




Potential of “Montado” Waste as Feedstock for Thermal Gasification

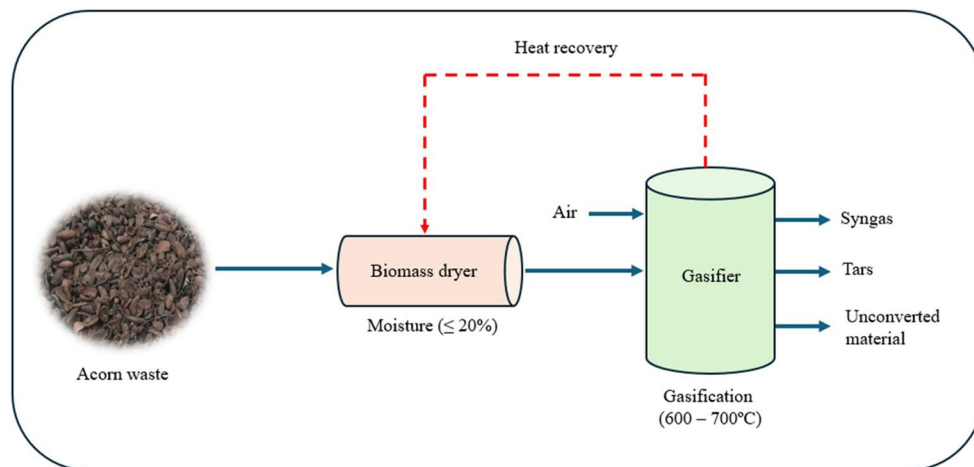
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Abstract

This study examines the feasibility of utilizing acorn wastes from *Montado* systems in the Alentejo region of southern Portugal as a sustainable feedstock for bioenergy production through thermal gasification. Approximately 45% of the annual acorn harvest remains unused, representing a locally available biomass resource with significant valorization potential. Acorn waste was characterized by proximate, ultimate, and calorimetric analyses, revealing moisture and volatile matter contents within ranges suitable for gasification. The relatively high ash content indicates potential challenges for fuel quality and process performance. Gasification experiments were carried out in a fixed-bed downdraft reactor at temperatures between 600 and 700 °C using air as the gasifying agent. The produced syngas consisted mainly of N₂, H₂, CO, CO₂, and CH₄, with methane concentrations remaining relatively stable across the tested temperatures (3.1–4.0 vol%). Increasing the gasification temperature reduced tar and char formation and improved cold gas efficiency, reaching a maximum of 68.5% at 700 °C, with a syngas lower heating value of up to 5.7 MJ/Nm³. Based on the experimental results, a techno-economic assessment was conducted for a decentralized gasification system with a nominal thermal capacity of 1.0 MW_{th} operating 8,000 h per year. The system requires approximately 244 kg/h of acorn waste and achieves an overall electrical efficiency of 24.0%, converting 80.5% of the input energy into useful outputs. The economic analysis indicates project feasibility, with a positive net present value (0.47 M€), an internal rate of return of 12.1%, a levelized cost of electricity of 0.10 €/kWh, and a payback period of 14.2 years. These results demonstrate that acorn waste from *Montado* management can support decentralized bioenergy production, contributing to circular economy strategies and renewable energy targets.

Graphical Abstract



Keywords Acorn waste · *Montado* · Thermal gasification · Energetic valorization

Extended author information available on the last page of the article

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Introduction

Energy production through renewable and more sustainable sources is a constant challenge for reducing the carbon footprint and minimizing environmental impacts that are leading to global warming. In this context, the energy recovery of biomass wastes can play a relevant role in reducing the production and deposition of waste in landfills and increasing resource-use efficiency through the circular economy framework [1]. Additionally, the use of endogenous biomass resources contributes to energy security by reducing dependence on imported fuels and minimizing transportation-related emissions [2].

In Portugal, a significant share of underutilized biomass originates from the *Montado* agro-silvo-pastoral system, which dominates large areas of the Alentejo region. This system is primarily composed of cork oak (*Quercus suber*) and holm oak (*Quercus rotundifolia*) stands and provides multiple ecosystem services when properly managed, including biodiversity conservation, soil protection, and wildfire risk mitigation [3–5]. Acorns produced within the *Montado* are traditionally used for animal feeding, particularly in extensive pig farming systems where they are typically consumed *in natura* rather than industrially processed. However, a substantial fraction remains unused each year. Recent estimates indicate that approximately 55% of total acorn production is left unused, resulting in hundreds of thousands of tonnes of biomass wastes annually [6]. Given their availability, calorific value, and lignocellulosic nature, acorn wastes represent a promising feedstock for energy recovery within regional circular economy strategies.

Several technological pathways can be considered for the energetic valorization of acorn waste, including biochemical and thermochemical routes. Biochemical processes such as fermentation or anaerobic digestion can produce bioethanol or biomethane, but they typically require homogeneous feedstocks, extensive pretreatment, and strict process control, which may limit their applicability to heterogeneous, seasonally available wastes such as acorns [7, 8]. Pyrolysis offers an alternative thermochemical route, yielding bio-oil, biochar, and gas. However, bio-oil upgrading remains technically complex and capital-intensive, particularly for decentralized applications [9].

