

Article

Thermochemical and Economic Analysis for Energy Recovery by the Gasification of WEEE Plastic Waste from the Disassembly of Large-Scale Outdoor Obsolete Luminaires by LEDs in the Alto Alentejo Region (Portugal)

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Featured Application: Energy recovery of agroforestry waste mixed with industrial plastic waste through gasification processes.

Abstract: The recovery of urban waste is a social demand and a measure of the energy-environmental sustainability of cities and regions. In particular, waste of electrical origin, waste of electrical and electronic materials (WEEE) can be recovered with great success. The plastic fraction of these wastes allows their gasification mixed with biomass, and the results allow for producing syngas with a higher energy potential. This work allows for obtaining energy from the recovery of obsolete materials through thermochemical conversion processes of the plastic waste from the disassembly of the luminaires by mixing the said plastic waste in different proportions with the biomass of crop residues (olive). The gasification tests of these mixtures were carried out in a downstream fixed-bed drown daft reactor, at temperatures of approximately 800 °C. The results demonstrate the applied technical and economic feasibility of the technology by thermal gasification, for the production of LHV (Low Heating Value) syngas with highest power energy (more than 5 MJ/m³) produced in mixtures of up to 20% of plastic waste. This study was complemented with the economic-financial analysis. This research can be used as a case study for the energy recovery through gasification processes of plastic waste from luminaires (WEEE), mixed with agricultural biomass that is planned to be carried out on a large scale in the Alentejo (Portugal), as a solution applied in circular economy strategies.

Keywords: co-gasification; WEE-wastes; industrial-wastes; plastics wastes; luminaires recovery; biomass; syngas; waste-management recovery; techno-economic analysis

1. Introduction

Energy sustainability based on the use of clean and decarbonized energy sources has become a priority and strategic objective for countries around the world. Currently, countries with environmental sensitivity are considering satisfying their current energy demand by applying environmental and energy integration strategies that allow the use of new sustainable energy models based on renewable



and more efficient energy. The welfare state of the societies of the future that allow future sustainable economic and social development must be oriented towards preserving the environment and oriented towards sustainability in terms of energy and waste recovery, within the strategies promoted by the EU (European Union) towards circular economy environments [1]. The change in the energy and production paradigm is a reality that implies a change in the energy model, replacing carbonized fossil fuels and oil derivatives with new forms of energy. On the one hand, for the development of a country, high investments are required in relation to the generation of electrical energy. This can be achieved by being more environmentally friendly and seeking more efficient and sustainable forms of clean renewable energy. On the other hand, policies aimed at the recovery and reuse of agricultural, forestry, municipal or industrial waste is a priority framed in the strategies of sustainable recovery and the circular economy [2]. Oil and its derivatives are still considered as the main source of energy, but this situation can be reversed in a short period of time. Researchers of various nationalities are developing new technologies aimed at replacing a reasonable part of fossil fuels with alternative fuels, thus following the new world order that seeks to rethink the ways of obtaining and producing electricity to preserve the environment [3]. Agricultural and forest biomass is a very interesting energy resource due to its high content in (LHV) Low Heating Value and therefore allows its energy conversion through thermochemical processes, such as gasification, with great success and with low environmental impact, contributing to the reduction of the serious problem of global warming [4].

Today, we find material waste of industrial or urban origin with a high potential for recovery or reuse, either as construction materials or in the form of energy. The high specific heat and energy potential makes them perfectly usable as fuel directly or as a raw material for the manufacturing of other fuels [5]. Biomass is a very interesting resource, in some cases with a high calorific power by thermochemical conversion (HLV), and, therefore, it can be converted into different forms of energy that also contribute to the relief of well-known environmental problems associated with global warming [6–9]. There are high-impact scientific studies that recommend thermochemical recovery as a very appropriate technology for the revaluation of materials through an energy conversion process for the production of syngas [9,10].

Since the oil crisis of 1973, Refuse-Derived Fuel (RDF) have emerged as possible low-cost replacement fuels. Over the past 10 years, there has been increasing interest in the mining, metallurgical and energy sectors in RDF due to economic and environmental problems. Furthermore, the European energy policy aimed at waste treatment and management has given a new impetus to the use and recovery of non-hazardous waste [11]. These RDF fuels have a biogenic carbon content of around 50–60% and therefore can contribute significantly to reducing CO₂ emissions and increasing the use of renewable energy [12,13]. On the other hand, plastic waste is, today, one of the most important problems on an urban and industrial scale. To perform energy recovery from plastics, there are two main types of processes to convert waste to energy and fuel: thermochemical and chemical processes [14]. These operations are generally called 'waste-to-energy'. The thermochemical conversion of biomass consists of several stages that include gasification, pyrolysis, hydrothermal process, and hydrolysis into sugars [15].

Thermal gasification could perfectly be a solution for the energetic recovery of the plastic material of the collected luminaires. This technology used partial oxidation at high temperatures, generally in the range of 800 to 1000 °C [16]. The idea would be to mix plastics, coming from luminaires with agricultural or forestry biomass, in adequate proportions to produce a high-quality synthesis gas rich in H₂ [17,18]. The plastic fuel mixture (RPF), and the wood pellets were tested in different research works, with very positive results, in the use of synthesis gas in an air-blown fluidized bed gasifier (FBG). GE (gas engine) [19]. With temperatures ranging from 700 to 940 °C and variable equivalency ratios (ER) of 0.3–0.5, noting that some of the most important characteristics of the gas product, including the lower heating value (LHV) and concentration levels of tar, were very satisfactory [20]. The results of the gas composition reveal that the concentration trends varied for the gases of the product CO,

H₂ and hydrocarbons, affecting the type of raw material, while the same trends are observed for the concentrations of CH₄ and tar [21].

The studies on the joint gasification of plastics made it possible to analyze the high energy value of the syngas produced, the production of hydrogen obtained in these processes being especially interesting [22]. It is possible to obtain up to 5 times more hydrogen content in the combined gasification of biomass mixed with plastics wastes than in similar processes using pyrolysis at 800 °C [23,24]. And up to seven times more compared to pyrolysis processes at 900 °C [25,26].

More than 27 million tons of waste plastics are generated in Europe each year, representing a considerable potential resource. Plastic waste is a global environmental problem, which reached 36 Mtons in 2019 and causes a very negative environmental impact on ecosystems.

In the present work, the possibility of recovering energy from waste electrical and electronic material (WEEE) was studied, specifically the plastic recovered from luminaires dismantled by the electricity supply company in the Alto Alentejo, Portugal area [27]. The experiments were carried out with a mixture of plastic waste from the Syntra-type luminaire, luminaires mostly replaced in the processes of replacement by light and energy-efficient (LED)-type luminaires in this region of Portugal. The objective is trying to take advantage of and recover these plastic residues mixed with agro-food industry biomass from the olive seed mixed in different percentages. An economic feasibility study was also carried out for the installation of a gasification unit.

