 FCI
		Offsite	Buildings	0.02 FCI
			Yard improvements	0.02 FCI
			Service facilities	0.08 FCI
			Land	0.01 FCI
	Indirect Cost (EUR)		Engineering and supervision	0.04 FCI
			Construction expenses	0.04 FCI
			Contractor's fee	0.02 FCI
			Contingency	0.05 FCI
	FCI (EUR)			1.724 C_p
Total Product Cost (EUR)	Direct Cost (EUR/y)		Energy requirements	0.1 TTC
			Waste treatment	C_{wt}
			Direct work	C_{ol}
			Operating supervision	0.1 C_{ol}
			Maintenance and repairs	0.02 FCI
			Operating supplies	0.005 FCI
			Laboratory charges	0.1 C_{ol}
			Royalties and patents	0.01 FCI
			Depreciation	0.082 C_p + 0.06 FCI
			Taxes and insurances	0.03 FCI
			Fixed charges	0.05 FCI
	General expenses (EUR/y)		Administrative expenses	0.02 TTC
			Distribution and marketing expenses	0.02 TTC
			Research and development	0.05 TTC

3. Results and Discussion

3.1. Biomass Characterization

The basic physicochemical characteristics of the substrates as well as their elemental analysis are presented in Table 2.

Table 2. Physicochemical characteristics of the substrates.

Characteristic	WB	CW	AB	MIXTURE	Reference
C (% DM *)	50.20 ± 0.9	14.93 ± 3.1	37.14 ± 1.1	51.53 ± 0.6	This work
O (% DM *)	41.57 ± 1.2	3.20 ± 4.0	50.38 ± 8.9	38.11 ± 9.7	[28–32]
H (% DM *)	5.49 ± 0.2	12.59 ± 1.2	5.28 ± 0.2	6.60 ± 0.1	[28–32]
N (% DM *)	0.30 ± 0.1	0.49 ± 0.7	3.04 ± 1.9	1.24 ± 3.0	This work
Moisture (%)	11.95 ± 6.2	2.25 ± 0.3	81.58 ± 0.1	33.53 ± 9.5	This work
Ash (%)	6.78 ± 4.7	65.52 ± 3.3	1.10 ± 0.1	14.67 ± 5.8	This work
Calorific value (MJ/kg_{DM})	18.31 ± 0.6	43.53 ± 2.7	12.33 ± 3.0	20.11 ± 1.8	Calculated

* DM: Dry matter.

WB is characterized by a high carbon content in terms of dry weight as well as a high oxygen content. The percentages of moisture and ash are relatively low (12% and 7%, respectively), making it an ideal waste for thermochemical treatment. CW showed less favorable characteristics for this type of treatment than WB as its carbon content reaches 15%. This fact was mainly due to the high content of wire inside the cables and other materials. The percentage of oxygen in this substrate is reduced by 3%, forming an O/C ratio of 0.21. AB has a high content of ash and moisture, which reduces the thermal value of the mixture material since they increase the latent heat (LH) of the feedstock. The specific substrates appeared to have high complementarity in their individual components, which demonstrates that the final mixture will have a typical biomass composition. The calorific value (CV) for each waste stream was calculated from the elemental analysis considering the percentage of C, H and O in dry biomass according to the equation:

$$CV\left(\frac{MJ}{kg_{DM}}\right) = 0.339\ (\%C) + 0.114\ (\%H) - 0.018\ (\%O) \quad (2)$$

The highest CV was exhibited in the WB waste stream mainly due to the high organic content of this type of biomass. The CV of the current waste streams was considered as a crucial parameter for the analysis. Nevertheless, only an estimation of this value was carried out without direct measurement. Slightly different values in CV may lead to different system performance, but the comparison results would be the same according to the analysis presented herein. Based on the above, the final characteristics of the biomass after the mixing of different substrates can be found in Table 2. The final characteristics of the biomass are quite similar to those of the WB, which is expected since it was mixed in a higher amount. The moisture after mixing increased by over 30%, which indicates that for this particular substrate, there may be a need for pre−treatment and drying before entering the main process.

