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Techno-Economic Assessment of an Off-Grid Biomass Gasification CHP Plant for an Olive Oil Mill in the Region of Marrakech-Safi, Morocco

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Abstract: A substantial number of off-grid olive oil mills in Morocco are powered by diesel-fired generators, which hugely contribute to air pollution and greenhouse gas emissions. In this research work, a biomass gasification combined heat and power (CHP) plant fueled with local by-products was explored as a renewable alternative to electrify off-grid olive oil mills in this country. The case study considered a gasification CHP plant with a rated power of 80 kW_e, in order to enable adaptation of the producer gas flow rate to abrupt changes in the power generation unit under dynamic operation. A downdraft gasifier and a producer gas conditioning unit were modeled under steady state operation using Cycle-Tempo, while the power generation unit was modeled in the Thermoflex simulation environment under partial and full load operation. Olive cake pellets and olive pruning chips were evaluated as biomass feedstock, with moisture contents ranging from 5% to 20% (wet basis). The results from the simulation of the gasification CHP plant showed net electrical efficiencies and CHP efficiencies around 18% and 35%, respectively. Finally, a profitability assessment of the gasification CHP plant was developed for 2 months of continuous operation, together with a sensitivity analysis. The results for the baseline scenario reveal a payback period of 7–8 years and a 68.5% accumulated profit based on the capital investment, which suggest that biomass gasification CHP plants can represent an economically feasible and sustainable solution for the electrification of off-grid areas in Morocco.

Keywords: combined heat and power (CHP); downdraft gasifier; load profile adjustment; off-grid electrification; producer gas; sensitivity analysis

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1. Introduction

Olive cultivation and olive oil extraction constitute a major cultural and economic activity in the Mediterranean basin. Olive groves occupy about 10 million hectares of land area in the Mediterranean countries [1], where around 95% of the world's olive oil production is concentrated [2]. Presently, the largest area under olive groves in North Africa is located in Morocco, with over 1.2 million hectares under olive groves and a marked growth trend [1]. In fact, the surface under olive groves in Morocco has increased by over 60% in the last 25 years, which constitutes one of the largest increasing ratios in the world. Nowadays, the olive tree already represents the first fruit-bearing species under cultivation in Morocco, with about 65% of the national arboreal surface [3]. In terms of olive oil production, Morocco is the world's fourth largest producer with roughly 150,000 tonnes on average in the last ten years [2]. In addition, with an average production of approximately 125,000 tonnes in the last ten years, Morocco ranks second only after Spain in the production of table olives [2].

Olive trees grow in a large part of the Moroccan territory, except in the coastal areas and desert regions. As shown in the map presented in Figure 1, the most important regions for olive production are Fes-Meknès, Marrakech-Safi, Tanger-Tétouan-Al Hoceima, and Oriental [4,5]. According to the recent statistics of the Moroccan Ministry of Agriculture, the three first regions account for about two thirds of the national olive production [3]. The olive oil industry in Morocco consists of about 11,000 traditional olive processing units (locally known as *maâsras*) with a capacity of just under 270,000 tonnes/year, 948 modern and semi-modern crushing units with a capacity of 1,803,000 tonnes/year, and nearly 75 olive canneries with a total capacity of 203,000 tonnes/year [4]. These olive processing units are mainly concentrated in the regions of Fes-Meknès (35.2%), Béni Mellal-Khénifra (17.3%), and Marrakech-Safi (11%). Moreover, beyond all these macroeconomics figures, which highlight the substantial economic significance of the olive grove in Morocco, it is noteworthy that this sector is an important driver for the development of rural areas, generating more than 380,000 permanent jobs, 20% of which are currently held by women [6].

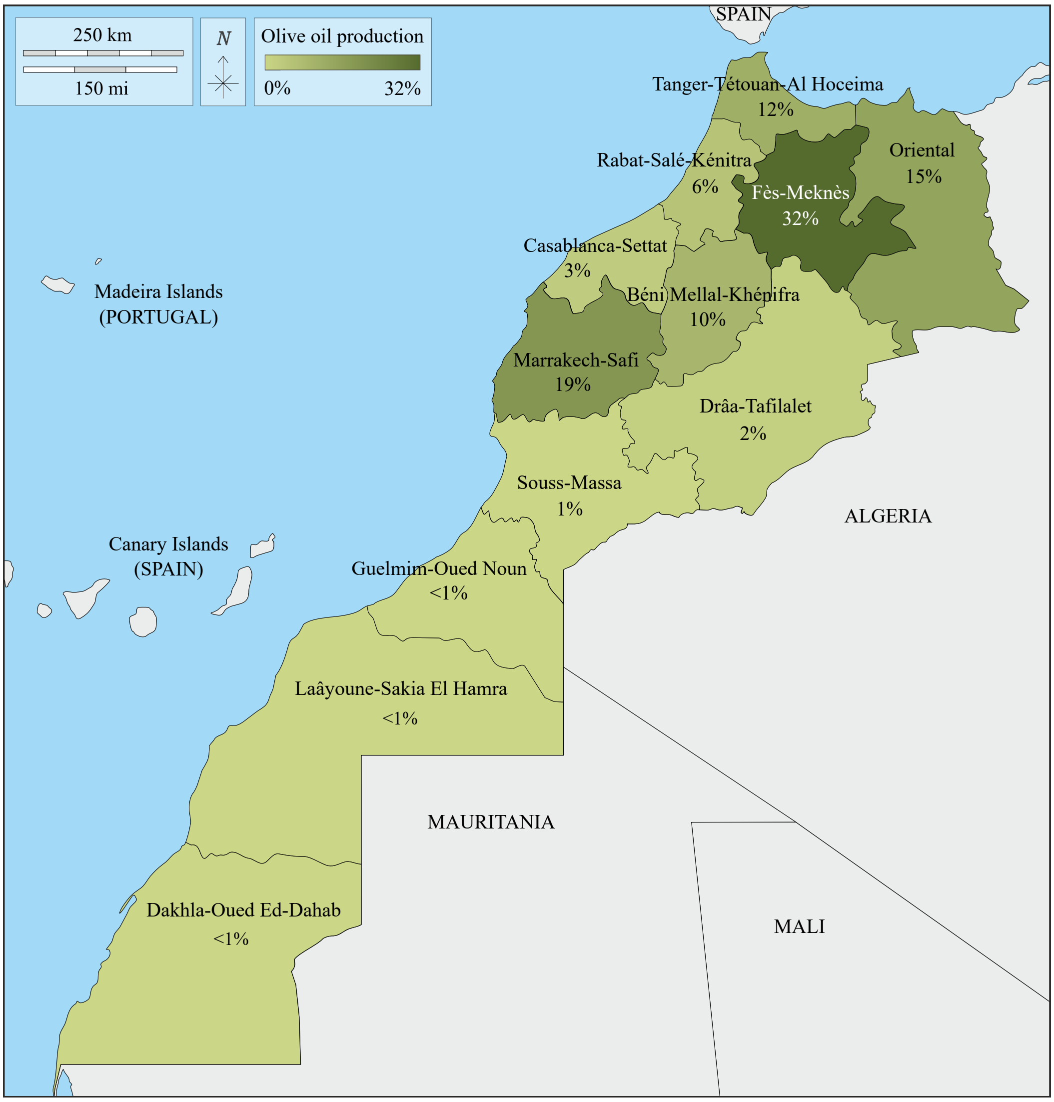

Figure 1. Main olive-growing regions in Morocco (adapted on the basis of data from the Moroccan Ministry of Agriculture, Fisheries, Rural Development, Water and Forests [3]).

In the olive oil industry, different methods are available to convert the olive fruit into virgin olive oil: a three-phase extraction process, a two-phase extraction process (continuous extraction), and a traditional press process (discontinuous) [7]. In Europe, the continuous two-phase extraction process is most widely used, mainly because of its reduced water consumption. Two-phase decanters are used in this oil extraction process, where olive pomace is massively obtained as the main by-product—a thick sludge made up of olive pulp and crushed pits [8]. However, the most commonly used process for olive oil production in North African countries is the three-phase extraction process. Three-phase centrifugal decanters allow for the separation of olive oil from three streams: two by-products—olive cake, a semisolid sludge composed of solid remains from the olives, and waste water from washing and processing of the olives [9]. The three-phase system typically produces about 20% olive oil, 30% olive cake, and 50% olive mill waste water [10], thus the weight of waste by-products is up to four times higher than that of olive oil. In the last ten years, a combination of the two-phase and the three-phase olive oil extraction processes is becoming increasingly more used in North African countries (Figure 2). In Morocco, the combined extraction system was introduced in high-capacity olive mills (>100 tonnes/day), where an additional extraction unit can lead to additional revenues [7]. The subsequent olive oil extraction process uses a three-phase decanter, which results in a dual extraction system combining two-phase and three-phase extraction processes. The olive oil is re-extracted from the olive pomace through a second decanter. The additional extraction process allows the recovery of between 40% and 50% of the olive oil remaining in the two-phase olive pomace, thus increasing profitability.