Obsolete Luminaires

The EU (Europe Union) is promoting policies that support technological renewal of luminaires, consisting of the massive replacement of obsolete luminaires that use discharge technologies (Metal Halide (HM) or high-pressure sodium vapor (VSAP)) for LED luminaires [28]. They use new, more efficient light and energy-efficient (LED) technology [29–31]. Most are obsolete luminaires that will have to be replaced in the short or medium-term by LED luminaires. This will generate a quantity of waste, to which a recycling solution would have to be found. In Europe (EU28), there are more than 1.6 million km of illuminated streets that consume approximately 35 TWh annually at a cost of EUR 4 billion for public authorities [32].

The luminaires, according to the Portuguese Environment Agency, are classified as waste electrical and electronic equipment WEEE [33,34]. Taking into account this classification and considering that the plastic fraction of these residues can be up to 80% by weight, it is necessary to look for solutions that allow for incorporating these residues in new industrial processes or energetically valorizing them without causing environmental impact [35].

According to data from EUCOLIGHT—The European Association of Collection and Recycling Organizations for Lamps and Lighting and AMBILAMP SA, 8843 tons of WEEE waste for recycling were collected in Spain alone, 72.5% more than in 2018. Collecting 6286 tons of waste lighting and 2557 tons of waste electrical and electronic material (WEEE). In total, almost 8843 tons of waste were collected and treated in the last year compared to 5126 in 2018, representing an increase of 72.51%. This represents a record 29,000 tons of recycled lamp waste (equivalent to approximately 220 million luminaire units). This activity only with recycling reverts to multiple environmental benefits, including avoiding the emission of millions of tons of CO_2 into the atmosphere [36].

According to the Portuguese Waste Management Association, there is an exponential growth in the collection of WEEE waste. Portugal in 2018 had a collection of 119,558 tons, which is equivalent to approximately 26.734 million units of WEEE electrical and electronic equipment [37].

The results of the collection of WEEE have increased in weight and in the number of units collected in the last five years. In 2018, there was an increase of more than 17,886 tons compared to 2017. It is possible to observe that the large amount with a tendency to increase WEEE comes from the collection of luminaires. Luminaires that largely correspond to large-scale replacement processes and changes by new LED technologies. Where the percentage of plastic waste is approximately 30% by weight [37,38].

2. Materials and Methods

The gasification tests were performed with a mixture of plastics and agro-food industry biomass, mixed in different percentages. Biomass residues originate from the extraction of oil from the olive seed. Both fuels were previously characterized and then gasified, under the following conditions: 100% olive seed; 10% WEEE (plastic) + 90% olive seed and 20% WEEE (plastic) + 80% olive seed [7]. For WEEE gasification tests, manual classification was necessary with the help of magnets to remove any small metals that may be present, as these materials could damage the reactor. In the joint gasification, the mixture between olive biomass and WEEE was tested to investigate the composition of the synthesis gas and its heating value at a temperature between 800 and 960 °C [39].

The plastic waste from the study luminaires was provided by the EDP (Energías do Portugal) (Portugal) [40], the company in charge of promoting the "Projeto Illupub-Projeto para la Melhoria energetic e Eficansa Iluminasao Publica" in charge of the electricity supply and dismantling of obsolete luminaires to replace them with LED luminaires in Alto Alentejo (Portugal) (Figure 1) [41]. The process consists of disassembling the luminaires by separating the plastic parts and removing most of the metal present. The most polymeric part is rectified and passes through magnetic mats for the best use of the metal part. Process waste is sent to landfill [42].



Figure 1. (a) Geographical distribution of waste electrical and electronic material (WEEE) collection areas based on local collection companies. (b) Study area for collecting the Syntra Luminaire in Alto Alentejo (Portugal) and details of the Campo Maior Zone. (Source: Projeto IlluPub and AMB3e).

With the information provided by EDP, it has been possible to count the total number of light points of conventional luminaires (sodium, mercury and metal Halogen discharge lamps (HM) in the Alto Alentejo area (Portugal) (45,160). The results are shown in Table 1. Of the total number of luminaires analyzed, 78% corresponded to the luminaire model, mainly installed, model Syntra, approximately (35,593).

Municipalities Alto Alentejo	Number of Luminaires to be Replaced by LEDs	Potentially Replaceable Syntra Model Luminaires
Elvas	6651	5121
Campo Maior	2253	1757
Arronches	1699	1172
Monforte	1354	1029
Fronteira	1414	1131
Avis	1838	1562
Ponte do Sor	6758	5339
Alter do Chao	3323	2293
Gaviao	2436	2192
Crato	1857	1448
Nisa	2809	2388
Castelo Vide	1679	1494
Marvao	2405	1780
Portalegre	6159	4866
Sousel	2525	2020
Total	45,160	35,593

Table 1. Total number of luminaries inventoried in the Alto Alentejo area by municipalities (Source: IluPub).

2.1. Fuel Analysis

The agro-food industry biomass used in the tests was olive seed. This material was supplied by a company located in the Alentejo, which collects and treats olive pomace, removing most of the oil and moisture and produces pellets.

Polymeric residues from urban luminaires were added to the mixtures. This residue was used to improve the thermal gasification process in terms of improving the calorific value of the gas.

For the use of these residues, it was necessary to dismantle, sort and grind the parts of the luminaires manually. The fractions used for the gasification process were between 1 and 4 cm. The metallic fractions in the waste were removed manually with the aid of a magnet, to prevent damage to the equipment [43].

The residues were analyzed in terms of final analysis, a thermogravimetric analyzer and a higher heat value (HHV) [44,45]. The description of the analyses and equipment used are presented in the following sections.

2.1.1. Final Analysis

The final analysis was carried out to determine the elemental composition of the biomass (C, H, N, S and O content), using a ThermoFisher Scientific Flash 2000 CHNS-O analyzer (See Table 2) [46].

Table 2. Technical characteristics of the ThermoFisher Scientific Flash 2000 CHNS-O analyzer (Source:ThermoFisher).

Designation	Technical Features Source
Thermo Scientific™ FLASH 2000 CHNS/O Analyzers	Instrument configurations—Fourteen; Detector—Thermal conductivity detector (TCD); External interface—RS 232 serial line; Instrument control—Eager Xperience for Windows™; Power supply—230 Vac; 50/60 Hz; 1400 VA;

2.1.2. Thermogravimetric Analysis

Thermogravimetry analyses were performed to obtain the moisture content, volatile matter and the fixed carbon content combined with ash. A PerkinElmer STA 6000 type measuring equipment

(see Table 3) was used using a nitrogen flow of 20 mL/ min for the inert atmosphere and a temperature growth rate of 20 °C/min.