3.2. Techno−Economic Evaluation of Alternative Treatment Methods of Biomass

3.2.1. Biomass Combustion Unit

An energy analysis was conducted regarding the specific feed material in order to evaluate the performance of the combustion unit. In the analysis, the high calorific value (HCV) of the specific biomass was calculated based on its characteristics as well as the energy losses that would result from the moisture contained in it through LH. The excess air of the system was 25% more than the stoichiometrically required amount in order to achieve maximum performance and the absence of intermediate combustion products. Based on this excess air, it was assumed that the percentage of monoxide in the gases leaving the system was 1%. The temperature of the main combustion unit was set at 800 °C. The composition of the gas stream leaving the combustion chamber was estimated as $CO_2/CO/O_2/H_2O/N_2$ equal to 12.6/1/2.5/19.5/64.4.

Based on the composition of the gases, the temperature of the chamber, and the excess air in the process, the efficiency of the burner for the specific type of biomass is estimated through Equations (3)–(5).

$$\mathrm{EP}\left(\frac{\mathrm{MJ}}{\mathrm{d}}\right) = \dot{n}_{\mathrm{CO2}}\Delta H_{f,\mathrm{CO2}} + \dot{n}_{\mathrm{CO}}\Delta H_{f,\mathrm{CO}} + \dot{n}_{\mathrm{H,in}}\frac{\Delta H_{f,\mathrm{H2}}}{2} - \dot{m}_{\mathrm{DM}}\Delta H_{\mathrm{DM}} \quad (3)$$

$$\mathrm{LH}\left(\frac{\mathrm{MJ}}{\mathrm{d}}\right) = \left(\frac{\dot{n}_{\mathrm{H,in}}}{2} + \dot{n}_{\mathrm{H2O}}\right)\Delta H_{f,\mathrm{H2O}} \quad (4)$$

$$\mathrm{UH}\left(\frac{\mathrm{MJ}}{\mathrm{d}}\right) = \mathrm{EP} - \mathrm{LH} \quad (5)$$

where EP denotes the energy produced, $\dot{n}$ refers to the molar flow of the elements in mol/d, ΔH_f refers to the formation enthalpy in MJ/mol, $\dot{m}_{DM}$ refers to the mass flow of dry biomass in kg/d, and ΔH_{DM} refers to the enthalpy of dry biomass in MJ/kg_{DM}. The molar flows were calculated stoichiometrically from the biomass combustion reaction.

It can be observed that an efficiency of 96% of the calorific value of the biomass was achieved, which makes the process particularly efficient for this specific feed stream. The process's LH, useful heat (UH), and HCV were estimated to be 343, 2674, and 2776 GJ/d, respectively.

Due to the high ash content of the biomass mixture, ash amounts of 20 tonnes per day are produced simultaneously from the treatment. This constitutes a waste stream of the process and needs special management, as it mainly consists of inorganic elements, metals, and wire scraps. For its processing, a cost of EUR 0.42/kg of ash is foreseen [33].

After treatment, the gas produced is used at a CHP plant. The yields of such plants vary depending on their specific type. For this study, the overall efficiency of the cogeneration plant was considered to be 87%, with individual efficiencies of 63% in thermal energy and 24% in electricity [34]. The produced thermal energy from the treatment was not an exploited stream. Some authors propose the exploitation of this stream for heating nearby residential areas after appropriate modification of the network (district heating) [35,36].

This specific project is a challenge as the cost of building substations for the transfer of thermal energy is quite high, considering that there is no previous installation in the area. Furthermore, a specific fraction of energy can be used to heat greenhouses in the winter months [37,38]. These practices potentially increase the viability of the plant. However, they were excluded from this study as they would further increase the total fixed costs as well as the size of the overall processing plant. The total energy production capacity of the biomass combustion unit was assumed at 6.41 MW of electric energy according to the analysis.