Gasification, by contrast, is a robust thermochemical conversion process capable of handling diverse lignocellulosic wastes with relatively high tolerance to feedstock variability. It converts solid biomass into a combustible synthesis gas (syngas) composed mainly of CO, H₂, CH₄, CO₂, and N₂, which can be directly used for heat and power generation or further upgraded into fuels and chemicals [10, 11]. Importantly, gasification is well suited for small to medium-scale, decentralized energy systems, making it

particularly compatible with the spatially dispersed nature of acorn waste across *Montado* landscapes [11]. Moreover, thermal gasification of biomass involves not only the use of forest or agricultural biomass wastes but also crops. While some crops are specifically cultivated for energy purposes, others, such as corn, soybeans, and palm oil, are primarily intended for human consumption. Within the European Union (EU), these crops are prioritized for food and feed uses and are therefore not extensively promoted for energy production [12]. In this context, the valorization of biomass wastes, whether of forestry or agricultural origin, represents a promising strategy to exploit the energy content of waste streams while diverting them from landfill disposal.

Numerous studies have demonstrated the technical feasibility of gasifying agricultural and forestry wastes, yielding syngas of suitable quality for decentralized energy applications. Kumar et al. [13] conducted fixed-bed gasification of corncobs and eucalyptus wastes, achieving hydrogen yields of 3.7 MJ/Nm³ and 5.3 MJ/Nm³, respectively. Tezer et al. [14] gasified olive pomace at temperatures between 700 and 900 °C using air as an oxidant agent, obtaining average hydrogen contents of 44% and syngas calorific values of 12.4 MJ/Nm³. Dafiqurrohman et al. [15] reviewed gasification studies using rice husks, reporting syngas heating values ranging from 3.1 to 5.4 MJ/Nm³ and cold gas efficiencies (CGE) as high as 72.3%, enabling stable power generation at the kilowatt scale. González et al. [16] explored the gasification of almond, including shells, peels, and pruning waste, achieving carbon conversion efficiencies (CCE) between 81% and 90% and syngas lower heating values (LHV) between 5.8 and 6.5 MJ/Nm³. These studies confirm the robustness of gasification across a wide range of lignocellulosic wastes and provide a relevant benchmark for evaluating less-explored feedstocks such as acorn waste. The gasification process is inherently complex, particularly when biomass is used as feedstock, as fuel properties are influenced by factors such as geographic location, soil composition, and species variability [17, 18]. Consequently, reactor configuration and operating conditions must be adapted to specific feedstocks or feedstock groups, while maintaining sufficient flexibility to accommodate locally available biomass resources.

Beyond the regional context, there has been a growing international interest in the energetic valorization of acorn-derived biomass and other oak-related wastes. Recent studies have explored the use of acorns as solid biofuels and as feedstock for thermochemical and biochemical conversion processes, revealing favorable fuel properties and potential energy yields. For example, torrefaction of oak acorns has been found to enhance fuel characteristics such as energy density and hydrophobicity, making them more suitable for solid bioenergy applications [19]. Similarly, emerging

biorefinery approaches have investigated acorn waste for the production of bioethanol and biomethane [20].

Despite these advances, experimental studies focusing specifically on the gasification of acorn waste remain scarce. In particular, there is a lack of integrated assessments combining gasification performance, syngas quality, energy efficiency, and techno-economic feasibility at the system level. Such evaluations are essential to determine whether acorn waste gasification can represent a viable and competitive solution for decentralized bioenergy production.

A preliminary version of this research, focusing on the influence of gasification temperature on the syngas composition of acorn waste at experimental scale, was previously published as a conference proceedings chapter [21]. The present manuscript substantially extends that earlier work by incorporating an expanded feedstock characterization, a regional assessment of biomass availability, complete mass and energy balance analysis, and a comprehensive techno-economic evaluation of a decentralized 1 MW gasification system. Accordingly, this work aims to evaluate the feasibility of gasifying acorn waste in a fixed-bed downdraft reactor. The study combines physicochemical characterization of the feedstock, experimental gasification trials under different operating temperatures, mass and energy balance analysis, and a techno-economic assessment of a decentralized gasification system. By addressing both technical performance and economic viability, this work seeks to clarify the potential role of acorn waste gasification as a sustainable energy pathway for rural and agro-forestry regions.

Materials and Methods

Sample Characterization

The sample used in this work corresponded to a mixture of waste acorns from different oak species in the North and Alentejo regions of Portugal. It was collected during the late winter, a period typically marked by rainfall in Portugal. The initial moisture content of the acorn waste sample received was approximately 60%, as determined by using a digital moisture meter (Dr. Meter, model MD812). The

acorn waste sample was dried by natural convection using air at 35 °C for 24 h. After this drying step, the acorn wastes were ground using a hammer mill and sieved to a particle size < 500 µm for characterization analysis (Fig. 1).