Table 3. PerkinElmer STA 6000 Technical Characteristics—Thermogravimetric Analyzer–(Source:PerkinElmerhttps).

Designation	Technical Features Source		
	Balance resolution 0.1 ug;		
	Balance measurement range Up to 1500 mg;		
	Temperature range 15 °C to 1000 °C Start experiments below room temperature to capture complete moisture and solvent evaporation		
PerkinElmer STA 6000— thermogravimetric analyzer	Heating rate Ambient to 1000 °C 0.1 to 100 °C/min, cooling rates from 1000 °C to 30 °C under 10 min Forced air and chiller to achieve fastest cool down for higher productivity, temperature metal standards such as Indium and Silver calibration		
	Temperature accuracy < ± 0.5 °C, temperature < ± 0.5 °C reproducibility,		
	Calorimetric data Accuracy/precision ±2% based on metal standards, Thermocouples PT-PT/Rh (Type R)		
	Autosampler Optional, 45-position for unattended operation 24/7		
	Hyphenated techniques Combine with MS or IR analyzers MS or IR connectivity capabilities, allow the analysis of evolved gases		

The thermogravimetric analysis was obtained for each one of the analyzed materials, measuring the variation of the mass with respect to the temperature and observing the inflexion points of the derivative of the mass with respect to the time factor [47,48].

2.1.3. Determination of the Higher Heating Value (HHV) or Gross or High Calorific Value and (LHV) Low Heating Value

A digital pump calorimeter (model IKA C2000) was used to measure the calorific value of the samples (Table 4) [49]. The calorific value of the biomass was calculated according to the methodology used in similar studies [50]. Studies have been carried out to predict the calorific value of biomass from the results of the analysis. The HHV (highest heating value) or LHV (lowest heating value) of the biomass were predicted by immediate analysis [51–54]. For the LHV calculation, Ozyuguran uses a similar model and the results were compared with those obtained in this article [55].

Designation	Technical Features Source
IKA C 200-System—calorimeter	Max. Measuring range—40,000 J; Dynamic measurement mode 25 °C—yes; Isoperibol 25 °C—yes; Dynamic measurement time—approx. 8 min; Measurement time isoperibol—approx. 17 min; Dynamic Reproducibility (1 g NBS39i benzoic acid)—0.1% RSD; Reproducibility Isoperibol (1 g benzoic acid NBS39i)—0.1% RSD; Max. Working temperature—25 °C;

Table 4. Technical characteristics of IKA C 200-calorimeter analysis.

2.2. Gasification Tests

The gasification tests were performed on an AllPowerLabs PP20 Power Pallets—a gasifier with a power of 15 kW (Table 5 and Figure 2), a common downdraft reactor that is combined with an electric power generator and an electronic control unit. [56]. The equipment consists of a storage silo, where the biomass is simultaneously dried by recirculating the hot gases produced in the reactor. Fuel is supplied from the top as the air moves downward, being preheated through contact with the reactor's walls.

Designation	Technical Features Source
	Power rating (W or kW)—15 kW at 50 Hz, 18 kW at 60 Hz;
	Available energy type (mechanical, thermal, electrical) Electrical (18 kW), thermal (20 kW);
	Description of biomass source(s)—Dense biomass such as nut shells and wood chips;
	Biomass input requirements (kg per hour)—0.33 m ³ every 3 h;
	Combustor type—Internal combustion engine;
	Biomass conversion efficiency (%)—Upwards of 35%; 1.2 kg of feedstock to 1 kWh of electricity;
	Lifecycle—More than six years, with routine maintenance;
AllPowerLabs PP20 Power Pallet	Performance: Continuous power rating: 15 kW@50 Hz/18 kW@60 Hz; Sound level @ 30 feet: 85 dB(A);
	Biomass consumption: 1.2 kg/kWh, 2.5 lbs/kWh; Run time per hopper fill (at 250 kg/m ³ fuel density): 10 h at 5 kW; 5 h at 10 kW, 3 h at 15 kW Max. continuous operation: >12 h, Startup time: 10–20 min;
	Operating Conditions: Ambient temperature: 5–40 °C (40–100 °F); Humidity: 5–95% RH, Installed footprint (without ash vessel or grid tie): 1.36 × 1.36 m (53.5 × 53.5 inches);
	Site requirements: Well-ventilated protected from rain and direct sun
	Additional safety handles and warnings are included on the product;Complementary technical systems: Performance of this product is improved with another technology (e.g., Cookstoves and

Table 5. Technical characteristics of PP20 Power Pallet-(Source: AllPowerLabs PP20 Power Pallet).



Wind-blocking skirts); Combined heat and power (CHP) module.

Figure 2. Scheme of operation of the system and detail of the reactor. (**a**) General description of gas pipes and routes. (**b**) Details of the gas samples' extraction site of the Valoriza—Polytechnic Institute of Portalegre reactor exit (Portugal). (Source: Power Pallet technician manual (PP20/v1.09) and own elaboration.

Ash collection is done in a separate tank in the lower part of the reactor, while the synthesis gas produced passes through a cyclone to remove the fine particles. The produced gas is also cleaned through a filter composed of biomasses of various granulometries and can be subsequently collected for analysis or injected directly into the generator. Condensate matter is collected at the bottom of the biomass filter.

The Otto cycle internal combustion engine burns the gas providing kinetic energy for the generator. In order to start the engine according to the manufacturer's instructions, the temperature in the reactor's lower part (reduction zone) must be at least 400 °C.

The tests were carried out using agro-food industry biomass, olive seed, in co-gasification with the polymeric residues, varying between 10 and 20% of incorporation. At the beginning of the experiment, 100% olive seed was used, which was the standard biomass for the tests. Synthesis gas was analyzed

During the entire gasification process, the temperature and pressure at the top (oxidation zone) and bottom of the reactor (reduction zone) were constantly controlled and monitored. In addition, the pressure of the biomass particle filter, the air flow at the inlet and the fuel consumption were carefully monitored during the tests. Likewise, the internal pressure in the reactor was measured using pressure probes located at the top at the reactor and on the particulate filter (see Figure 2). The coals were deposited at the bottom of the reactor and the tars are retained in the biomass filter. The power generator (3 kW) was running constantly and without stopping for 2 h.