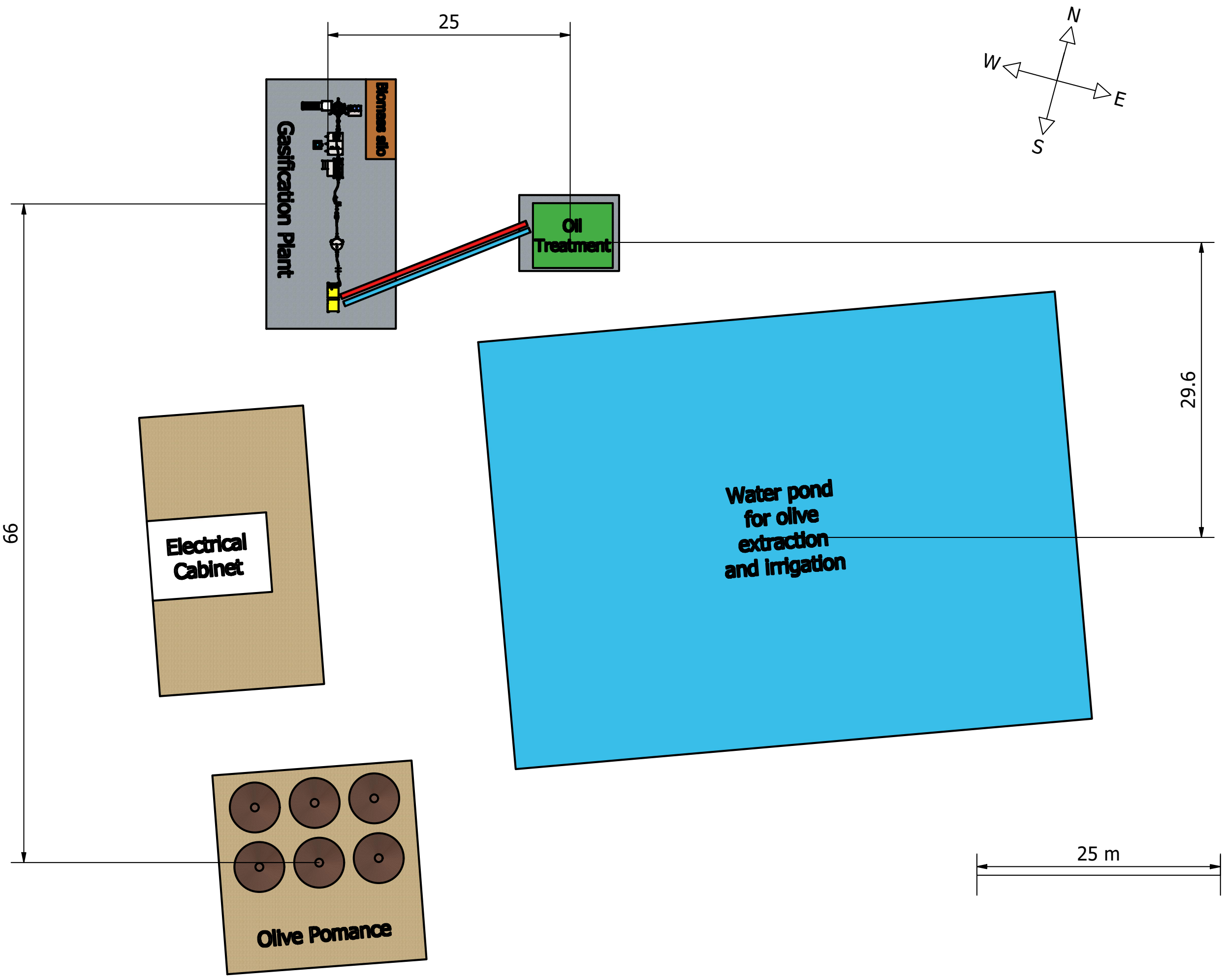

Figure 2. Top-viewlayout diagram of the different buildings and facilities that constitute the olive oil mill (dimensions in meters).

In recent years, biomass gasification has been gaining attention as a sustainable technology to promote the circular economy in the olive oil industry through decentralized combined heat and power (CHP) generation, also known as cogeneration [11–20]. Gasification is a process in which a carbonaceous solid feedstock such as biomass is partially oxidized by a gasifying agent in order to produce a gaseous fuel [21]. The resulting gas, called synthesis gas or syngas, is a mixture of combustible gases along with small amounts of non-combustible gases such as carbon dioxide and water vapor. When ambient air is used as the gasifying agent, the resulting gas mixture contains a significant amount of nitrogen and is called producer gas. In air-blown gasification, the feedstock is partially oxidized through an autothermal process, where exothermic oxidation reactions generate enough heat to sustain the endothermic reduction reactions required for producer gas formation. Downdraft gasifiers are widely regarded as the ideal choice for small-scale CHP plants (<500 kW_e) [22] that prioritize distributed generation, owing to their simple design, low investment cost, reliable operation, and ability to effectively convert various biomass feedstocks into usable gas with sufficient carbon conversion efficiency. After a subsequent conditioning stage, the producer gas can be utilized as fuel for decentralized electricity and/or heat production. Internal combustion engines are the most commonly used option for small-scale biomass gasification CHP plants due to their many advantages, such as affordability, modular design, and efficient operation at partial loads [20,22,23].

Several research works have examined the potential benefits and implications of decentralized biomass gasification CHP plants for off-grid power supply systems located in remote areas. For example, Ejiofor et al. [24] conducted a load assessment of an off-grid gasification power supply option for eastern Nigeria fueled with rice husk. The gasification system was designed and sized based on the mass flow rate of producer gas required to power the gas engine at full load; however, it was not experimentally tested. Salisu et al. [25] performed a techno-economic assessment on co-gasification of rice husk and plastic waste for off-grid power supply of a small scale rice mill in Nigeria. The co-gasification CHP plant showed promising economic feasibility with a net present value (NPV) value of $1.47 million over 15 years and a levelized cost of electricity (LCOE) value of $0.07–0.11/kWh. Sánchez et al. [26] compared different renewable energy generation solutions for the rural electrification of isolated communities in the Amazon Region, including run-of-the-river and hydrokynetic, biomass (direct burning or gasification), biofuels and vegetable oils, and hybrid (solar–wind–diesel). The gasification system was fueled with the core of açaí (an amazonic fruit) and included the implementation of a 12 km mini-grid. The demonstration plant had a power output of 80 kW_e, which was intended for demand production (processing of açaí pulp); collective demand (school, church, community center, water supply) and residential demand. In all the scenarios, gasification proved to be a more convenient option than the direct burning of the waste. Chattopadhyay and Ghosh [27] presented a techno-economic assessment of a biomass-based combined power and cooling plant suitable for off-grid rural areas. Integration of cold storage provided effective utilization of waste heat and saved additional electricity for conventional vapor compression refrigeration based cooling system. The estimated payback period of the plant, without subsidy, was estimated to be 14.4 years, and with 50% capital subsidy it was reduced to 6.6 years. Naqvi et al. [28] investigated waste gasification based off-grid electricity generation in developing countries, such as Pakistan, utilizing mixed biomass composts. Although the estimated electricity price was higher in all studied scenarios as compared to the average governmental electricity tariff, a large potential of gasification for off-grid electricity generation was reported. Ramamurthi et al. [29] performed an economic analysis on the utilization of rice residues for decentralized electricity generation in Ghana. They found that husk gasification mini-grids can be a suitable electrification solution, as their cost was lower than the average cost for grid extension of diesel mini-grids and off-grid solar systems in remote communities of Ghana. Finally, Palit et al. [30] presented a model for the financial viability of biomass gasifier power projects for enhancing electricity access in India and other developing countries. They concluded that large-scale rural electrification of remote rural areas requires an alignment of financial incentives and institutional structures to implement, operate, and sustain the projects. However, no previous work has been found that focuses on the techno-economic viability of biomass gasification CHP plants for the electrification of olive mills located in remote areas using their own by-products as feedstock.

Accordingly, the main aim of the present work is to demonstrate that biomass gasification CHP plants can be a feasible technology for electrification of off-grid olive mills in remote areas. The outline of the remainder of this work is described as follows. Section 2 introduces the case study and describes the simulation approach, as well as the experimental procedure. The data from the measurement campaign along with the results from the simulation are described in Section 3, in addition to a mass and energy balance overview. Subsequently, a detailed techno-economic assessment of the proposed biomass gasification CHP plant with a sensitivity analysis is included in Section 4 to determine the feasibility of gasification CHP plants as an alternative to diesel generators for electrification of off-grid olive mills. Finally, conclusions are drawn in Section 5.

2. Methodology

The methodological approach for this work is divided into several parts. First, the case study is presented. Next, the biomass wastes from the olive oil mill proposed as feedstock for the gasification CHP plant are physicochemically characterized. The measurement procedure of the load profile of the olive oil mill is included thereafter. Finally, the process simulation approach and governing equations for plant performance evaluation are described.

2.1. Case Study

The olive oil mill of the present case study is located in the province of Rehamna, since 2015 within the region of Marrakech-Safi, Morocco. The oil mill is located at the geographical coordinates of latitude 32°11′26.8008″ N and longitude 7°45′5.6988″ W. As shown in Figure 2, the olive oil mill consists of different buildings and facilities:

- The olive mill building, where the extraction of olive oil takes place. The olive oil mill is based on a combined two-phase/three-phase extraction process with a maximum processing capacity of around 1200–1400 kg of olives/h (about 30 tonnes of olives per day).
- The combined two-phase/three-phase extraction process requires about 20 L/min of hot water at 45 °C. The hot water is currently supplied by means of a water heater that consumes olive cake.
- A water pond is used to supply water for olive oil extraction and field irrigation.
- An open area is available for storage of olive cake.
- An olive tree plantation is used to supply the olive oil mill. The surrounding olive grove extends over an area of 20 hectares, with a tree density of 334 trees per hectare (in a frame of 6 m × 5 m).
- An open area of approximately 300 m^2 is available for installation of the biomass gasification CHP plant.
- The olive oil mill is disconnected from the utility power grid, which constitutes an off-grid system. Power supply in on-grid mode is not an economically feasible option for the mill owners.

The case study involves the installation of a biomass gasification CHP plant about 25 m away from the mill building. A biomass storage silo also needs to be placed near the gasification plant to satisfy the biomass demand.

2.2. Biomass Feedstock

The biomass wastes generated in the olive oil mill with potential use as feedstock to the gasification CHP plant come from two different activities:

- Olive oil extraction process (combined two-phase/three-phase olive oil production). This process generates vegetable water (also called olive mill waste water, and frequently abbreviated as OMWW), olive leaves and a moist solid by-product known as olive cake (sometimes also referred to as olive husk).

- The pruning activities in the olive groves produce about 2–3 tonnes of woody wastes per hectare each year.

A schematic process flow diagram of the biomass wastes and by-products generated in the olive oil mill of the present case study is displayed in Figure 3.