Proximate analysis of the acorn waste sample was carried out using a Perkin Elmer thermogravimetric analyzer (TGA). The thermograms were obtained using Pyris Manager software. The tests were carried out at an initial temperature of 30 °C up to a maximum temperature of 950 °C, using a heating rate of 30 °C/min, with an entraining gas flow rate of 20 mL/min. Approximately 5 mg of sample was placed in a ceramic crucible in each experiment.

Ultimate analysis was determined using a Thermo Scientific Flash 2000 Organic Elemental Analyzer. High Heating Value (HHV) was determined using an IKA C200 Calorimeter.

Gasification Tests

The gasification experiments were performed in a commercial downdraft gasifier (PowerPallet PP20, ALL Power Labs), equipped with an integrated gas cleaning train. Downstream of the reactor, a cyclone separator was used to remove entrained char and ash particles, followed by a filtration unit for tar reduction.

Prior to gasification, the dried and ground acorn waste sample was pelletized to improve bulk density, ensure stable feeding, and minimize channeling and thermal gradients within the reactor bed. The resulting pellets had a diameter of approximately 6 mm and a length of about 15 mm, with a moisture content of 10.6 wt%.

Gasification trials were conducted using air as the gasifying agent at three nominal reactor temperatures (600, 650, and 700 °C). The air flow rate was maintained at approximately 6 m³/h, corresponding to a biomass feeding rate of 5.2 kg/h. For each operating condition, synthesis gas samples were collected under steady-state operation using Tedlar[®] bags and subsequently analyzed to determine gas composition (MCA 100 Syn 2 Portable) [21].

The LHV of the syngas was calculated using Eq. 1 [22]:

$$LHV = 12.74 (H_2) + 12.63 (CO) + 39.84 (CH_4) \quad (1)$$

Fig. 1 Acorn waste sample used in this work. (a) Acorn waste sample as received; (b) Air-dried acorn sample; (c) Acorn sample ground and sieved for characterization analysis



The experimental gasification results correspond to representative steady-state operation of the gasification system under each tested condition.

Techno-Economic Analysis

The techno-economic analysis of biomass gasification is an important and necessary step to identify the cost of energy production and ensure the viability of the project. In order to bring this analysis closer to a real application scenario, this study was built based on the results of the gasification of the acorn waste sample in a 15 kW downdraft gasification unit, coupled to an existing internal combustion engine. A detailed explanation of the features of this system can be found at [23–25], as well as a literature review related to investment projects in large-scale electricity generation systems through biomass gasification [26–28]. From the experimental results of the gasification of the acorn waste sample (*Montado* waste), it is possible to size a new gasification unit with similar characteristics that considers the availability of biomass. Therefore, the first step for the economic analysis was to calculate the availability of biomass (acorn waste). Next, the gasification unit was sized based on the available biomass and the operating time of the unit in hours per year. Subsequently, the respective mass and energy balances were conducted. Once all this information was obtained, the economic evaluation of the project was carried out and additional information about other aspects, such as the electrical consumption of the equipment and the costs of purchasing and transporting biomass, was incorporated.

Biomass Availability

The estimation of acorn waste availability is based on forest area, the relative distribution of cork oak and holm oak stands, representative acorn yields per tree, and the fraction of acorns remaining unused; these parameters are combined to obtain an order-of-magnitude estimate of available biomass.

The Alto Alentejo sub-region covers approximately 623,000 ha, of which around 294,153 ha are classified as forest, largely dominated by cork oak (*Quercus suber*) and holm oak (*Quercus rotundifolia*). Within this region, the municipality of Portalegre comprises 44,620 ha, including 8,007 ha occupied by these two oak species [29, 30]. Although annual acorn production is highly variable due to climatic conditions, tree age, and irregular fruiting cycles, a representative estimate of biomass availability can be obtained using typical values reported in literature. Cork oak stands generally contain 80–150 trees per hectare (with 135 trees/ha commonly used in regional

assessments), while holm oak stands average around 200 trees/ha. Reported acorn yields range from 7 to 40 kg per tree per year. These ranges are presented to contextualize variability and to justify the adoption of a conservative average yield. To avoid overestimation and maintain consistency with previous regional studies, a single representative value of 15 kg per tree per year was adopted for both species [31, 32].

Based on these assumptions, the estimated annual acorn production in Portalegre is approximately 18.9 million kg. Considering that about 55% of total acorn production remains unused [6], this corresponds to roughly 10.4 million kg per year (10,403 t/year) of acorn wastes potentially available for energy recovery. These availability values are derived from literature estimates of harvested acorn production and are used here solely to assess the order of magnitude and regional sufficiency of the resource. As shown in the subsequent mass–energy analysis (Sect. 3.3), a 1 MW gasification system operating 8,000 h per year requires approximately 1,959 t of biomass, representing less than 20% of the estimated available acorn wastes. This confirms that the regional supply is sufficient to sustain continuous operation of the proposed decentralized gasification system without compromising existing uses.