2.3. Methodological Description of Economic Viability

An economic analysis will now be carried out using the usual financial and economic indicators to justify the feasibility of installing the complete equipment (gasifier–engine–generator, includes installation). We will estimate an investment of \in 1200/kW for the complete electrical energy production equipment with a direct sale to the Electricity Distribution Company in Portugal (EDP). The gasifier was based on a type of fixed bed, mounted with a gas engine and with the possibility of future installation of a module for the recovery of thermal energy connected to the engine.

It was considered that the electrical energy purchased or consumed through the national energy network, managed by (EDP) by the company that is going to exploit the gasifier generating equipment. It will be complemented with the energy produced or sold as a result of the gasification generator process and will be sold to the same company that manages electricity in Portugal (EDP) at the legally established price. The analysis carried out was based on the results of the previous gasification tests, using the amount of the necessary plastic waste and biomass, the calorific value of the synthesis gas and the income that the company will obtain from the use of the electrical energy produced through gasification. This waste is currently sent to the landfill, where the amount currently paid for the deposit is $9.9 \notin/t$, with an annual adjustment of 1.12% per year. The cost of electricity is approximately $0.16 \notin/kWh$ [44].

Taking into account the type of gasification unit that was used during the tests, it is estimated that the cost of installing similar equipment will cost \in 1200/kW. For calculations of the use of the gasifier, was consider that the company works from Monday to Friday, for 12 h (Table 6) [59].

Parameters	
Gasifier Type	Fixed bed
Operation time (h)	12
Days per month	25
Days per year	300
Raw material	
WEEE plastic waste from luminaires	
Landfill treatment price (€/ton)	45.00
The annual increase over landfill price (%)	1.25
Agricultural biomass (olive)	
Pellet price (€/ton)	30
Economic parameters	
Investment in the gasifier/engine/alternator Includes installation (€/kW)	1200
Price of electricity produced (€/ kWh)	0.20
Price of electricity consumed (€/ kWh)	0.16
Operating costs (% of investment)	5%
Life time (years)	10

Table 6. Parameters for the economic analysis of the feasibility of installing a gasification plant. (Source: self-made).

Next, the economic-financial analysis for the gasifier installation for the three cases studied, was made. (90% olive + 10% WEEE), (80% olive + 20% WEEE) and (100% olive). The evaluation of the period of return on investment (payback) (PP), net present value (NPV), internal rate of return (IRR) and the average cost of index benefit (IB_mC), for each case was also made [60–63].

2.3.1. Net Present Value (NPV)

NPV, also called "capital value", consists of updating the casw-flow "Ct" (the difference between income and expenses for each period analyzed.) of the project for the different periods to an estimated discount interest rate "i" (discount rate or calculating interest). Assuming, as usual, the same interest rate, "i", for all periods, N, generally equal to each other and equal to the calendar year. We considered the first time period, the first year of amortization, as year 1. So "t" takes values between 1 and N. We consider the time period t = 0 is related to the investment during the design and construction phase of the gasifier. The NPV considers this discount rate "i" (calculated as WACC—weighted average cost of capital) during the useful life of the project, giving the annual cash flows at current values. NPV can be equated as [63]:

NPV(i, N) = -K +
$$\sum_{t=1}^{N} \frac{Ct}{(1+i)^{t}}$$
 (1)

where "i" is the financial discount rate, "Ct" is the annual cash flow (Income minus expenses) each year, and "N" is the total number of years. The time period t = 0 is related to the investment during the design and construction phase of the gasifier.

The NPV represents the net profit generated by the project, obtained by financial equivalence at time zero. If the NPV is greater than zero, the project is viable for that interest rate. It is, therefore, a necessary condition although it does not have to be sufficient.

The WACC is calculated based on the cost of capital and the cost of debt (borrowed capital), which allow for determining the discount rate applicable to cash flows to calculate the NPV. The WACC is given by [64]:

WACC =
$$\left(\frac{E}{E+D}\right)K_{e} + \left(\frac{D}{E+D}\right)K_{d}(1-T)$$
 (2)

where "E" is the market value of the equity, "D" is the market value of the debt, " K_e " is the cost of equity, " K_d " is the cost of debt and "T" is the marginal tax rate.

2.3.2. Internal Rate of Return (IRR)

The internal rate of return (IRR) or rate of return that is the type of update or discount that nullifies the NPV. Hence, it can also be called the marginal efficiency of capital. The rate is internal because it does not depend on factors exogenous to the investment.

In this way, the IRR is calculated by obtaining the rate, r, which meets the following equation [60,65]:

NPV(IRR, N) =
$$-K + \sum_{t=1}^{N} \frac{Ct}{(1 + IRR)^{t}} = 0$$
 (3)

Only those projects that meet the "feasibility" condition will be viable: r > i, where i is the interest rate that corresponds to the "cost of capital". The higher r, the better the investment.

The calculation is usually laborious unless some computer program is used. Although it is not difficult to do it with the help of a calculator and following an iterative process of testing until you reach the solution.

There has been a lot of controversy about which method is preferable: the NPV or the IRR. However, more than a preference problem, the interesting thing is to find the reconciliation of both methods, if possible, in the event that they can reach different results when we compare several projects.

2.3.3. Payback Period—PBP

The Recovery Period is the number of time periods it will take for the investment to recover with the cash flows generated by the project. If call K the investment made and C_T the cash flows in each period, the recovery period, t, will be the one that enforces the expressions.

$$K = \sum_{t=1}^{N} \frac{Ct}{(1+i)^{t}}$$
(4)

2.3.4. Index Benefit Average Cost—IBmC

The Average Benefit Cost Index discriminates the lower risk investments associated with the requested investment [60]. The equation is:

IBmC(i, N) =
$$\frac{1}{n K} \sum_{t=1}^{N} \frac{Ct}{(1+i)^{t}}$$
 (5)

where "K" is the investment made.

3. Results

Table 7 shows the steps taken to disassemble the luminaires, as well as the respective weights for each material present in them. In Figure 3, olive seed (**a**) and luminaire residues (**b**) after pre-treatment are shown.

Designation	Mass Fraction (g)	Picture
Closed Public Light	8624.1	
Glass and Porcelain (difficult degradation)	0.1654	
Electronics (difficult degradation)	3906.4	
Metal Components (difficult degradation)	2756.4	
Plastic Components (easy degradation)	1795.9	

Table 7. Measurement by the weight of the Syntra luminary decompressed.



(a) Olive seed Lignocellulosic fuel

(b) PE lights Polymeric fuel

Figure 3. Raw materials used for joint gasification in the reactor. (**a**) Olive biomass residues (pellet). (**b**) Plastic waste. (Source: self-made).