The C_p was estimated based on the description of a combustion unit of a specific capacity from the work of [34], by increasing the cost of the unit in relation to the capacity using the two−thirds rule. The total C_p for the combustion unit was estimated at EUR 6,461,358. The FCI of the combustion unit was estimated through Table 1 as EUR 9,621,144. In the work of Sagani et al. [39], the specific capital cost (SCC) was estimated at EUR 3000/kWel for a plant designed for the region of Argolis, Greece, with a capacity of 4.5 MWel. In the present work, the SCC was calculated at EUR 1636/kWel for a capacity of 6.41 MWel, which is in good agreement with the work of Sagani et al. and the economy of scale. For the calculation of the immediate labor, it was assumed that three workers were required per MW of electricity [34]. Moreover, annual staff remuneration was set at EUR 24,000 gross revenue per employee. Based on this analysis, the treatment cost per kg of feed material was estimated at EUR 0.09. The unit's total annual revenue (TAR) was the profit from electricity production, as the development of a district heating network has not been included in the analysis. The sale price for electricity derived from biomass, based on Greek legislation, is set at EUR 140/MWhel for units larger than 5 MW and EUR 162/MWhel for units larger than 1 MW [40]. The gross income per kg of feed material was calculated at EUR 0.12.

The loan for the investment was estimated at EUR 4,714,361. The cash flows for the fifteen years of unit operation are presented in Figure 3a. It becomes clear that the specific investment plan shows great sustainability as all economic parameters have acceptable values. The profitability index (PI) was estimated to be greater than 1 (PI = 1.72). When this investment index estimated greater than 1, the investment could be made, and it is a measure of the investment's attractiveness [41]. At the same time, the net present value (NPV) after the end of the investment is positive (EUR 4,826,477) at the given rate of return (5%). The economic parameter values are presented in Table 3. The internal rate of return (IRR) of the business plan was calculated at 10%, comparable with the same economic parameter for the combustion units described in the works of Candia et al. and Morato et al. [42,43], with a value of 12%.

Table 3. Economic parameters of the analysis carried out for the proposed treatment methods.

Characteristic	Combustion	Gasification	Pyrolysis
IRR	10%	9%	0%
PI	1.72	1.9	0.73
NPV (M EUR)	4.8	5.3	−21.1
Payback Time	8.9	9.3	-

3.2.2. Biomass Gasification Unit

A theoretical analysis was conducted regarding the specific mixture of biomass streams, corresponding to the analysis examined in the combustion unit, in order to estimate the outputs and inputs of the gasification unit. The percentages of gas compounds in the output of the main gasification unit were estimated for $CO_2/CO/CH_4/H_2/N_2$ to be equal to 24/3/3/39/32. The oxygen entering the gasifier was set at 20% of the amount required for complete oxidation of the biomass. At the same time, the extent of the reaction was set at 94% based on the technical characteristics disclosed by the supplier. The temperature of the produced gas (syngas) was set at 600 °C. Regarding the solid stream outflow, the daily mass flow was calculated at 24 t/d with an organic/ash ratio equal to 0.36 with 90%

of carbon, 9% of oxygen, and 1% hydrogen. The volume of the outflow gas from the main gasification unit was calculated at 992,000 m^3 (STP) with a ratio of $N_2/H_2/CO/CO_2/CH_4$ equal to 0.35/0.34/0.06/0.22/0.03.