Energy Analysis

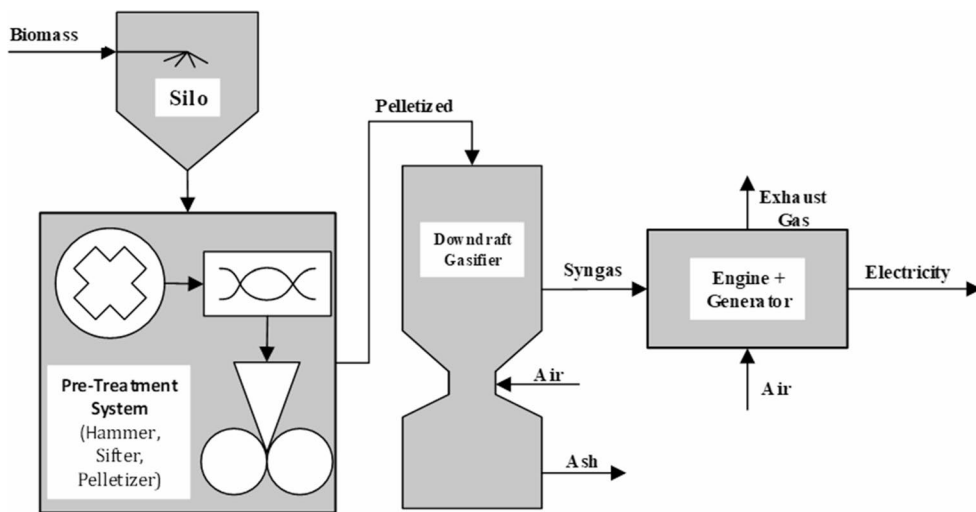
To analyze the potential for electricity production from acorn waste and evaluate process efficiency, a mass and energy balance was developed for a proposed gasification system with 1 MW of thermal power. The analysis focuses on the direct gasification of acorn waste using air in a downdraft gasification system and the subsequent use of syngas for electricity generation in an internal combustion engine generator (ICE-G). A schematic representation of the integrated processes is shown on Fig. 2.

The proposed system comprises several components, including a covered storage silo, a pretreatment system consisting of a hammer mill, a vibrating screen, and a pelletizer, a gasification system, and the ICE-G motor generator. The acorn waste is pelletized and gasified in an atmospheric downdraft reactor, with air serving as the gasification agent. A dry-cleaning system integrated into the gasification process removes impurities from the syngas. The clean syngas is then used as fuel for electricity generation in the ICE-G.

The energy balance is based on the principles of mass and energy conservation, as dictated by the first law of thermodynamics, and is expressed by Eq. 2 [33]:

$$\dot{Q} + \sum m_{in} \left(h_{in} + \frac{V_{in}^2}{2} + gZ_{in} \right) = \dot{W} + \sum m_{out} \left(h_{out} + \frac{V_{out}^2}{2} + gZ_{out} \right) \quad (2)$$

Fig. 2 Proposed system diagram (gasification system integrated with ICE-G)



To simplify the analysis, a series of assumptions were followed. In the system described, the energy balance can be written according to Eq. 3:

$$\dot{Q} + \sum \dot{m}_{in} \cdot h_{in} = \dot{W} + \sum \dot{m}_{out} \cdot h_{out} \quad (3)$$

where \dot{Q} is the heat rate, \dot{W} the work rate and h the specific enthalpy. At this point, the gasification system and the motor generator will be evaluated separately. For the gasification system, the energy balance is described in the following equations:

$$\dot{Q}_{fuel} + \dot{Q}_{heat} = \dot{Q}_{syngas} + \dot{Q}_{tar} + \dot{Q}_{system} \quad (4)$$

The fuel energy input can be calculated as:

$$\dot{Q}_{fuel} = \dot{m}_{fuel} \cdot LHV_{fuel} \quad (5)$$

where LHV is the lower heating value and \dot{m}_{fuel} is the mass flow rate for fuel (acorn waste). As long as there is no condensation occurring, the power of the supplied air can be given by Eq. 6:

$$\dot{Q}_{air} = \dot{m}_{air} \sum_1^j w_j C_{p_j} (T - T_0) \quad (6)$$

where w_j is the mass fraction and C_{p_j} the specific heat of a component, $(T - T_0)$ represents the pre-heat gas temperature and ambient temperature, respectively. To calculate the energy associated with the syngas (\dot{Q}_{syngas}) and tar (\dot{Q}_{tar}), the following equations are used:

$$\dot{Q}_{syngas} = \dot{m}_{syngas} \cdot LHV_{syngas} \quad (7)$$

$$\dot{Q}_{tar} = \dot{m}_{tar} \cdot LHV_{tar} \quad (8)$$

To calculate the energy efficiency of the cold gas, the useful output energy is divided between the energy from the input to the system, as described in Eq. 9:

$$\eta_{coldgas} = \frac{\dot{Q}_{syngas}}{\dot{Q}_{Fuel} + \dot{Q}_{air}} \quad (9)$$