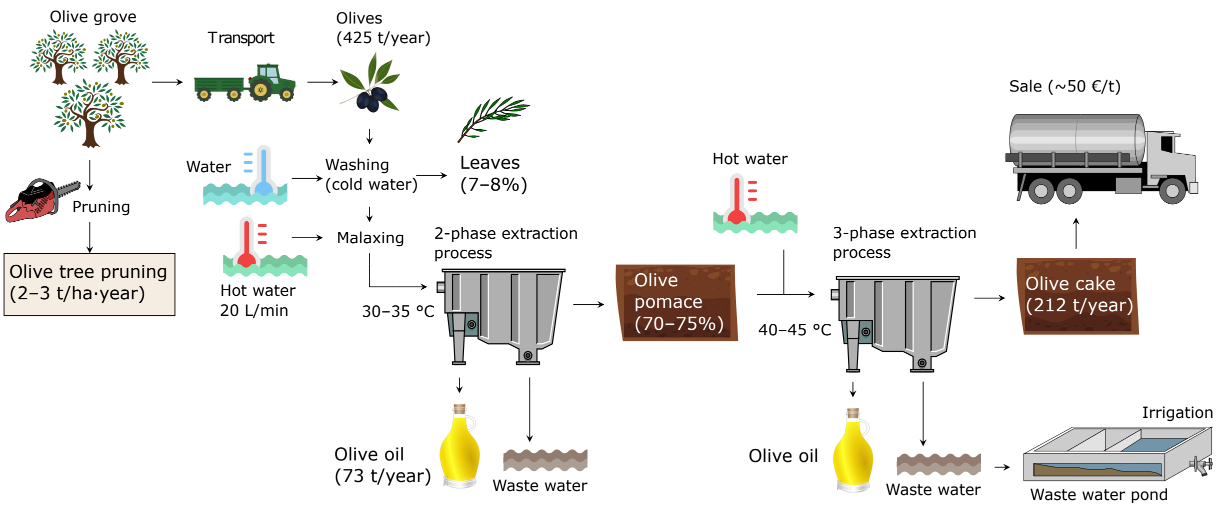

Figure 3. Process flow diagram of the wastes and by-products generated in the dual olive oil extraction process combining two-phase and three-phase decanters.

Olive cake is a pasty sludge with a relatively high moisture content (45–50%, dry basis) made up of skins, pulp residues, and fragments of pits [31]. In order to be used as feedstock in biomass gasification systems for power generation, the olive cake must be previously dried down to a moisture content of 20% or lower. The solid waste represented by the olive cake does not pose major environmental issues, given their relative ease of transportation and their use either for the extraction of the residual oil or as fuel. In Morocco, dry olive cake is used either as livestock feed or as fuel for biomass boilers.

Another important biomass waste in terms of quantity is the residual biomass from olive tree pruning activities. The amount of olive tree pruning generated per hectare is estimated at around 2–3 tonnes yearly [18]. Olive-tree pruning is composed of a mixture of woody particles and some small branches and leaves. In Morocco, this olive residual biomass is often chipped and is mainly used as a soil enhancer by spreading the pruning chips over the olive grove.

Table 1 summarizes the physicochemical properties of the biomass wastes and by-products available at the olive oil mill [18]. It is important to note that the particle size of the biomass feedstock should remain in the range of 3–51 mm for use in fixed-bed gasifiers [21]. As their particle sizes are out of specification, neither olive cake nor olive tree pruning wood can be directly fed to fixed-bed gasifiers and must therefore be pretreated through the physical processes reported at the bottom of Table 1.

Table 1. Physicochemical properties of the biomass wastes generated in the olive oil mill.

Proximate analysis (wt.%)	Olive cake	Olive pruning
Moisture content (as received)	45–50	10–15
Ash content (dry basis)	6.3	4.3
Volatile matter (dry basis)	76.4	79.4
Fixed carbon (dry basis)	17.3	16.3
Ultimate analysis (wt.%, dry basis)	**Olive cake**	**Olive pruning**
C	50.4	47.4
H	6.2	5.8
N	0.9	0.6
S	0.1	<0.1
O	36.1	41.9
Other properties	**Olive cake**	**Olive pruning**
LHV (MJ/kg, dry basis)	19.3	17.2
Ash melting point (°C)	>1200	>1200
Bulk density (kg/m^3)	715.8	347.9
Average article size (mm)	1–10	20–50
Required pretreatment	Drying and pelletizing	Chipping

2.3. Load Profile of the Olive Mill

In order to determine the optimal size of the biomass gasification CHP plant, it is convenient to previously record the power consumption of the oil mill during the milling process. In this regard, a record of the load profile during the operational time, including power transients and duration, as well as maximum and minimum power peaks, is essential. For this purpose, a network analyzer (PEL-103, Chauvin Arnoux, Foxborough, MA, USA [32]) was used to record the line voltages, the phase currents, and the total active, reactive, and apparent power of the three-phase load for a 2 day period. In the first test, the olive oil mill was operated continuously in order to detect the maximum peak power and time of the transients during the olive oil production process. The load profile is very useful in sizing the gasification CHP plant, because it allows the optimization of the nominal power of the engine–generator set. By contrast, in the second test, the olive oil mill was operated intermittently in order to determine the rated power consumption of each motor and evaluate the need for soft starters and/or variable frequency starters. When starting these motors, large consumption peaks are expected to occur, which can compromise the stability of the generator. In the case of high-power electric motors, the possibility of installing soft starters to reduce the peak current and prevent voltage drops shall be considered [33,34].

2.4. Simulation of the Downdraft Gasifier

In order to determine the biomass consumption and the volumetric composition of the producer gas, which is a key aspect in sizing the downdraft gasifier for a given the power output of the engine–generator set, a model was developed in Cycle-Tempo® [12,13,17,18]. Olive cake pellets and olive pruning chips were evaluated as biomass feedstock, with moisture contents ranging from 5% to 20% (wet basis).

The reference ambient temperature and pressure conditions for simulation of the biomass gasification plant were 25 °C and 1.013 bar, respectively. The model of the downdraft gasifier assumed that the residence time of the reactants was sufficiently high to assume that thermodynamic equilibrium was reached during the gasification process. About 7% of input energy was considered to be losses in the gasifier, with 2% corresponding to the pyrolysis stage and 5% to the oxidation-reduction stage [17]. The gasifier-generation system operated in a steady state, meaning that transient behavior was not considered, and the maximum temperature reached during the drying-pyrolysis stage was about 600–650 °C, while the temperature of the oxidation-reduction stage was set at 1000 °C [35]. To ensure complete cracking of the tars, a gasification temperature above 1000 °C was set. The maximum moisture content of the biomass feedstock for this type of gasifier is 20%, and about 5% of the carbon contained in the biomass is not transformed into producer gas [12,36]. Of this carbon, 4% is lost through the ash deposit and 1% leaves with the producer gas in the form of soot [37]. The transient period of a downdraft gasifier, which includes start-up and stabilization, lasts for about 30–60 min [20,21].

The presence of impurities in the producer gas can lead to severe fouling and corrosion issues to all mechanical equipment, which in turn involve a decreased overall efficiency and increased maintenance costs [8]. Therefore, including a producer gas conditioning unit was essential to limit the presence of impurities such as dust and tars in the producer gas before being supplied to the engine–generator set [20]. The producer gas conditioning unit aims to prevent any damage to the generator and minimize emissions of pollutants to the environment.

As shown in Figure 4, the simulation was divided into two distinct parts: the downdraft gasifier and the gas conditioning unit. The downdraft gasifier, located in the top left, models the chemical reactions that lead to the producer gas formation. The thermal losses in each section were taken into account, and air was used as a gasifying agent. The second part modeled the producer gas conditioning process. At the gasifier outlet, the gas encounters a cyclone, which separates the heaviest particles. Next, a wet scrubber cools the gas and removes tars. Thereafter, a heat exchanger finishes cooling the producer gas, which then passes through a series of fine filters before reaching the flare or the engine. This process ensures that the producer gas is thoroughly cleaned and cooled before being used as fuel for CHP in the engine–generator set. The gasification efficiency after the gas cleaning and cooling stage, commonly known as cold gas efficiency (η_{cg}) [21], was determined as follows:

$$\eta_{cg} = \frac{\dot{v}_{cg}\,\mathrm{LHV}_{cg}}{\dot{m}_f\,\mathrm{LHV}_f}, \tag{1}$$

where $\dot{v}_{cg}$ and $\dot{m}_f$ represent the volume flow rate of clean producer gas and biomass consumption, respectively.

2.5. Simulation of the Engine–Generator Set

The simulation of downdraft gasifiers fueled with biomass wastes from the olive oil industry has already been addressed and validated in previous works of the authors [8,12,13,17,18]. However, given the unavailability of commercial engines in Cycle-Tempo, the engine–generator set was modeled separately in a different simulation environment [13]. For simulation of the engine–generator set, Thermoflex® was used, which is a product of Thermoflow Inc. (Jacksonville, FL, USA) [38]. This software provides simulation and modeling tools for a variety of power plants, including combined cycles, conventional steam cycles, and repowering, as well as a wide range of power generation plants and renewable energy systems. In addition, it includes a rich library of market products [38,39].

The producer gas composition from the simulation in Cycle-Tempo was used as input data to model the engine–generator set in Thermoflex, for both olive cake and pruning. The model of the engine–generator enables the determination of the required flow rate of producer gas to generate the electric power demanded by the olive oil mill, as well as the thermal power from the exhaust gas and jacket cooling water circuit.

Furthermore, the mass flow rate of water in the jacket cooling circuit was determined through a heat exchanger model. This heat exchanger was designed to increase the temperature of the supply water required by the olive oil extraction process from 25 °C to 45 °C. To ensure a conservative scenario, we assumed key parameters for the heat exchanger, including a conservative heat loss of 15% to the environment and a pressure drop of 2% [40,41]. The jacket cooling water circuit operated within a temperature range of 70 °C to 90 °C.