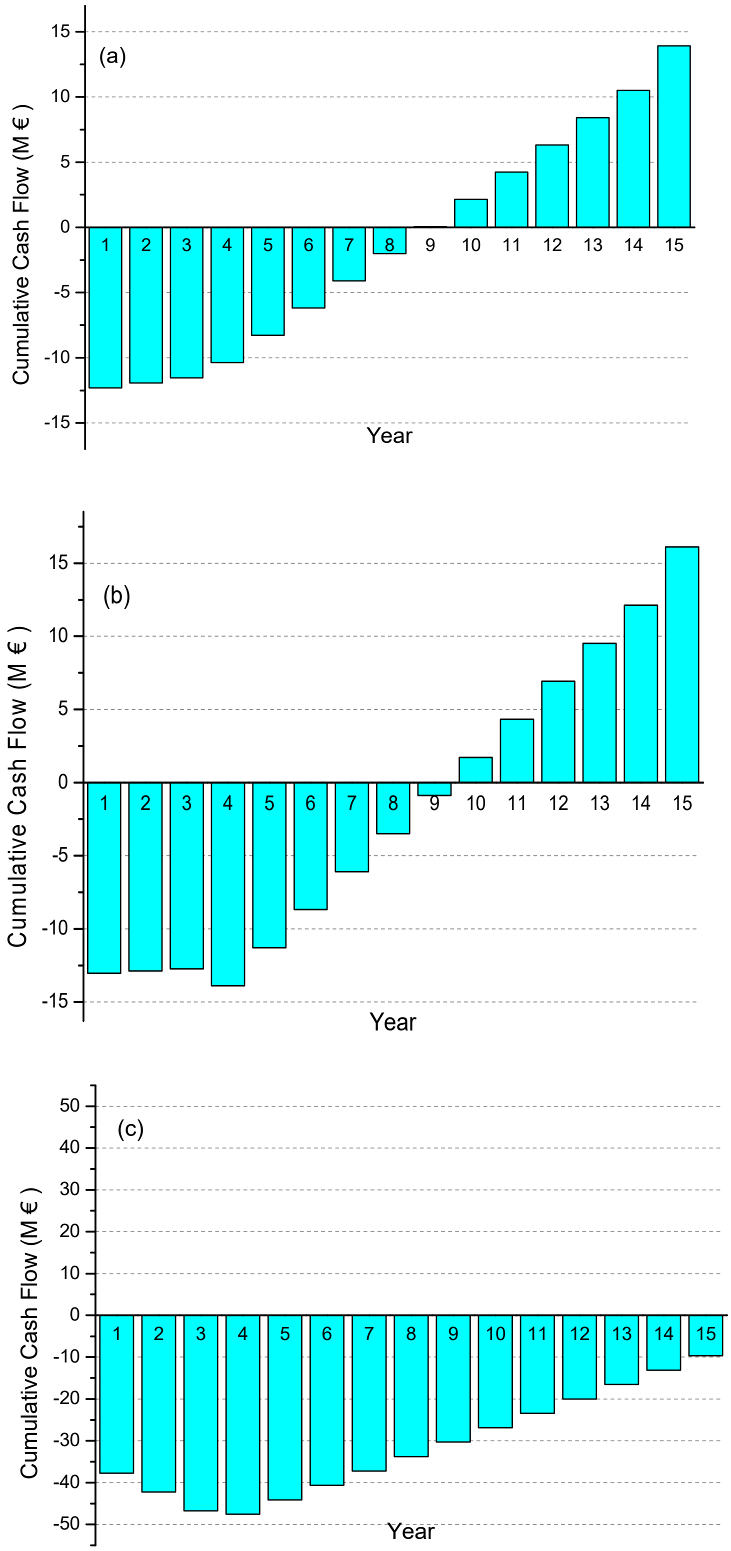

Figure 3. Annual discounted cash flow representation for the combustion (**a**), gasification (**b**), and pyrolysis (**c**) business plan.

The main gasification unit was estimated to recover 84% of the HCV of the biomass in the gas stream. Certain amounts of ash were identified in the solid effluent stream, which can potentially be removed by sieving. The amount of ash that is left over can be handled in the same way as in the combustion unit. The system has an electricity and heat cogeneration unit with efficiencies of 26% in electricity and 37% in thermal energy. Part of the thermal energy is utilized in the biomass dryer of the plant.

The C_p was estimated through the two−thirds rule from data provided by a supplier for a 200 kW unit. Based on this, the total Cp was estimated at EUR 5,730,869 and the FCI was estimated at EUR 9,880,808. Regarding the treatment cost of the process, it was calculated through Equation (1) to be EUR 5,203,955/year. The total number of employees was estimated to be 18. Finally, the treatment cost per kg of feed material was calculated to be EUR 0.09. This value indicates that the processes of combustion and gasification lead to similar treatment costs even though the combustion plant produces a higher amount of electric energy (6% higher).

The total annual revenue (TAR) of the plant came from electricity production, as well as the sale of the total amount of the organic fraction of the solid residue (biochar). The price for electricity derived from biomass was established at EUR 140/MWhel [40], based on Greek legislation, while for the organic solid fraction, this was estimated at EUR 540/t based on the market price. The gross income of electric energy production and biochar was calculated at EUR 6,811,945 and EUR 1,157,506, respectively. The income per kg of biomass was estimated at EUR 0.13. The total revenues are 25% higher than those of the combustion unit, which is mainly due to the sale of biochar. On the other hand, the total revenues from the sale of electricity are reduced by 6%, which is mainly due to the different yields of the two processes, both in the main processing unit and the CHP unit.