The energy of the syngas that enters the ICE-G is calculated by Eq. 10 shown below. The complete combustion of syngas depends on chemical composition. The general equation for the complete combustion of syngas with the theoretical amount of air required is given by Eq. 10:



The values of the unknown coefficients a, b, c, d, and e, in the above equation, can be determined by applying the principle of conservation of mass to each element that constitutes the syngas [34]. The total heat loss in the ICE-G is calculated by Eq. 11:

$$\dot{Q}_{lossICE-G} = \dot{Q}_{syngas} - \dot{W}_{CE-G} \quad (11)$$

The thermal efficiency of the ICE-G is generally determined as the ratio of the power output between the incoming fuel energy, as given by Eq. 12:

$$\eta_{ICE-G} = \frac{\dot{W}_{ICE-G}}{\dot{Q}_{Syngas}} \quad (12)$$

The overall system efficiency is determined by Eq. 13:

$$\eta_{overall} = \frac{\dot{W}_{ICE-G}}{\dot{Q}_{Fuel}} \quad (13)$$

Economic Analysis

The general approach to economic analysis involves comparing the project costs with the expected revenues over its lifetime. This analysis evaluates the performance of the designed system in terms of energy efficiency, capital cost, operation and maintenance costs, energy generation cost, investment payback periods, and technology acceptance. Several parameters must be considered, including the availability and cost of biomass at the gasification site, energy production capacity, quality of produced energy, process efficiency, system optimization, and applications of the generated energy [33].

As previously described, the gasification unit is designed to operate at 1 MW for 8,000 h per year. The operational staff structure for a system of this size consists of 12 full-time employees, divided into five salary levels: two in management, two in specialized roles, six in base staff positions, and two in administrative tasks.

Determining the cost of the raw material, considered waste, is challenging due to the lack of available data. To establish the price of acorn waste, the price of acorns must first be determined. Acorns are not a commonly traded biomass and are not subject to price regulations, so their value depends on the seller and established conditions, which are often not clearly expressed. Research indicates that prices can range from 0.5 to 5.0 €/kg [35, 36]. Prices are generally set independently by each entity, with factors such as transportation and acorn quality influencing the final cost.

Transportation represents another critical factor in determining the price of acorn waste. In this case study, the gasification unit is assumed to be located near an acorn processing factory in the municipality of Portalegre. This proximity would significantly reduce transportation costs, which are typically among the most expensive components of an economic plan. The raw material would be transported from the factory to the gasification unit's silo via a conveyor belt. Since the factory and gasification unit are separate entities, the gasification unit would purchase the raw material from the factory. Given that the raw material is considered waste, it would be purchased at a lower price, estimated at 5 €/t.

After establishing the biomass flows and costs, the next step was to determine the capital expenditure (CAPEX) required for electricity production at the proposed system. The CAPEX is directly proportional to the thermal power of the proposed system, which is rated at 1 MWth. According to Cardoso et al. [24], the CAPEX for a gasification system with these specifications is 1320 €/kW. Additionally, an extra 7% is allocated to cover maintenance and repair costs. Table 1 presents financial data and details the cost factors considered in modeling the economic feasibility of the proposed system.

Table 1 Initial input financial data and cost factors considered to model the system in this work

Item	Value	Comments	Ref.
CAPEX (€/kWth)	1320.0	CAPEX for downdraft gasification plants (includes all plant components).	[24]
$C_{\text{Electricity}}$ (€/MWh)	121.34	Electricity sales price practiced in Portugal.	[37]
$C_{O\&M_{\text{Fixed}}}$ (%)	3.5	Fixed operation and maintenance (O&M) costs refer to 3.5% of the total investment, applied accordingly to both systems. Includes operating costs such as salaries, insurance, electricity, water, consumption for lighting, ventilation and other consumptions, and the maintenance costs for buildings, roads and others not related to the process.	[38, 39]
$C_{O\&M_{\text{Var}}}$ (€/MWh)	3.5	Variable O&M costs include operating costs such as electricity consumption, waste disposal, etc. and the maintenance costs of the process equipment (gasifier, turbine, generators and others), that are related to the process.	
r (%)	1.4	Interest rates on credit operations.	[40]
C_{Waste} (€/t)	5.0	Acorn waste acquisition costs for Portugal include transportation, splintering and sieving.	-
$(i)_{2020}$ (%)	8.5	Average discount rate considered per year. Applied to both systems.	[41]
IR (%)	1.6	Inflation rate; Harmonized inflation Portugal 2023.	[42]
H (h/year)	8000	System operating hours per year	[26]
Project lifetime (years)	25	System lifetime	[39]

Economic analysis methods evaluate the costs and benefits of investments. One of the most frequently utilized economic methods to assess the economic feasibility of a project is the total present value. This method is a combination of several economic indicators: Net Present Value (NPV), Levelized Cost of Energy (LCOE), Internal Rate of Return (IRR), and Period of Return on Investment (Payback), each having their own strengths and limitations.