The quality of the producer gas is affected by fuel characteristics (composition, size, and moisture content). Compared with great-sized fuels, reduced-size fuels produce a better-quality producer gas. However, smaller sizes have a tendency to produce a higher pressure loss inside of the reactor, due to a lower bed porosity. Moisture content in the feedstock also affects the quality of the producer gas. Fuels with lower moisture content yield better producer gas quality. Table 8 presents the proximate, ultimate and calorific analysis [66].

Analysis	Parameters	Units	PE lights Polymeric Fuel	Olive seed Lignocellulosic Fuel
	Moisture	%	0.2	9.4
Duranianata	Volatile Matter	%	78.3	66.5
Proximate	Fixed Carbon	%	20.9	19.7
	Ashes	%	0.6	4.4
	Nitrogen	%	0.46	1.7
	Carbon	%	81.89	53.4
Ultimate	Hydrogen	%	12.37	7.5
	Sulphur	%	1.92	0.1
	Oxygen	%	2.76	32.9
LHV (Low Heating Value)		MJ/kg	41.8	20.5

Table 8. Fuel analysis. (Source: self-made).

The results from LHV of olive seed is similar to another studies [67,68] and also typical of dry pellet wood biomass [69]. The LHV obtained in the case of the polymeric fuel, 41.8 MJ/kg, was double the value of olive seed, having results similar to those reported by other studies [70]; in fact, the amount of carbon present in polymeric fuel is responsible for the high energy value [71]. This observation leads us to think about the interesting use of these materials as fuel with high energy power. On the other hand, it is interesting to note that plastic waste has a high energy, which can affect equipment that is not well designed for it. Due to its high LHV, to avoid damage to the equipment and following the manufacturer's instructions, the co-gasification process is used for waste with a high calorific value.

3.1. Analysis of the Syngas Produced

The gasification parameters and results obtained for the tests carried out are presented in Table 9. The results demonstrate the feasibility of this type of reactor to gasify the studied fuels. In fact, hydrogen, carbon monoxide and methane are the main gases responsible for the LHV of synthesis gas.

		Tests						
Parameters	Units	100% Olive	10% Plastic & 90% Olive	20% Plastic & 80% Olive				
Olive	%	100	90	80				
Plastic	%	0	10	20				
T _{max} oxi	°C	720	708	758				
T _{max} red	٥C	515	547	526				
Fuel Feeding	Kg/h	5.2	6.9	5.0				
Air Inlet	m ³ /h	11.21	14.17	12.04				
ER	-	0.27	0.26	0.28				
V _{Tars}	ml/h	146.8	127.96	11.54				
Chars	Kg/h	0.161	0.123	0.133				
CO ₂	%	9.914	9.775	10.839				
C_2H_4	%	0.479	0.618	0.427				
C ₂ H ₆	%	0.122	0.138	0.042				
N ₂	%	55.99	56.97	58.749				
CH ₄	%	2.073	2.556	1.799				
СО	%	18.480	17.744	18.852				
H ₂	%	13.369	12.711	13.045				
Experimen time	s	4.940	5.708	5.610				
V _{Syngas}	m ³ /h	15.73	19.10	14.51				
Q Biomas	Kg/h	5.20	6.90	5.00				
LHV	MJ/m ³	5.280	5.422	5.225				

Table 9. Gasification tests of plastics and olive biomass pellets.

After a first analysis of the results obtained, it is possible to demonstrate that the gas produced contains a greater quantity of carbon monoxide than hydrogen. This situation occurred in all experiments of the mixtures tested. A lesser percentage of methane appears in the syngas. The high percentage of Nitrogen is because co-gasification has been carried out with atmospheric air [72].

For the blank test, accomplished only with olive seeds, the results present an expected rich syngas in the first analysis. In water gas shift reaction, CO and H_2O are consumed, whereas CO_2 and H_2 are synthesized. The consumption rate is higher than the formation rate for CO, especially at higher temperatures [73], because CO is consumed to form hydrogen and methane in the water–gas shift and methanation reactions:

$$CO + H_2O \iff CO_2 + H_2$$
 (water-gas shift)

 $2CO + 2H_2 \iff CH_4 + CO_2$ (Methane reforming)

The amount of H_2 is higher than the other experiments with polymeric mixtures. This observation is due to the relatively high experimental temperatures during the experiments. Besides, the H_2 concentration increase may also be related to the promotion of tar-reforming reactions [74,75]. During the gas chromatographic analysis, small amounts light hydrocarbons, such as C_2H_4 and C_2H_6 , were observed. Note that, under similar experimental conditions, for the non-catalytic gasification of olive seed, higher temperatures increased the formation of hydrogen and light hydrocarbons such as methane [76]. The cracking of tars can contribute to the increase in the CH_4 and to the consumption of CO_2 ; however, both can be consumed through the enhancement of methane reforming, in the gasification process with the rise in temperature [77]. This behavior may be the reason for the decreasing tendency observed in the values of CO_2 concentration, compared with the other experiments. Olive seed gasification provides a gas with a high energy density (5.3 MJ/m³) and similar properties than wood gas. However, our obtained values on LHV are lower than those found by Borello et al. [78], but higher than those reported by Vera et al. [79].

An interesting aspect of the presented results is that the addition of 10% plastic to the olive seeds leads to an increase in the calorific value of the syngas regarding the experiences of 100% olive seed and 20% plastic, because of the capitalization in the production of hydrocarbons and mainly the methane [80]. The increase in the temperature, namely the gasification temperature, is the responsibility of the greater presence of volatiles that the plastic bring fuel [81]. However, the temperature in the 10%experiment (708 °C) is not so high compared with the additional experiments; this aspect is related to the literature and indicates that, as the gasification temperature increases, the concentration of the resulting hydrogen and carbon conversion efficiency increases [25]. Meanwhile, the content of CH_4 increased slightly with the decrease in temperature. The main reason for the decrease in CH_4 content in the product gas is the increasing proportion of gasification gas and the decreasing proportion of pyrolysis gas [82]. Another reason was attributed to the thermal decomposition of methane at a temperature greater than 700 °C [83]. On the one hand, the produced tars were further cracked into gas at the higher temperature. The increase in temperature can rapidly activate the carbon atom and breakdown the carbon chain in the aromatic ring, reacting with the CO_2 to produce gas [84]. This aspect can be observed in the 20% plastic experiment, which has a smaller amount of hydrocarbons in gas produced and also a smaller amount of tars, compared to the 10% plastic experiment.

The H_2 concentration is similar in all the experiments performed, and the above result indicates that the concentration of H_2 is not only dependent on the temperature but also on the type of feedstock and gasifying media. The main reason for the increment of H_2 concentration is supposed to be the result of the chemical breakdown (thermal cracking) of heavy hydrocarbons, which favors molar fraction of the permanent gases, such as H_2 and CO, at an elevated temperature. What happens with the experiments with 20% plastic agrees with the experiments conducted by Xiao et al., Kim et al. and Cho et al. [85–87].