For the assessment of the investment cash flows over a 15-year period, it was also assumed that 25% of the investment was covered by equity capital. The amount of the loan, after receiving a subsidy of 40% of the initial investment, was estimated at EUR 4,714,361. Based on the development law 3299/2004 and the characteristics of the investment mentioned in the combustion unit, the investment plan for the construction of a gasification unit is presented in Figure 3b. At the same time, the financial parameters showed a profitable investment compared to the other studied treatment units that could potentially be financed with an IRR of 9% (Table 3). This IRR value is in line with the work of Luz et al. [44] where the IRR for a gasification unit plant for municipal solid waste was estimated at 7.5–15% depending on the plant's capacity. The payback period of the investment was estimated at 9.34 years, the PI was estimated at 1.9, while the NPV was calculated at EUR 5,348,112 after the 15−year period of unit operation. The results for the gasification unit were considered similar to the results of the work of Rentizelas et al. [45] where the gasification process has about a 50% increased NPV compared to the combustion plant unit.

3.2.3. Biomass Pyrolysis Unit

The case study of pyrolysis of biomass fractions considered in the present work can be analyzed according to the mass and energy balances of the process. In the pre−treatment step of the unit, glass and metal can be removed. Since most of the remaining ash after the thermochemical treatment comes from the wire inside the construction waste cables, a first screening of the copper part of the wire can be carried out at this point. This amount is estimated to be 75% of the total ash and therefore 10% of the total biomass. The fuel for the operation of the burner is natural gas, which is considered in the analysis. The resulting inert solid can be used as a soil fertilizer in further processes. The biochar produced was calculated at 19 t/day (11% of the feed material) and the cost for the energy demands of the unit were estimated at EUR 805/d. The estimated energy produced from this type of feed stream was estimated at 11.7 MJ/kg_{DM} which is in the same order of magnitude with the values of other studies with microalgae biomass as feedstock (18.4 MJ/kg_{DM}) [46].

In addition to the financial part, the manufacturing company of the unit also provides detailed information on the waste gases that come out of it after cleaning. Their values are extremely low and certified by the strict specifications of the state of California. Moreover, a cogeneration unit of electricity and thermal energy with an efficiency of 67% in thermal energy and 22% in electricity was derived from the analysis of the energy balances of the unit.

Several products could be produced from the pyrolysis process (bio−-oil and biochar) which could be used as the final product and channeled into the market. Nevertheless, in this study electricity was considered as the main product of the process considering that energy is a stable product that can be fed directly into the power grid. Moreover, this type of unit can be easily compared with the units of combustion and gasification for power generation.

The total C_p was estimated from the FCI of the unit from Table 1 and the two−thirds rule. The FCI of the proposed unit was calculated at EUR 31,949,131. This value is two times higher than the processes of combustion and gasification. This observation was established in the work of Solarte-Toro [47], where the capital cost of the pyrolysis unit was 2.24 times higher than the gasification plant. This fact has a very strong effect on the selection of the optimal investment scenario, as the first parameter for comparison is the FCI value. The cost of natural gas, according to the current provider charges in Greece, was set at EUR 0.83/kg. Most of the processing costs are depreciation due to the high price of equipment compared to the aforementioned biomass processing methods. The final treatment cost per kg of feed material was estimated at EUR 0.1.

The revenues of the plant come from the production of electricity and the organic solid residue (biochar) in the proportions of 61% and 39%, respectively. This type of biochar tends to have a lower surface area and denser structure compared to biochar produced by gasification. This is because pyrolysis is typically performed at lower temperatures and without oxygen, resulting in a higher yield of biochar. Biochar produced by pyrolysis units, with its denser structure, is often used as a carbon sequestration method and for long−term soil improvement [48]. Pyrolysis biochar can also be used as a feedstock for the production of activated carbon, which is used for water and air purification applications [49]. The TAR was estimated at EUR 8,990,000/y or EUR 0.15/kg of feed material. The revenues from the pyrolysis unit are considered approximately the same as those from the gasification unit.

The loan for the pyrolysis unit investment was calculated at EUR 22,045,000. The business plan was considered unsustainable, mainly because of the high equipment costs (Figure 3c). The economic parameters support this claim since the PI is estimated at 0.73 while the NPV was negative at the end of the equipment operation period (Table 3). In the work of Pighinelli et al. [50], it was also reported that a fast pyrolysis unit of biomass (eucalyptus as the substrate) for electricity production presents negative NPV values and cannot be financially competitive. For this reason, a break−even cost for the electricity produced was set (USD 0.62/kWh). In addition, in the work of He et al., it was denoted that other processes such as hydrothermal liquefaction could be more sustainable than pyrolysis or gasification for biomass with high moisture content, but further research must be carried out in order to optimize the process conditions [51].