To compute the economic indicators, an analysis of cash flows was conducted. Initially, the costs and income of cash flow before taxes (CFBT) are incurred in an initial investment period, related to the design and construction phase of the system, amortizations of the debt contracted with the acquisition of the project, investments in fixed assets,

and working capital. These costs are then deducted from the amortizations to recover the investments, along with the costs related to operation and maintenance (O&M), employees, and structure. Financial income from capital investments and income obtained from the sale of the fuels produced (butane and propane) are also considered. CFBT is calculated by balancing revenues and expenses while further applying the discount rate, as shown in Eq. 14 [23, 33]:

$$CFBT = \left(\sum Revenues - \sum Expenses \right) / (1 + i)^t \quad (14)$$

Cash flows after taxes (CFAT), is one of the most useful liquidity measures to assess the financial health of a project or company since it considers the effect of the tax burden on the obtained profits. It also allows calculating the economic viability of the future investment while measuring the profitability or growth of an investment. CFAT is determined by Eq. 15, which relates CFBT minus taxation (Tax) [33].

$$CFAT = CFBT - Tax \quad (15)$$

$$Tax = TXI \times TXR \quad (16)$$

$$TXI = CFBT - (DEP \times Inv) \quad (17)$$

The depreciation of assets in Portugal (DEP) follows the regulatory decree 25/2009 from the Ministry of Finance and Public Administration, which considers a depreciation rate of 8.3% for energy companies. Before and after-tax cash-flows for cost and revenue calculations over the life of the project are applied to an economic model based on a spreadsheet developed to calculate these economic indicators.

The NPV is an economic indicator that allows the evaluation of the profitability of a project by considering all the inflows and outflows of cash throughout its useful life. A positive NPV indicates that the project is profitable, while a negative NPV indicates losses. Thus, the NPV refers to the current values of all costs and revenues associated with the system and in this work, it is calculated by Eq. 18 [39].

$$NPV(i; N) = \sum_{t=0}^N \frac{CFBT}{(1 + i)^t} \quad (18)$$

The period t=0 relates to the initial investment stage of the project and corresponds to the investment costs associated with the purchase and installation of the equipment.

The LCOE is a metric used to evaluate the cost of producing energy over the project’s lifetime. It represents the minimum average price at which the electricity generated must be sold to cover the total production costs. The LCOE calculation is closely related to the concept of NPV, and like NPV, it can be used to assess the profitability of a project

[43]. The LCOE is determined by relating the initial investment costs to the sum of the annualized operation and maintenance costs, as well as the costs of electricity production in kWh over the project’s lifespan, as follows:

$$LCOE = \frac{I_{Total} + C_{O\&M}}{E_{out} \cdot H \cdot PL} \quad (19)$$

The IRR is the interest or return rate offered by an investment. The higher the IRR, the greater the profitability of the project will be. Also, the IRR is the discount rate that makes the NPV of all cash flows equal to zero, determining the minimum rate of return for the project to be viable. If the IRR is higher than the discount rate, the project is feasible. The IRR is calculated by Eq. 20.

$$NPV(IRR; N) = \sum_{t=0}^N \frac{CFBT}{(1 + IRR)^t} = 0 \quad (20)$$

The payback period is the time needed to earn back the initial capital investments. The shorter the payback, the stronger the financial viability of the project. In this analysis, payback is calculated by finding the year in which the cumulative NPV cash flow becomes positive, following Eq. 21, where A is the last year with a negative cumulative NPV, B is the absolute value of cumulative NPV at the end of that year, and C is the total annual cash flow during the year after [39].

$$Payback = A + \frac{B}{C} \quad (21)$$

Results and Discussion

Physical and Chemical Properties of Acorn Waste

The results of the proximate analysis, ultimate analysis, and selected combustible properties of the acorn waste sample used in this study are summarized in Table 2.

All characterization analyses were performed on the dried and ground acorn waste sample (after the air-drying step). Biomass feedstocks commonly present challenges during thermochemical conversion due to elevated initial moisture and volatile matter contents. Therefore, appropriate pre-conditioning is required prior to gasification. After the applied drying step, the moisture content of the acorn waste was reduced to 10.6 wt%, which falls within the range generally considered suitable for stable biomass gasification operation. The volatile matter presented a high value (61.6 wt%), typical for raw biomass waste. The high percentage of volatiles in the acorn waste makes it well-suited for

Table 2 Characterization of the acorn waste sample

Parameters	Acorn waste
<i>Proximate analysis (wt%*)</i>	
Moisture	10.6
Volatile matter	61.6
Ash	5.6
Fixed carbon	22.2
<i>Ultimate analysis (wt%, db)</i>	
C	39.9
H	5.6
N	12.3
S	n.d.
O**	20.0
<i>Combustible properties (wt%, db)</i>	
H/C atomic ratio	1.68
O/C atomic ratio	0.37
HHV (MJ/kg)	14.7

*After air-drying

**Oxygen was determined by difference in a dry ash-free basis (daf)

combustion and facilitates devolatilization during thermochemical conversion processes[44].