The increase in polymeric residue favors an increase in temperature. As the reactor temperature increased, concentrations of H_2 and CO increased. The reason for the increase in the concentrations of H_2 and CO can be mainly explained by Le Chatelier's principle. According to this principle, the increase in temperature favors not only the reactants in exothermic reactions, but also the products in endothermic reactions [88]. Therefore, the endothermic reactions in gasification, such as the water–gas shift reaction and Boudouard reaction, will contribute to increasing concentrations of H_2 and CO at higher temperatures. With increasing temperature, however, the concentration of hydrocarbons and tars content decreased in producer gas, due to active thermal cracking. These aspects lead to a decrease in LHV. The very low tar content and the high LHV (5 MJ/m³) of the producer gas, such as internal combustion engines.

3.2. Energy Analysis

The Gasifier–Generator equipment was running for 2 h (120 min), even though, for the first twenty minutes, it was running in torch mode without connecting the 3-kW motor, connected to the alternator (see Supplementary Materials). With the values of the electrical energy produced by the alternator, we can determine the kWh/kg, that is, the energy produced per kilogram of agricultural biomass and plastics mixture. We can calculate the efficiency of the gasifier from the average volumetric flow of air, with an anemometer. For the calculation of syngas production during gasification tests, an anemometer is used that is connected to the air inlet. Moreover, with the quality of the syngas produced, it is possible to obtain the amount of N_2 present. Another important factor is related to the amount of N_2 present in the air. The data are applied in Formula (2), and the is volume calculated.

$$V_{\text{syngas}} = V_{\text{air}} \times (0.781/N_2) \tag{6}$$

where: V_{syngas} volume of syn-gas produced Nm³/h; V_{air} is the volume of air introduced in Nm³/h; 0.781 is the percentage of nitrogen in the air; N_2 is the percentage of nitrogen in the syngas.

Taking advantage of the fact of calculating the volume of synthesis gas, the equivalence ratio was calculated. The equivalence ratio is commonly used to quantitatively indicate whether a fuel oxidant mixture is rich, lean, or stoichiometric. The equivalence relationship is defined as:

$$ER = (A/F)_{stoic}/(A/F)$$
(7)

where: ER is the equivalence relation; (A/F)_{stoic} is the ratio of air/fuel mass under stoichiometric conditions; (A/F) is the same mass ratio but under the experimental conditions that were adopted.

Therefore, for fuel-rich mixtures, ER > 1, and for lean fuel, ER < 1, and for stoichiometric mixture, ER = 1.

Gasifier efficiency, total efficiency and engine efficiency are calculated as follows [89]:

$$\eta_{gas} = (V_{syngas} \times LHV_{syngas}) / (m_{fuel} \times LHV_{fuel})$$
(8)

$$\eta_{\text{tot}} = E_{\text{el}} \times 3.6 / (\text{LHV}_{\text{fuel}} \times m_{\text{fuel}})$$
(9)

$$\eta_{\text{eng}} = ((\eta_{\text{tot}} \times \eta_{\text{gen}})/\eta_{\text{gas}}) \tag{10}$$

where: η_{gas} is the efficiency of the reactor-gasifier; LHV_{syngas} is the lowest heating value of the syngas, in MJ/m³; m_{fuel} is the fuel mass used during the test, in kg; η_{tot} is the total efficiency; LHV_{fuel} is the lower heating value of the fuel or inlet mixture, in MJ/kg. E_{el} [kWh] is the electrical energy generated; η_{eng} is the motor efficiency (0.3); η_{gen} is the efficiency of the generator (0.8).

3.3. Results of the Technical-Economic and Financial Analysis

Next, the results of the technical-economic-financial viability analysis obtained for the three cases analyzed will be presented [90].

3.3.1. Results of the economic-financial analysis (100% olive-pellet)

The results for a mixture introduced into the gasifier formed by 100% olive biomass and applying Formulas (6), (8)-(10) are shown in Table 10.

	Units	Results	Olive (100%)
LHV _{bio}	MJ/kg	20.50	20.50
LHV _{syngas}	MJ/m ³	5.280	
V _{syngas}	m ^{3/} h	15.73	
η_{gas}	%	0.78	
η _{eng}	%	0.30	
η _{gen}	%	0.80	
η_{tot}	%	0.29	
biomass	kg/h	5.20	5.2
		Total ton/month	1.56
		Total ton/year	18.72

Table 10. Gasification results and yields for 100% olive biomass (Source: self-made).

Therefore, from Formula (9) obtains the electrical energy produced for one hour 8.65 kWh/h, totaling the total annual energy produced at 31,145.40 kWh/year and the income from annual energy sales, according to which the expected annual operating hours it will be $6229.00 \notin$ /year.

With this power, one will have to install a 10-KW gasifier, so the necessary investment (K) according to Table 10 will amount to 12,000.00 € (applying a 23% VAT in Portugal); the total investment would be 14,760.00 euros. On the other hand, this type of clean energy production equipment in Portugal is 65%

subsidized with POSEUR Aid [91], which means that, for an economic study with 10 years of useful life, a subsidy of € 780.00/year is needed.

On the other hand, it will have operating expenses of around 5% of the investment costs ($600 \notin$ /year), along with personal costs for the supervision of the Gasifier, which amounts to $3150.00 \notin$ /year, in addition to the costs of purchase of olive biomass that rises to $561.60 \notin$ /year. The results are shown in Table 11.

Years	1	2	3	4	5	6	7	8	9	10
Ct	2697	2697	2697	2697	2697	2697	2697	2697	2697	2697
$(1+i)^{t}$	1.050	1.103	1.158	1.216	1.276	1.340	1.407	1.477	1.551	1.629
$\frac{\operatorname{Ct}}{(1+i)^t}$	2569	2447	2330	2219	2114	2013	1917	1826	1739	1656
$\sum_{t=1}^{N} \frac{\mathrm{Ct}}{(1+i)^{t}}$	-9431	-6984	-4654	-2435	-321	1.691	3.608	5.434	7.173	8.829
K Investment (€)			12,000							
NPV (5 years) (€)			-321							
NPV(10 years) (€)			8829							
IRR (%)			18.29							
IBmC			0.19							
PBP (year)			6							

Table 11. Economic Analysis Results (100% olive biomass) (Source: own elaboration).

3.3.2. Results Economic-Financial Analysis (90% Olive and 10% Plastic)

For a mixture introduced into the gasifier consisting of 90% olive biomass and 10% plastic applying Formulas (6), (8)–(10), the results are presented in Table 12.