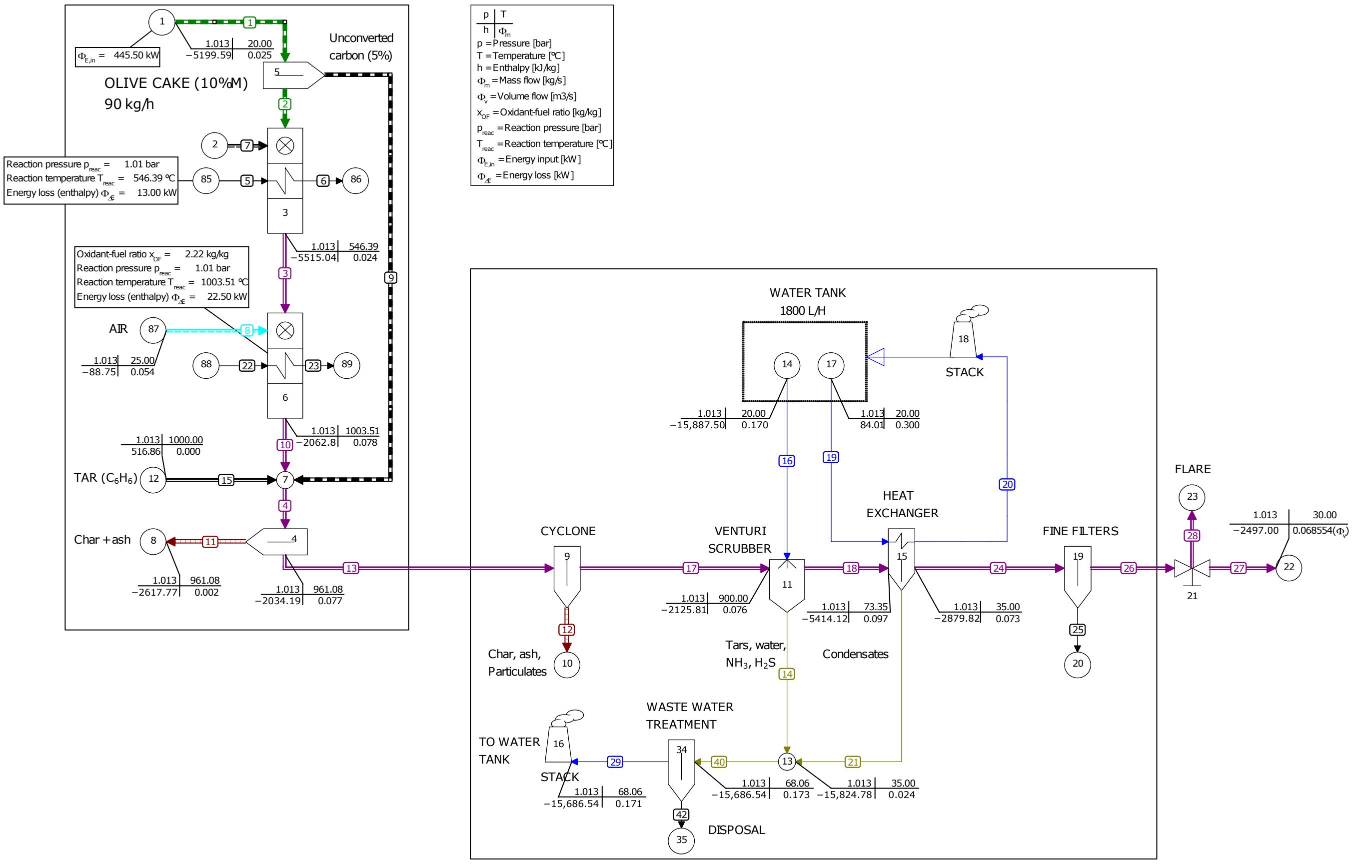

Figure 4. Process simulation flowsheet of the downdraft gasifier and producer gas conditioning unit in the Cycle-Tempo environment.

The net electrical efficiency (η_e) and the CHP efficiency (η_{CHP}) of the power generation unit were determined as given by the expressions shown below in Equations (2) and (3), respectively [16,20].

$$\eta_e = \frac{P_e}{\dot{v}_{pg}\,\mathrm{LHV}_{pg}} \tag{2}$$

$$\eta_{CHP} = \frac{P_e + P_{th}}{\dot{v}_{pg}\,\mathrm{LHV}_{pg}}, \tag{3}$$

where P_e is the net electric power developed by the engine–generator set, P_{th} is the heat flow required to raise the temperature of the water in the olive oil extraction process from 25 °C to 45 °C, and $\dot{v}_{pg}$ and LHV_{pg} are the volume flow rate and LHV of the producer gas, respectively.

Figure 5 shows the process simulation flowsheet of the engine–generator set in Thermoflex for a rated electric power of 80 kW. In this example, the engine–generator set was fueled with the producer gas from gasification of olive cake pellets with a 10% moisture content (wet basis).

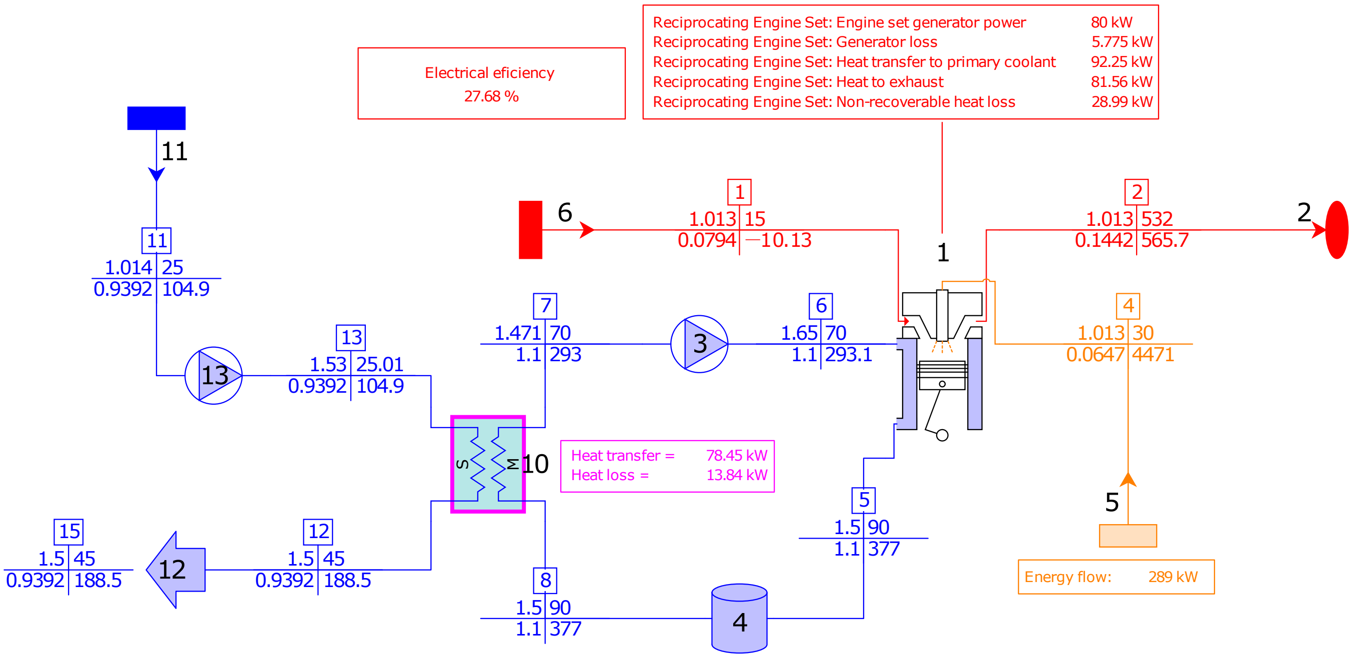

Figure 5. Process simulation flowsheet of the engine-generator set in the Thermoflex environment.

3. Results and Discussion

In this section, the results from simulation of the biomass gasification CHP plant are discussed. Initially, the load profile of the olive mill is displayed. Then, the results from simulation of the biomass gasifier fueled olive cake pellets and olive pruning chips at various moisture levels are presented, together with the results from simulation of the producer gas conditioning unit. Various performance parameters were analyzed, including biomass consumption, producer gas composition and flow rate, LHV and diverse energy conversion efficiencies. Subsequently, the results for the power generation unit are presented, which include the required producer gas flow rate, hot water flow rate, electrical efficiency and CHP efficiency. In order to provide a final overview of the energy flows and losses of the biomass gasification CHP plant, a Sankey diagram was eventually incorporated.

3.1. Load Profile

As shown in Figure 6, the power consumption of the olive oil mill during normal operation is around 12–15 kW_e. The peak power consumption is near 55 kW_e. It is also very important that the engine–generator set operates with a certain offset from the full load. Therefore, the power output of the engine–generator set should be about 80 kW_e. This is because the gasification plant has slow load dynamics, which means that it cannot adapt the generated producer gas flow rate to meet abrupt changes in the power demand of the engine–generator set. Accordingly, if sudden load surges occur, the generator will require more gas from the gasifier than the gasifier can provide, resulting in disconnection of the generator.

The relatively low value of the power factor in Figure 6 indicates that the mill does not include a capacitor bank. During the monitoring test, it can be seen that the power factor drops to values as low as 0.4, while the average value remains around 0.55. This power factor is not suitable for grid-connected operation but, in this case, the olive oil mill operates in off-grid mode. It is noteworthy that, when sizing the power lines, a power factor much lower than normally estimated should be used.

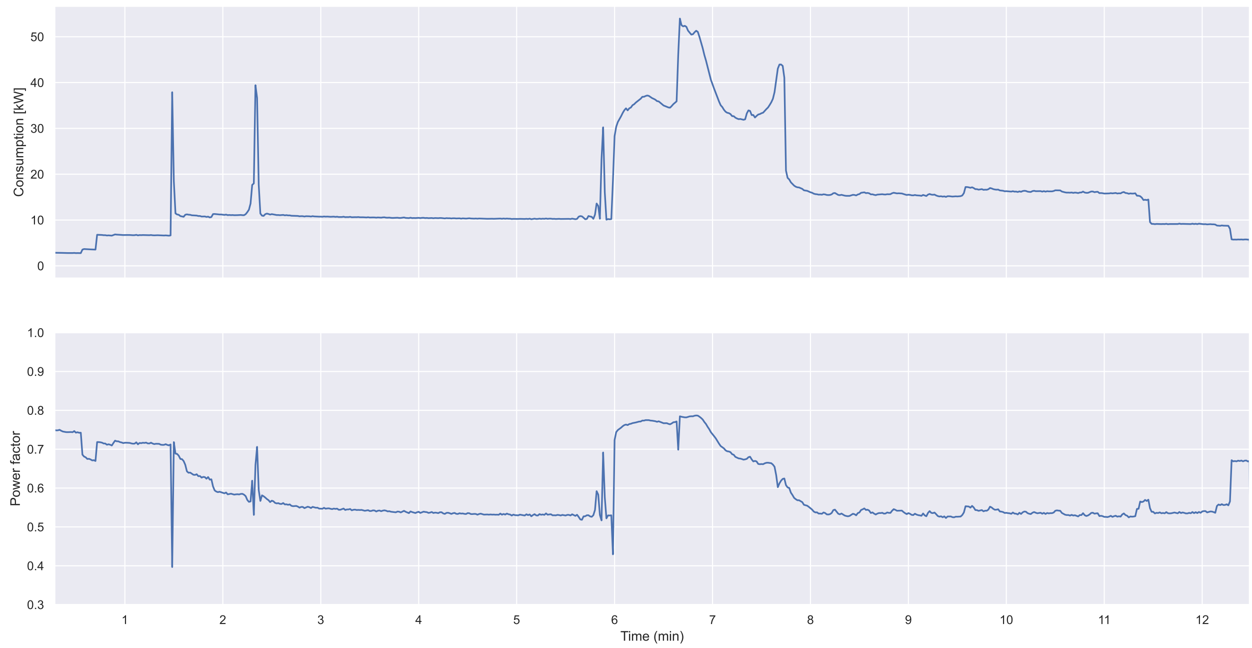

Figure 6. Power consumption and power factor of the olive mill under continuous operation.