Ash content presented a high value compared to other *Quercus* biomass wastes (*Q. aegilops*, *Q. calliprinus*, and *Q. infectoria*), comprising 5.6 wt% of the acorn waste sample [45]. This high value may be associated with soil contamination of the sample and represents a potential concern regarding its thermal valorization by gasification. The presence of ash in biomass is undesirable for energy recovery since it is abrasive and does not add to the energy content [46]. The composition of biomass ash varies widely depending on feedstock origin and growing conditions and is typically dominated by silica, alkali metals, and alkaline earth metals. Interactions among these components can lead to the formation of low-melting eutectic mixtures, increasing the risk of deposition and equipment degradation at elevated temperatures. Fixed carbon accounted for 22.2 wt% of the acorn waste, which is consistent with values reported for other oak species [47].

Ultimate analysis revealed a comparatively low carbon content (39.9 wt% db) relative to many biomass wastes commonly employed in gasification systems [48, 49]. This characteristic is likely associated with the advanced state of biological degradation of the acorns prior to collection, which can result in partial loss of carbon-rich compounds. The relatively high nitrogen content suggests that NO_x formation could occur if the material were directly combusted, although this aspect is less critical in the present gasification-based configuration. From a fuel quality perspective, pre-treatment options such as torrefaction could be considered to further enhance the properties of acorn waste, as torrefaction is known to reduce moisture, limit biological degradation, and increase energy density through partial

devolatilization [19]. Based on the elemental composition, the acorn waste exhibited H/C and O/C atomic ratios of 1.68 and 0.37, respectively, corresponding to a higher heating value of 14.7 MJ/kg. Considering that this value was obtained without any thermochemical upgrading, it indicates a relatively favorable energetic potential, supporting its suitability for gasification-oriented energy recovery.

Thermal Gasification

Gasification experiments were conducted at three operating temperatures, and syngas samples were collected under steady-state conditions for compositional analysis. Table 3 summarizes the main operating parameters, syngas composition, by-product formation, and performance indicators obtained at each temperature, enabling a comparative assessment of process behavior within the investigated range.

The measured ER values align with those reported in the literature, especially in the context of biomass gasification [50]. The syngas composition obtained at the three temperatures showed only modest variations, and these differences should be interpreted with caution. As expected for air-blown fixed-bed gasification, N₂ constituted the largest fraction of the syngas (contributing to the comparatively low LHV of air-blown gasification products), while CO, H₂, CH₄, and CO₂ appeared in smaller proportions [51, 52]. Excessively high ER values are known to dilute combustible gas species while increasing nitrogen concentration [53]. Within the investigated operating range, increasing temperature was associated with a slight reduction in N₂ concentration in the syngas, reaching a minimum value of

Table 3 Gasification conditions and Syngas composition of acorn waste at different temperatures

Parameters	Units	Gasification temperature			
		600 °C	650 °C	700 °C	
Air temperature	° C	13.5	18.7	12.0	
Air volume	m ³ /h	6.2	5.8	5.6	
Pyrolysis temperature	° C	505.0	562.0	576.0	
Oxidation temperature	° C	604.0	661.0	705.0	
Syngas composition	N ₂	%	52.0	49.7	46.9
	CO ₂	%	11.2	11.2	11.4
	H ₂	%	15.5	17.1	17.0
	CH ₄	%	4.0	3.1	3.4
	CO	%	17.3	18.9	20.8
LHV _{syngas}	MJ/Nm ³	5.3	5.3	5.7	
\dot{V}_{tars}	mL/h	146.8	128.0	111.5	
\dot{V}_{chars}	kg/h	0.2	0.1	0.1	
Equivalence ratio (ER)	-	0.3	0.2	0.2	
\dot{m}_{syngas}	kg/h	10.3	10.5	10.4	
CGE	%	62.6	64.4	68.5	
η_{syngas}	m ³ /kg	2.0	2.0	2.0	

46.9% at 700 °C. CO₂ levels remained essentially constant at around 11% across all trials. Minor increases in CO and H₂ concentrations were observed as the temperature increased from 600 to 700 °C, while CH₄ content remained relatively stable across the tested conditions. Although these tendencies are consistent with temperature-dependent cracking and reforming reactions reported in the literature, the magnitude of the observed changes was limited and may partly reflect experimental variability or analytical uncertainty. For this reason, no definitive conclusions are drawn regarding a significant enhancement of combustible gas fractions at higher temperatures.

In comparison to earlier studies reported in other biomass gasification research, the results of this work show significant differences. Although the composition of syngas can differ depending on the type of feedstock, gasifier design, and operational conditions, similar studies provide valuable benchmarks for assessment. For example, comparative gasification of various feedstocks in fixed and fluidized beds showed H₂ and CO fractions, syngas lower LHV, and CGE values across pine, olive pomace, and refuse-derived fuel under air gasification conditions [54]. Additionally, broader analyses of biomass gasification outcomes across forest and agricultural wastes indicate that H₂ and CO levels under air gasification typically fall within similar ranges. However, exact values vary depending on feedstock properties and operating conditions [55].