3.3. Comparison of the Sustainability of the Business Plans

A strategy based on total investment or incremental investment should be followed in order to compare alternative and mutually exclusive business plans [52]. Based on the above criteria, an analysis was conducted for the definition of the optimum investment plan for biomass processing.

The minimum allowable rate of return (MARR) is set at 5%. The first step of the analysis was to reject investment plans where the investment exceeded the available funds. An initial assumption was made that the available funds are sufficient for the implementation of any of the alternative scenarios since this fact lies with each investor. The business plan for pyrolysis was rejected because of IRRpyrolysis< MARR. Comparing the case studies on the combustion and gasification of biomass, the combustion unit was considered as the baseline scenario due to the smaller FCI value. The incremental investment is characterized by Equations (6) and (7):

$$FCI_{Incremental} = FCI_{Gasification} - FCI_{Combustion} = \text{EUR } 9\,880\,808 - \text{EUR } 9\,621\,144 = \text{EUR } 259\,664 \quad (6)$$

$$TAR_{Incremental} = TAR_{Gasification} - TAR_{Combustion} = \text{EUR } 7\,969\,451 - \text{EUR } 7\,216\,496 = \text{EUR } 753 \quad (7)$$

The incremental investment was characterized by a δIRR = 1% < MARR. For this reason, the alternative solution of the combustion treatment plant is rejected. The gasification plant is regarded as the optimal investment plan, with it having a higher capital return rate. This scenario was estimated as optimal with the assumption that the entire quantity of the final organic residue would be channeled to the market by the end of each year. For this reason, a promotion strategy for the product would potentially increase the cost of biomass processing.

The proposed technical solutions for the processing of these types of biomass have been extensively studied in the literature [45,53–55]. In the work of Ramos et al. [53], a comparison of environmental and techno−economic analyses was conducted to evaluate different thermochemical techniques, resulting in slightly improved results for the combustion unit compared to gasification, with a plant capacity of 1 t of feed per hour (8 times less than in this work). On the other hand, in the work of Rentizelas et al. [45], the gasification of olive tree, almond tree, and peach tree prunings showed better results for the combustion unit, with a calculated IRR of 18.1%.

4. Conclusions

Thermochemical processes are environmentally friendly and efficient methods for waste treatment and energy production. In the present study, a comparison of different biomass processing methods was completed in order to assess the economic sustainability of the alternative management solutions. The comparison included three thermochemical treatment methods (combustion, gasification, and pyrolysis), indicating encouraging results for the processes of combustion and gasification, while the pyrolysis process was unsuitable because of the high Cp. Regarding the gasification process, the analysis showed that the investment in such a unit provides great economic sustainability, with higher revenues than combustion, even though a smaller amount of energy is produced. This fact is due to the production of biochar. The analysis predicted the TAR of approximately EUR 7.9 million for an initial investment of EUR 9.8 million with an IRR of 9% for a subsidized processing plant in the region of Greece.

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Abbreviations

$\dot{m}_{DM}$	Mass flow of dry biomass [kg/d]
$\dot{n}$	Molar flow [mol/d]
ΔH_{DM}	Enthalpy of dry biomass [MJ/kg$_{DM}$]
ΔH_f	Enthalpy of formation [MJ/mol]
AB	Algal biomass
CHP	Combined heat and power unit
CM	Construction materials
CV	Calorific Value [MJ/kg$_{DM}$]
C_{ol}	Labor cost
C_p	Equipment cost
C_{wt}	Waste treatment cost
EP	Energy produced
EU	European Union
FCI	Fixed capital investment
HCV	High calorific value
IRR	Internal rate of return
LH	Latent heat
MARR	Minimum allowable rate of return
NPV	Net present value
O/C	Oxygen/carbon ratio
PI	Profitability index
TAR	Total annual revenue
TOC	Total organic carbon
TTC	Total treatment cost
UH	Useful heat
WB	Woody biomass

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