Figure 7 shows the consumption of each part of the mill. The most critical motors from the olive oil mill are the shredder, decanter, and the centrifuge. These motors should have installed variable frequency drive to adjust the power consumption with the needed load factor, or at least a soft starter in order to decrease the peak consumption. The motor starting procedure will be described; in the first rectangle, the washer pump was started up and in the second rectangle, a no load start of the plant was carried out. The third shows a sequential start-up of the entire plant. After that, all the plant was stopped, and the fourth rectangle shows the shredder motor. Following, the next motor started was the centrifuge and soon after, the wash pump and the wash system were restarted. The final motor started was the decanter.

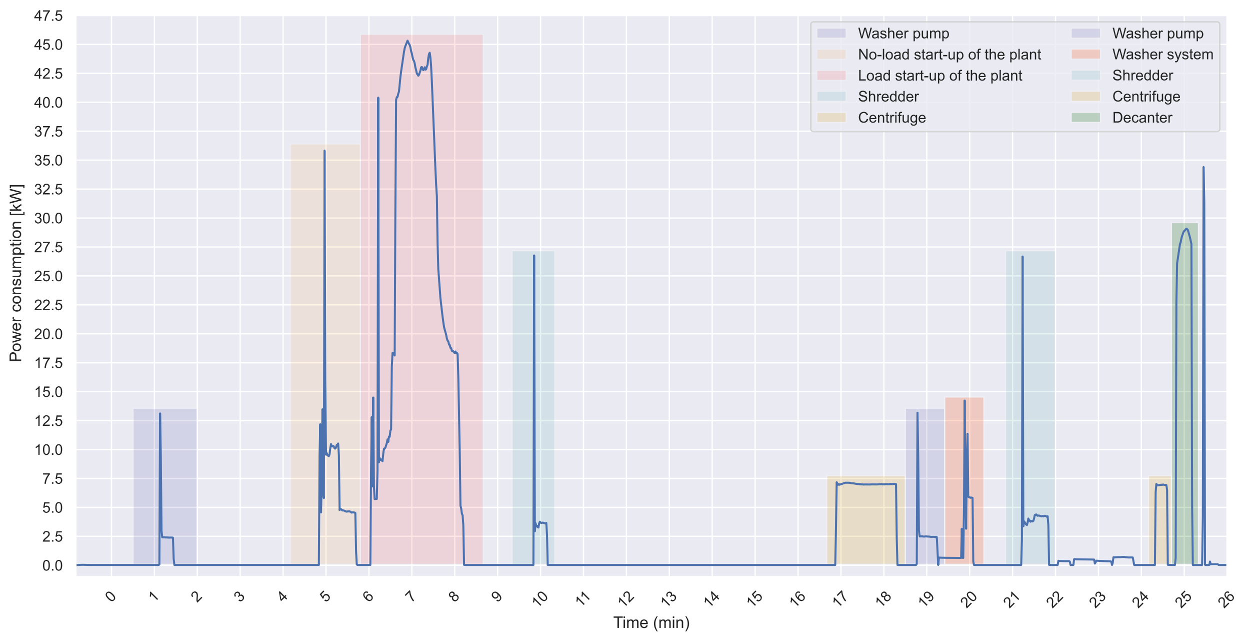

Figure 7. Power consumption of the olive mill under intermittent operation of each section.

In the case of the power factor under intermittent operation, a very irregular trend was detected, and in some points, the power factor falls to values under 0.3. This low power factor causes the engine–generator set of the olive oil mill to consume more diesel than it should under normal operating conditions with a power factor of around 0.8.

The rated power consumption of the all electric motors used during the operation of the olive oil mill are included in Table A1 of Appendix A.

3.2. Biomass Gasification

Figure 8 shows the producer gas composition from gasification of pelletized olive cake and chipped pruning for different moisture contents. The results indicate that the moisture content affects the composition of the producer gas. In particular, the H_2 and CO_2 concentrations increase with higher moisture content, whereas the N_2 concentration decreases with higher moisture content. The CH_4 concentration is virtually constant and considerably lower. It is interesting to note that the CO formation decreases significantly with higher moisture contents of the biomass feedstock. Once the volume flow rate of producer gas consumed by the engine–generator set to produce the required electric power is known, the biomass consumption needed to produce the required amount of gas can be calculated. The results are reported in Table 2, where the biomass consumption was determined by the required electrical power output and the gas yield was calculated for each biomass feedstock (olive cake pellets and olive pruning chips) at several levels of moisture content ranging from 5 to 20%. When biomass contains high levels of moisture, the water present in the biomass absorbs a significant amount of heat during gasification, which increases the feedstock consumption, decreases the producer gas yield, and affects the producer gas composition.

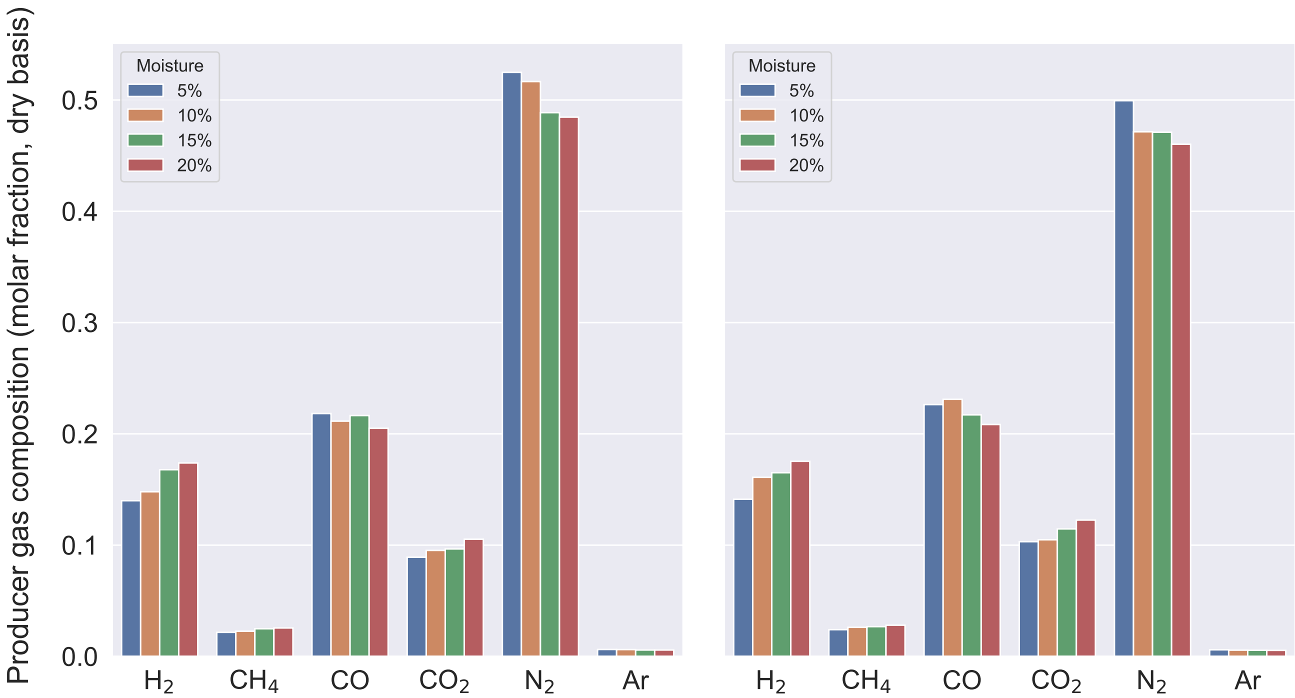

Figure 8. Producer gas composition from gasification of olive cake pellets (**left**) and olive pruning chips (**right**) for different moisture contents.

Table 2. Performance parameters of the downdraft gasifier fueled with olive cake pellets and olive pruning chips for different moisture contents.

Biomass Feedstock	Biomass Moisture Content (wt.%, as Received)	Biomass Consumption (kg/h, as Received)	Producer Gas Density (kg/Nm^3)	Producer Gas Flow Rate (Nm^3/h)	Producer Gas LHV (MJ/Nm^3)	Producer Gas Yield (Nm^3/kg)	Cold Gas Efficiency (%)
Olive cake pellets	5	81.83	1.143	235.80	5.02	2.88	67.3
	10	85.39	1.137	232.92	5.05	2.72	67.3
	15	84.87	1.115	213.12	5.41	2.51	69.7
	20	90.96	1.113	215.28	5.35	2.36	69.0
Olive pruning chips	5	87.78	1.151	228.24	5.22	2.60	69.0
	10	88.53	1.126	209.52	5.56	2.37	70.2
	15	94.50	1.130	214.20	5.46	2.26	69.8
	20	100.83	1.121	210.96	5.50	2.09	68.4

3.3. Power Generation Unit

Based on the producer gas composition results from the gasifier simulation in Cycle-Tempo, the engine was evaluated for electrical power outputs ranging from 25 kW to 80 kW in 5 kW increments. The corresponding values of the engine–generator set for each biomass feedstock (olive cake pellets and pruning chips) are presented below.

From the charts presented in Figure 9 and the data shown in Table 2, one can note that, as the moisture content of the biomass feedstock decreases, the gas consumption in the engine–generator set increases. Nonetheless, when analyzing the system from a holistic perspective, it becomes evident that, for a given power electrical power output, the biomass consumption decreases as the moisture content of the biomass feedstock decreases.