	.			Fuels
	Units	Kesults	Olive (90%)	Plastic-WEEE (10%)
LHV _{fuel}	MJ/kg	22.63	20.5	41.8
LHV _{syngas}	MJ/m ³	5.422		
V _{syngas}	m ³ /h	19.10		
η _{gas}	%	0.66		
η _{eng}	%	0.30		
η _{gen}	%	0.80		
η _{tot}	%	0.25		
Fuel Consumption	kg/h	6.90	6.21	0.69
		Total ton/month	1.86	0.21
		Total ton/year	22.36	2.48

Table 12. Results for 90% olive and 10% plastic. (Source: self-made).

Therefore, based on Formula (9), it will obtain the electrical energy produced for one hour (10.79 kWh/h), and the total annual energy produced at 38,835.08 kWh/year. We expected annual energy sales, of 7767.02 €/year.

With this power, we will have to install a 15-KW gasifier, so the necessary investment (K) according to Table 10 will amount to EUR 18,000.00 (applying a VAT of 23% in Portugal) the total investment would be EUR 22,140.00. On the other hand, this type of clean energy production equipment in Portugal is subsidized with POSEUR Aid by 65%. Which means, for an economic study with 10 years of useful life, a subsidy of 1170.00 €/year. In addition, it will avoid having to send plastic WEEE waste to the landfill with a saving of 125.19 €/year according to Tables 10 and 13.

Years	1	2	3	4	5	6	7	8	9	10
Ct	4342	4342	4342	4342	4342	4342	4342	4342	4342	4342
$(1+i)^t$	1.050	1.103	1.158	1.216	1.276	1.340	1.407	1.477	1.551	1.629
$\frac{\operatorname{Ct}}{(1+i)^t}$	4135	3938	3750	3572	3402	3240	3085	2939	2799	2665
$\sum_{t=1}^{N} \frac{\mathrm{Ct}}{\left(1+i\right)^{t}}$	-13,865	-9927	-6177	-2.05	797	4036	7122	10,060	12,859	15 <i>,</i> 524
KInvestment (€)			18,000							
NPV (5 years) (€)			797							
NPV (10 years) (€)			15,524							
IRR (%)			20.33							
IbmC			0.21							
PBP (year)			5							

Table 13. Economic analysis results (90% olive and 10% plastic) (Source: own elaboration).

On the other hand, it will have operating expenses of around 5% of investment costs (900 \notin /year), along with personal costs, which amounts to 3150 \notin /year, in addition to the purchase costs of olive biomass that rise to 670.68 \notin /year. The results are shown in Table 13.

3.3.3. Results Economic-Financial Analysis (80% Olive and 20% Plastic)

Finally, the results for the fuel mixture of 80% olive biomass and 20% plastic applying formulas, the results obtained are presented in Table 14.

	T T 1 .		Fuel			
	Units	Results	Olive (80%)	Plastic-WEEE (20%)		
LHV _{fuel}	MJ/kg	24.76	20.5	41.8		
LHV _{syngas}	MJ/m ³	5.225				
V _{syngas}	m ³ /h	14.51				
η_{gas}	%	0.61				
η _{eng}	%	0.30				
η _{gen}	%	0.80				
η_{tot}	%	0.23				
FuelConsumption	kg/h	5.00	6.21	0.69		
		Total ton/month	1.20	0.30		
		Total ton/year	14.40	3.60		

Table 14. Results for 80% olive and 20% plastic. (Source: self-made).

Therefore, it obtains the electrical energy produced for one hour (7.90 kWh/h), totaling the total annual energy produced at 28.430.53 kWh/year and the income from annual energy sales, according to which, the expected annual operating hours it will be 5686.11 €/year.

With this power, one will have to install a 10-KW gasifier, so the necessary investment (K) according to Table 10 will amount to EUR 12,000.00 (applying a 23% VAT in Portugal); the total investment would be 14,760.00 euros. On the other hand, this type of clean energy production equipment in Portugal is subsidized with POSEUR Aid by 65%, which means, for an economic study with 10 years of useful life, a subsidy of 780.00 €/year. In addition, it will avoid having to send plastic WEEE waste to the landfill with a saving of 181.44 €/year according to Tables 9 and 14.

On the other hand, it will have operating expenses of around 5% of investment costs ($600 \notin$ /year), along with personal costs, which amounts to $3150 \notin$ /year, in addition to the purchase costs of olive biomass that rise to $432.00 \notin$ /year. The results are shown in Table 15.

Años	1	2	3	4	5	6	7	8	9	10
Ct	2466	2466	2466	2466	2466	2466	2466	2466	2466	2466
$(1+i)^t$	1.050	1.103	1.158	1.216	1.276	1.340	1.407	1.477	1.551	1.629
$\frac{Ct}{(1+i)^t}$	2348	2236	2130	2028	1932	1840	1752	1669	1589	1514
$\sum_{t=1}^{N} \frac{\mathrm{Ct}}{(1+i)^{t}}$	-9652	-7416	-5286	-3257	-1325	514	2267	3935	5525	7038
Kinvestment (€)			12,000							
NPV (5 years) (€)			-1325							
NPV (10 years) (€)			7038							
IRR (%)			15.81							
IbmC			0.18							
PBP (year)			6							

Table 15. Economic analysis results (80% olive and 20% plastic) (Source: own elaboration).

4. Discussion

The combined gasification of agricultural biomass waste from the olive seed and industrial plastic waste (basically plastic from luminaires (WEEE), in a mass portion of between 10 and 20%, has been shown to be energetically valorized in a very efficient way, through the production of sintered gas or syngas. The synchronous gas produced in the reactor has a synthesizing calorific value LHV, which is interesting enough to consider the exploitation of this valuable resource, for its industrial exploitation through generation as an alternative form of energy in appropriate rural settings [92].

The results of the economic analysis indicate that there is viability in the construction of a gasification unit [93]. The HLV of WEEE plastics showed good prospects for converting this fuel into energy. For thermochemical energy conversion processes, due to the specificity of the biomass, it is not possible to introduce it only into the reactor. The highly volatile matter makes the plastics of the luminaires analyzed as WEEE more easily not volatilized during pyrolysis and gasification, and lower volatile matter values reduce LHV. More adjacent energy is required for gasification reactions. The high ash content makes WEEE prone to slag in thermochemical conversion systems. As such, downdraft gasification is recommended as this is reported at lower grate temperatures, reducing ash slag trends. The results of this study are perfectly aligned with the results of similar studies in which the joint gasification of biomass and polyethene (PE) residues was observed, where the results showed a synergistic effect on the gas and tar yields when the PE was especially fed with a maximum PE content of 20%. For higher PE content, total gas and H₂ decreased because more chain hydrocarbons with a relatively large molecular size derived from PE volatiles are more difficult to break than oxygenates from biomass pyrolysis [22,94].