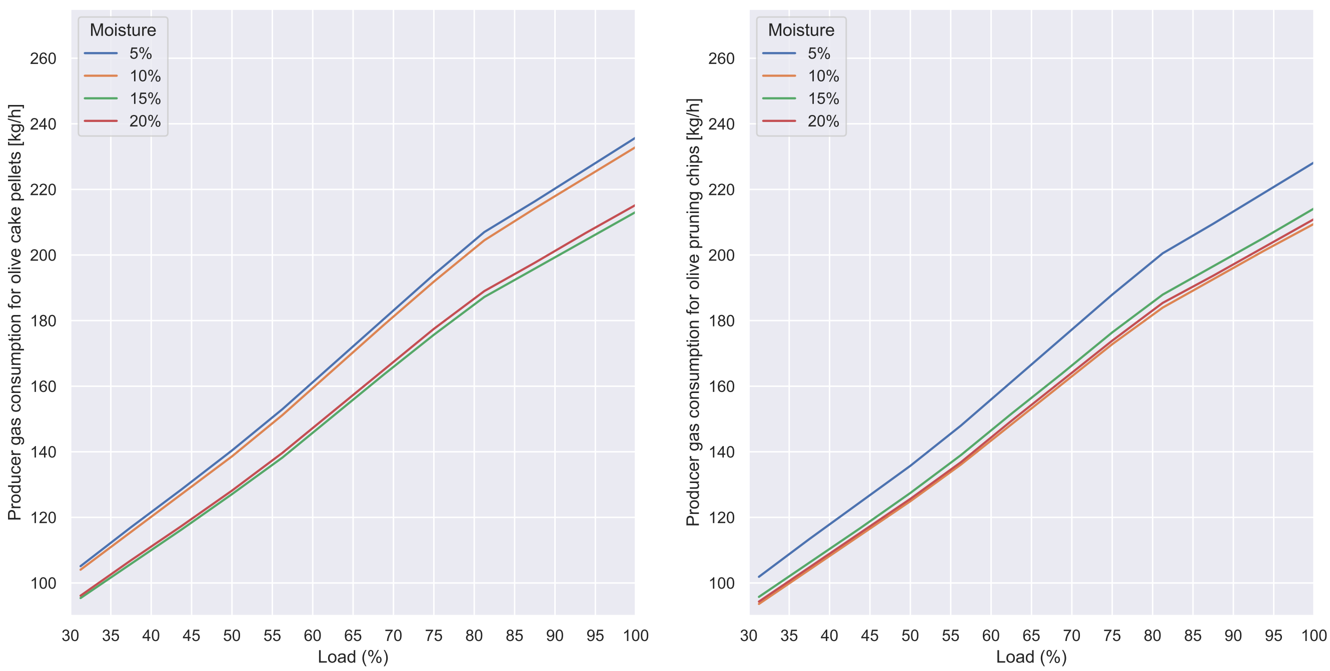

Figure 9. Producer gas consumption in the engine–genetator set for gasification of olive cake pellets and pruning chips at different moisture contents.

The minimum water consumption required for olive oil extraction in the olive mill is 21.4 L per minute. As can be observed in Figure 10, for all the load percentages of the engine generator–set operation, a flow rate of water at 45 °C higher than that required by the olive oil mill was obtained, making the gasification plant self-sufficient in delivering the thermal output. An almost linear trend can be observed, with minimum values of 25.1 L/min at 31% load and maximum values of 56.2 L/min at 100% load. It should be noted that the mass flow rate of hot water does not depend on the moisture content or type of biomass. This is because the power required to generate electricity comes from the mass flow rate and the lower heating value of the producer gas. Therefore, with biomass with higher moisture content, it will be necessary to increase the mass flow rate of the producer gas to reach the same load percentage. Figure 10 also shows that, regardless of the load percentage, the gasification CHP plant is able to supply all the hot water at 45 °C demanded by the olive oil extraction process.

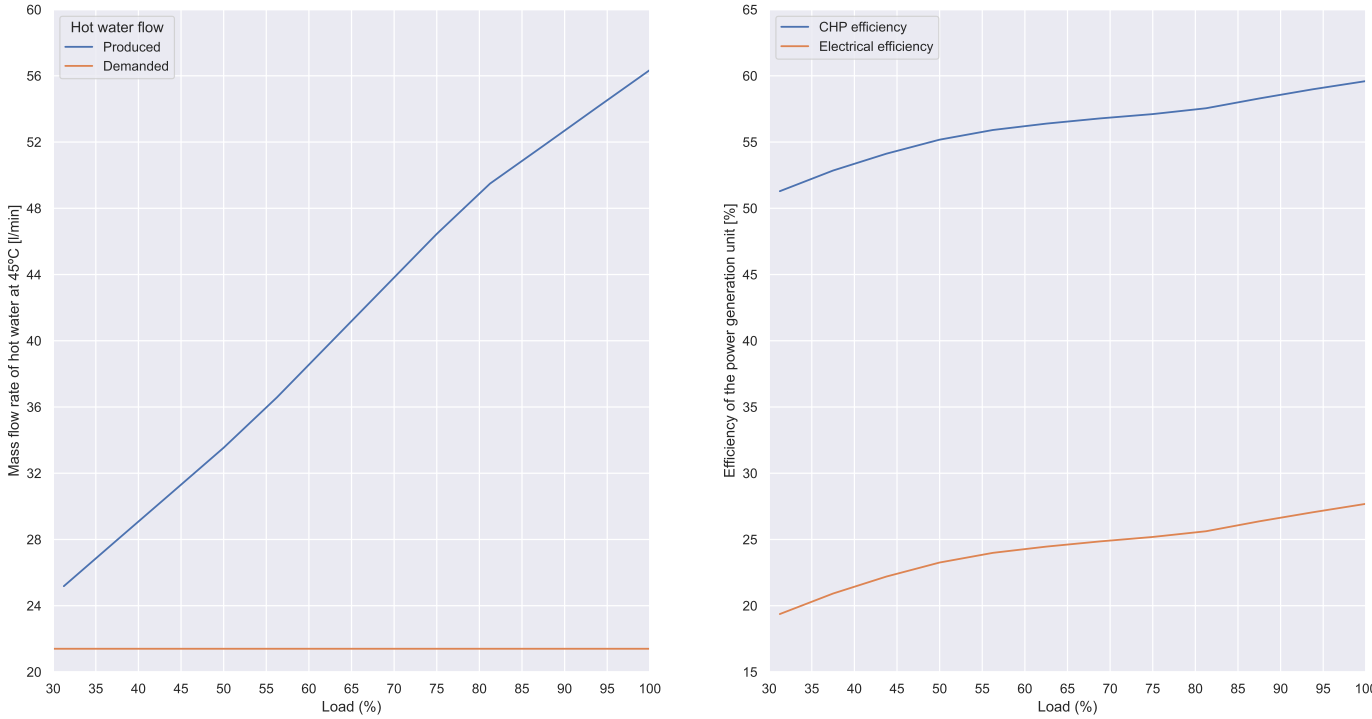

Figure 10. Hot water flow at 45 °C (**left**), electrical, and CHP performance of the power generation unit (**right**).

The electrical and CHP efficiencies of the engine–generator set were calculated and are presented in Figure 10. The results indicate that the efficiencies are not significantly influenced by the biomass type or moisture content, consistent with the findings on hot water production. The electrical efficiency ranges from 19% to 27.6% with typical values, while the CHP efficiency ranges from 51% to 59.2% at full load.

3.4. Mass and Energy Balance Overview

To conclude this section, Figure 11 shows an energy flow diagram of the gasification CHP plant for olive cake pellets with a moisture content of 10% at full load operation (80 kW_e). The diagram illustrates how the input biomass provides 445 kW, which is then fed into the gasifier. During the gasification process, there are heat losses of 47 kW, which correspond to 10.6% of the total energy input, in addition to 108 kW of thermal losses due to the producer gas conditioning, which represent about 24.4% of the input energy flow. After this stage, 289 kW are left at the input of the power generation unit, of which 86 kW are delivered as mechanical power—92 kW to cooling water, and 82 kW to the exhaust gases. The remaining 29 kW are thermal losses from the engine. Finally, the total CHP efficiency of the system is 35.6%, with an electrical efficiency of 18.0%. The energy flow diagram of the gasification CHP plant for olive pruning was not included, because a very similar distribution of the energy flows was obtained.

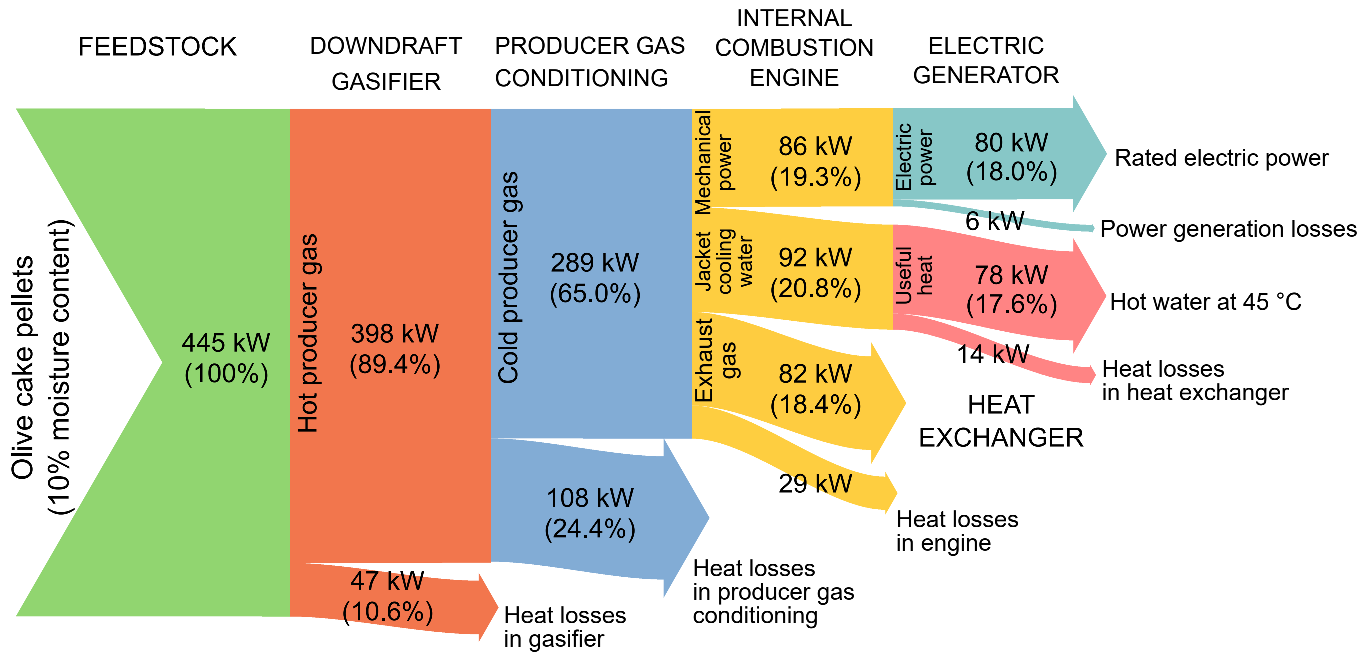

Figure 11. Energy flow diagram of the gasification CHP plant fueled with olive cake pellets with a 10% moisture content (wet basis).

4. Techno-Economic Assessment

This last section aims at demonstrating the techno-economic feasibility of the proposed biomass gasification CHP plant for an off-grid olive oil mill in the region of Marrakech-Safi, Morocco. The gasification plant consists of a biomass storage silo, a downdraft gasifier, a producer gas conditioning unit and engine–generator set fueled with the producer gas from biomass gasification. The techno-economic feasibility involves the comparison of two scenarios:

- Current scenario. A 100 kVA (80 kW_e) engine–generator set fueled with 210 L/day of diesel is used to power the off-grid olive oil mill. The engine–generator set is rented at a monthly cost of EUR 2500. A cost of EUR 1.5/L is assumed for the diesel fuel.
- Alternative scenario. A 100 kVA (80 kW_e) engine–generator set fueled with producer gas is used to power the off-grid olive oil mill. A gasification CHP plant fed with either olive cake pellets or pruning chips is used to generate the producer gas. The cost of the biomass feedstock used as fuel is negligible, as it is produced onsite.

Listed below are all the considerations and assumptions made for the economic feasibility assessment of the alternative scenario:

- The gasification plant operates continuously for 2 months (December and January) and only requires two monthly maintenance stops. The operational lifespan of the gasification plant for the economic feasibility assessment is estimated at 20 years [22].
- The cost of the gasification technology for CHP on a distributed scale is estimated at approximately EUR 3000/kW_e on a commercial scale. This value takes into account the cost of the gasifier, the producer gas conditioning unit and the engine–generator set, which for a 80 kW_e CHP plant would amount to EUR 240,000. For comparison, Alves et al. [42] estimated a slightly higher power capital expenditure of EUR 3486/kW_e for a pilot-scale gasification plant (model PP20, All Power Labs, Berkeley, CA, USA) processing 12.6 ton/h of municipal solid waste in Portugal. The power capital expenditure considered in this work is also slightly below the value of EUR 3544/kW_e declared by Yassin et al. [43] for a gasification CHP plant fueled with municipal solid waste in the UK, although the reaction configuration was different (fluidized bed), as well as the power generation unit (combined cycle gas turbine). By contrast, a considerably lower investment cost of USD 2580/kW_e was reported

by Salisu et al. [25] for an off-grid gasification CHP plant fueled with rice husk and plastic in Nigeria. In the work of Cardoso et al. [44], a lower capital cost of EUR 1760/kW was assumed for the case of a 100 kW_e gasification CHP plant fueled with forest biomass, while an even lower capital cost of EUR 1320/kW was assumed for the case of a 1000 kW plant as a result of economies of scale in the deployment of a larger unit. Thus, a capital expenditure of EUR 3000/kW_e seems to be a conservative, and yet reasonable, assumption for the biomass gasification CHP plant considered in this work.

- The civil works amount to EUR 15,000, while the biomass pretreatment cost (pelletizer or chipper) is estimated at around EUR 20,000. The fixed and installation costs of the gasification plant (civil works, electrical and mechanical assemblies) are estimated as 10% of the total investment. As a result, the turnkey cost of the gasification CHP plant amounts to roughly EUR 302,500.
- The gasification plant was installed for self-consumption of renewable electricity during the whole olive oil production period, leading to a substantial reduction in the energy cost for the olive oil mill. An average electricity price of EUR 0.15/kWh was considered.
- In addition to the renewable power generation for self-consumption by the olive oil mill, the gasification CHP plant produces two waste heat streams from the gas engine: jacket cooling water and exhaust gases. Since the return temperature of the cooling water from the combustion engine is close to 90 °C [45], it can be used to supply the hot water demanded by the virgin olive oil extraction process. The use of this residual hot water makes it possible to abandon the current practice of burning olive cake, which can later be sold at about EUR 60/t.
- Biomass gasification produces biochar, a carbonaceous solid by-product that can be used as soil amendment in olive groves [20]. Biochar provides several benefits to the soil, including improving water holding capacity, preventing erosion and leaching, supporting plant growth and increasing crop yield, and constituting a long-term carbon sequestration in the soil, thereby reducing greenhouse gas emissions [20]. Biochar production affects the profitability potential of the gasification technology in the olive oil sector. The average sale price of this by-product from gasification in international markets ranges between EUR 150 and EUR 500/t [46–48]. However, as the potential use of this by-product is yet unknown to most farmers and there is still no consolidated market in Morocco, its future price was estimated at EUR 80/t.
- The discount rate (interest rate) was set at 10% [22,25].

The economic feasibility assessment of the gasification plant was performed in accordance with the standard methods for the financial appraisal of investments. These methods include the net present value (NPV), internal rate of return (IRR), simple and discounted payback period (SPB and DPB, respectively) and levelized cost of electricity (LCOE) [22,23,25,45,49,50]. The economic feasibility assessment of the gasification plant within 20 years of the operation period is shown in Figure 12. The economic feasibility assessment considers a 30% subsidy on the initial investment from the Moroccan government. The return on investment is less than 8 years, which lies within the typical range of payback periods (5–10 years) of bioenergy projects [25,49]. The NPV of the biomass gasification CHP plant is EUR 145,085. In other words, after the break-even period, the project can make a profit of EUR 145,085; this is equivalent to 68.5% accumulated profit based on the initial capital investment.

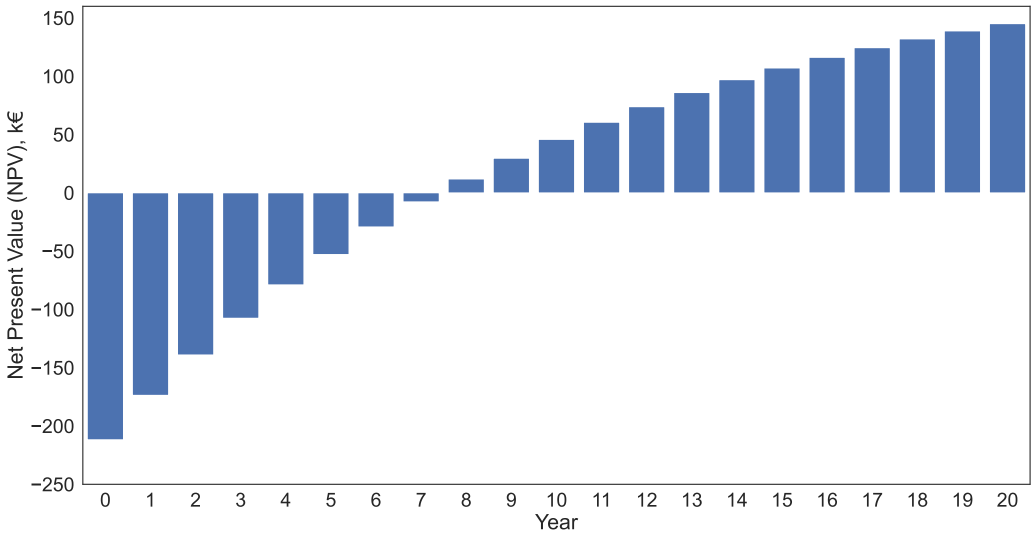

Figure 12. Results of the techno-economic assessment for the baseline scenario.

Figure 13 examines the impact of variations in the percentage of subsidy from the Moroccan government on the initial investment, as well as the electricity price and biochar price. The LCOE was not considered in the sensitivity analyses for the prices of biochar and electricity, because it is not affected by these parameters. The electricity price is a variable of extreme importance significantly affecting the viability of the projects as it is a rather uncertain parameter due to the energy market price fluctuations and subsidies, both highly dependent upon political decisions [50]. The NPV considers all costs necessary to maintain the system fully operational. Among the parameters with the highest impact on the NPV are the discount rate and the percentage of subsidy on the initial investment.