The economic viability of a gasification unit depends on the availability of waste and the size of the unit. In fact, the units with the highest energy generation require a greater quantity of raw material that may not be available in the region, which implies waste transportation costs over considerable distances.

This is the reason why gasification systems that use the biphasic combination of agricultural and/or forest resources and industrial wastes from sources close to electricity production centers with gasifiers are especially interesting to favor the circular economy of regions with the ability to supply both resources [66,95].

Table 16 shows the comparative results of the economic analysis carried out for the three cases studied.

	100% Biomass Olive Test 1	10% WEEE-plastic/90% Olive Test 2	20% WEEE-plastic/80% Olive Test 3
K Investment (€)	12,000	18,000	12,000
NPV (5 years) (€)	-321	797	-1.325
NPV(10 years) (€)	8829	15,524	7038
IRR (%)	18.29	20.33	15.81
IBmC	0.19	0.21	0.18

Table 16. Comparative results of the analysis of economic indicators (Source: self-made).

The results in Table 16 show that the best economic results in all economic indicators are for a gasifier that runs on 10% WEEE fuel with 90% olive biomass. In this more favorable case, it would have to supply the reactor with a total of 2484 kg/year of plastic waste (2.48 t/year). On the other hand, the total amount potentially available of the Syntra model luminaire is 35,593 luminaires in the Alto Alentejo region. (Figure 1 and Table 1). Thus, the total plastic coming from the substitutions of this luminaire in the entire Alto Alentejo area would total 63,921.46 Kg.

Therefore, only the plastic recovered from the Syntra model luminaires in the Alto Alentejo Region would allow having guaranteed plastic fuel for 25 years. Taking into account that the biomass of the olive tree is close to the production centers, it would guarantee the availability of fuel in the long term.

Indeed, the power of the production equipment has been adjusted to the total power that we are going to obtain based on the energy characteristics of the synthesis gas produced. This allows the equipment to adjust to the power we expect to produce and therefore reduces the "K" investment costs, making the solution and equipment dimensions more in line with the expected production reality. We have observed that the gas with the highest energy quality, for the reasons argued in that section, results in the proportion of 10% of plastic. The consequences are that the total electrical energy that we hope to produce is also for this higher proportion of approximately 10.79 kWh/h, or approximately 38,835.08 kWh/year, which makes us have an annual income of € 7767.02/year, compared with 8.65 kWh/h, and 31,145.40 kWh/year in the case of 100% olive biomass. Additionally, 7.90 kWh/h, and 28,430.53 kWh/year produce 20% plastic, despite having to make a slightly greater investment in a 15-kW gasifier, 5 kW more in the case of 10% plastic. Then, we observe that adding the plastic fraction in a moderate proportion (10%) produces a more energetic synergistic gas with more hydrogen, capable of producing more electrical energy and producing numbers in the form of better economic indicators. In particular, the VPN. However, when the plastic fraction exceeds 10% and we are at 20%, the energy quality of syngas decreases as we analyze in Section 3.2 (an analysis of the syngas produced). It is for this reason that, in order to achieve a better performance of the equipment as a whole, a gasifier with more power has been chosen in the case of 10% plastic, as we expect a higher annual energy production. However, we have also carried out the simulation for a 10-kW gasifier unit, (K Investment (EUR 12,000)), for 10% plastic, observing that even the economic indicators improve even more obtaining a 4-year amortization with an NPV of EUR 3096 and a 10-year NPV of EUR 20,829, with an IRR 33.45% and an IBmC of 0.31. However, it would be advisable to make a design for 15 kW in anticipation of future expansions of the production plant, although the investment is higher and the indicators are slightly lower

On the other hand, from the environmental point of view, the establishment of a gasification unit for WEEE will help to reduce the environmental impact of its deposition causes. Compared to traditional combustion technology [96], gasification contributes to less atmospheric emissions produced per kWh; in addition, as mentioned above, increasing the efficiency of a gasification system will also have an environmental impact [97], reducing the amount of lignocellulosic biomass used [98]. However, the higher efficiencies attributed to gasification systems usually come with higher initial capital requirements compared to combustion technology [99]; but, on the other hand, gasification systems will save on operating costs while reducing greenhouse gas emissions, helping the Portuguese government meet increasingly stringent EU pollution standards [100,101].

5. Conclusions

This work allows us to confirm that there is great potential for energy recovery through the gasification of waste from plastic products of industrial origin, mixed with agricultural biomass. In particular, of plastics of electrical and electronic equipment (WEEE or WEEE) and in particular of the plastic waste of obsolete luminaires dismantled in vials. By mixing these plastics with agricultural biomass, in a suitable proportion, it is possible to obtain a highly energetic synthesis gas for gasification, and then for its transformation into electrical energy.

Gasification products show that WEEE plastics have great gasification potential along with agricultural biomass and, in particular, pellets from biomass residues from olive milling. The fundamental question is to be able to find the exact proportion that allows for obtaining the best results from the energy, economic and environmental points of view. With the correct combination of 90% of agricultural biomass from the olive seed and 10% of plastic from the dismantling of luminaires on a large scale, in the Alto Alentejo area, it has been able to find a fuel that produced rich synthesis gas, with more than 5 MJ/m³ and a low amount of coal and tar production. Both coal and tar can be reintroduced into the fuel and gasified again.

This work also demonstrates the technical and economic feasibility of using mixtures of industrial plastic waste and biomass of agricultural origin, as fuel for the production of synthesis gas very rich in hydrogen with a very interesting energy value for use in electricity generation by energy transformation and for industrial use.

This work demonstrates the technical feasibility and economic profitability of transforming this type of industrial plastic waste mixed with agricultural biomass into electrical energy. In particular, for a mixture of 10% plastics with 90% olive biomass, the best results were obtained from the technical, energy and economic point of view, according to the analysis of the analyzed indicators. Likewise, the economic-financial viability for the installation of medium-sized gasification equipment (below 15 kW) with amortizations of less than 5 years with returns of around 20% that would justify the investment made was verified.

This study demonstrates the potential that the gasification of the mixture of biomass resources of agricultural origin and industrial plastic waste could have, as future technology and source of clean and renewable energy production, in strategies aimed at the valorization of agricultural, forestry, industrial and municipal residues in environments close to production centers and within the framework of the strategies promoted by the EU oriented towards the circular economy and the approach of the life cycle of agricultural and industrial products.

Supplementary Materials: The following are available online at http://www.mdpi.com/2076-3417/10/13/4601/s1, Gasification practical process, Video S1: Gasification WEEE Plastic-Biomass Olive.

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