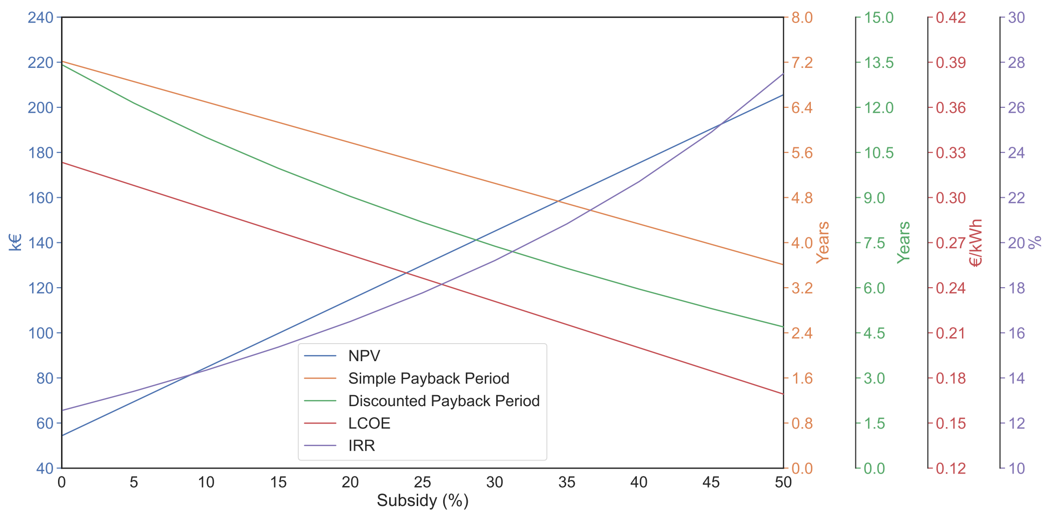

Figure 13. *Cont.*

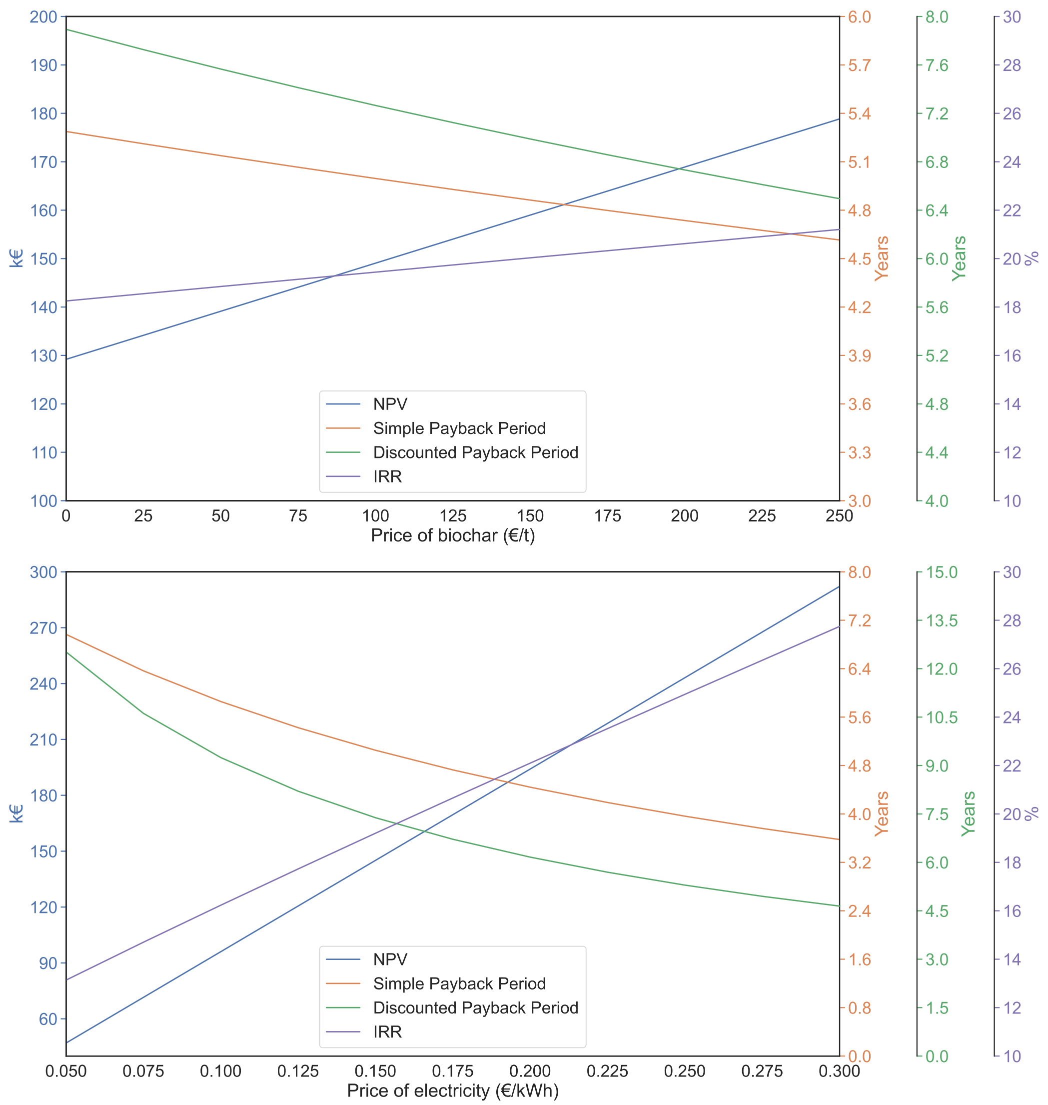

Figure 13. Sensitivity analysis for variations of the percentage of subsidy on initial investment (**top**), biochar selling price (**center**) and electricity price (**bottom**).

The percentage of subsidy on the initial investment is the most influential variable, since the DPB is reduced from 13.5 years with no subsidy to only 4.6 years with a 50% subsidy. The IRR is found within a range of values between 12–28%. The project can withstand an interest rate as high as 20.8% for a 30% subsidy on the initial investment. The LCOE ranges from EUR 0.32/kWh to EUR 0.17/kWh for subsidy percentages of 0% and 50%, respectively. The biochar price does not have as much impact as the percentage of subsidy on the return of investment. There are also no significant variations in the IRR. The NPV ranges from EUR 129,000 to EUR 178,000 for EUR 0/t and EUR 250/t sale prices of biochar, respectively. Finally, focusing on the electricity price, strong impacts are observed, reducing the DPB from 12.5 years to 4.8 years as the electricity price increases from EUR 0.05/kWh to EUR 0.30/kWh. A strong dependence with the electricity price is also found for the IRR and NPV.

5. Conclusions

This work has demonstrated the techno-economic viability of installing a biomass gasification CHP plant for the electrification of an off-grid olive oil mill in Morocco. The biomass gasification CHP plant has a total CHP efficiency of 35–40%, with an electrical efficiency of 15–20%. The gasification CHP plant exhibits better performance parameters if fueled with olive cake pellets compared to olive pruning chips.

The installation of a biomass gasification CHP plant in the olive oil industry can have a significant impact on its self-sufficiency, allowing for the transformation of the biomass waste generated during the olive oil production process into valuable by-products. This technology enables the conversion of biomass waste into a producer gas that can be used as an energy source for the olive oil extraction process, reducing the dependence of olive oil mills on external energy sources. Furthermore, potentially profitable by-products are generated during the gasification process, such as biochar, which can be used as a soil enhancer. This not only reduces the amount of waste generated by the mill but also adds economic value to these by-products, resulting in additional incomes.

The profitability assessment of the gasification CHP plant for the baseline scenario shows that the plant can generate a 68.5% accumulated profit based on the capital investment with a 30% subsidy from the Moroccan government, with a payback period of 7–8 years for 2 months of continuous operation. The findings suggest that biomass gasification CHP plants can be an economically viable and sustainable solution for electrifying off-grid areas in Morocco and other regions with similar conditions.

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Abbreviations

The following abbreviations are used in this manuscript:

Symbols	
$\dot{v}_{pg}$	Volume flow rate of the producer gas [$m^3 \cdot s^{-1}$]
LHV_{pg}	Lower Heating Value of the producer gas [$kJ \cdot kg^{-1}$]
LHV_f	Lower Heating Value of the biomass feedstock [$kJ \cdot kg^{-1}$]
$\dot{m}_f$	Consumption of biomass feedstock [$kg \cdot s^{-1}$]
P_e	Electric power developed by the engine–generator set, [kW]
P_{th}	Heat flow required to raise the temperature of the water in the olive oil extraction process from 25 °C to 45 °C [kW]
η_e	Net electrical efficiency of the power generation unit
η_{CHP}	Net thermal efficiency of the power generation unit
Abbreviations	
CHP	Combined heat and power
LHV	Lower heating value [$MJ \cdot kg^{-1}$]

OMWW	Olive mill waste water
NPV	Net Present Value [k€]
DPB	Discounted Payback Period [Years]
IRR	Internal rate of return [%]
LCOE	Levelized Cost of Energy [EUR/kWh]

Appendix A. Electrical Loads in the Olive Oil Mill

The individual electrical loads are detailed below in Table A1. These electrical components mostly include three-phase electric motors used in the olive oil extraction process.

Table A1. List of electrical loads in the olive oil mill.

Component	Working Regime	Motor Type	Power (kW)	Voltage (V)	cos φ	Current (A)	Freq. (Hz)	RPM
Belt conveyor feeder washer	Intermittent	Belt conveyor motor (×1)	1.1	220/380	0.83	4.5/2.6	50	2825
		Leaf blower motor (×1)	1.1	220/380	0.79	4.5/2.6	50	2825
		Scraper cleaner motor (×1)	0.37 0.44	230/400 276/480	0.74	2.02/1.17 2.02/1.17	50 60	1370 1644
Washer	Intermittent	Water pump & fan motor (×1)	2	220/380	0.79	9.1/5.3	50	2825
		Filter motor (×1)	0.37	230/400 276/480	0.81	1.93/1.11 1.93/1.11	50 60	1370 1644
		Vibrator motor (×1)	0.75	230/400	0.74	2.9/2.2	50	1370
Shredder	Intermittent	Screw elevator motor (×1)	1.0	380	0.77	1.97	50	1380
		Screw feeder motor (×1)	0.5	230/400 265/460	0.71	3.06	50	1380
		Tami motor (×1)	0.5	230/400	0.74	2.9/2.2	50	1370
		Shredder motor (×1)	18.5	230/400	0.91	56/32	50	2920
Malaxer	Continuous	Screw motor (×3)	0.75 0.8	230/400 265/460	0.75 0.8	3.5/2 3.5/2	50	1385 1685
		Dough pump motor (×1)	0.75 0.9	230/400 276/480	0.78	3.5/2.03 3.5/2.03	50	1380 1656
Decanter	Continuous	Decanter motor (×1)	11	220/380 240/420	0.9 0.86	50/29 48/26	50	2865 2895
		Cleaner motor (×1)	0.37	230/400 276/480	0.74	1.93/1.11 1.93/1.11	50	1370 1644
		Vibrating motor (×1)	0.18	220/380 240/415	0.78	2	50	3000
		Pomace screw motor (×2)	1.5	230/400 240/415 230/400 260/440 280/480	0.79	6.17/3.55 5.92/3.42 6.17/3.55 6.17/3.55 6.17/3.55	50	1120 1420 1680 1680 1680
		Oil transfer centrifuge motor (×1)	0.75	230/400	0.8/0.7	3.28/1.14	50	1435
		Water pump motor (×1)	0.75	230/400	0.8/0.7	3.28/1.14	50	1435
Centrifuge	Continuous	Centrifuge motor (×1)	7.5	230/400	0.74	32.6/18.7	50	1370
		Oil pump motor (×1)	0.37	230/400 276/480	0.81	1.93/1.11 1.93/1.11	50 60	1370 1644

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