Olive pomace gasification in a fixed-bed downdraft reactor has been shown to produce syngas with H₂ concentrations ranging from 15.6% to 16.52% and CGE values between 58.99% and 66.80% at approximately 700 °C using air as the gasifying agent [56].

The syngas produced from acorn waste at 700 °C exhibited H₂ and CO ratios consistent with those reported for other lignocellulosic biomass samples, including olive pomace and multiple feedstocks in fixed and fluidized bed reactors [54].

In contrast to the relatively small variations observed in syngas composition, the effect of temperature on by-product formation was more pronounced. Tar production decreased by approximately 24% between 600 and 700 °C, reaching a minimum value of 111.5 mL/h at the highest temperature tested. This behavior is significant, as tar formation is one of the main operational challenges in biomass gasification due to its propensity to foul and clog downstream equipment

[57]. Char formation also declined with increasing temperature, representing only 0.1 kg/h at 700 °C. The total syngas production rate remained relatively constant, ranging from 10.3 to 10.5 kg/h across all conditions, which is typical for systems operating within a narrow temperature window.

The CGE increased from 62.6% at 600 °C to 68.5% at 700 °C, corresponding to an overall increase of 9.4%. Similar temperature-related improvements in CGE have been reported in previous studies [55, 58], but this increase should be regarded as indicative rather than definitive, given the limited number of operating conditions investigated.

The mass balance of the acorn waste gasification reactor at 700 °C is represented in Fig. 3.

In the case of syngas and air, their mass flow was found by multiplying their volume by their corresponding density. Air density was determined as 1.222 kg/m³ (air density at sea level), and syngas density was calculated as 1.037 kg/m³ using data from Olanrewaju et al. [59]. Syngas represented 87.2% of the gasification products, followed by tar and unconverted material, which accounted for 11.7% and 1.1%, respectively.

At the system level, including syngas conversion in the internal combustion engine, 80.5% of the total input energy is converted into electricity, while the remaining 19.5% is transformed into other types of energy, including thermal and sound (Fig. 4). A fraction of the available thermal energy could potentially be recovered and reused within the system, for example to support biomass drying, thereby reducing the overall energy demand of the process. While Fig. 3 refers exclusively to the gasification reactor, the subsequent energy balance in Fig. 4 considers the integrated gasification–internal combustion engine system.

Techno-Economic Analysis

In this section, the term “system” is used to describe the integrated gasification–ICE-G configuration, encompassing the gasifier, gas cleaning units, and the electricity generation module.

To analyze the distribution of energy flows in each stream of the gasification system, an energy analysis was conducted using the first law of thermodynamics. Table 4 presents the steady-state mass and energy balance of the integrated downdraft gasification system coupled to an ICE-G, based on a nominal thermal input of 1.0 MW from acorn waste.

Fig. 3 Mass balance from the gasification of acorn waste at 700 °C

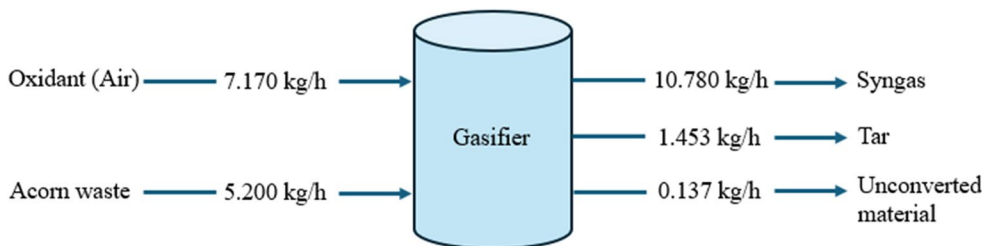


Fig. 4 Energy balance of the integrated gasification–ICE system operating with acorn waste at 700 °C

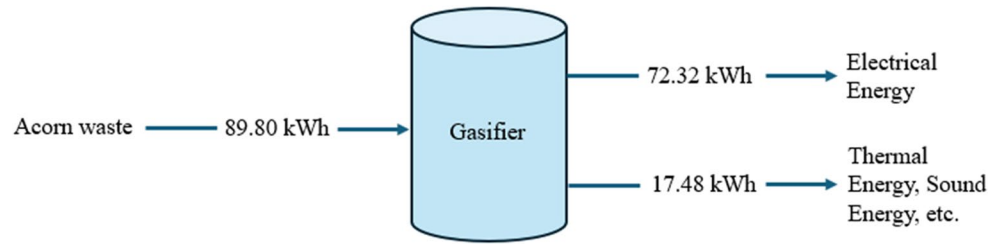


Table 4 Mass and energy flow rates of the integrated downdraft gasification and ICE-G system at nominal operating conditions (1.0 MW_{th} input)

Description	m (kg/h)	T (K)	P (kPa)	W (MW)
Biomass	244.2	298.2	101.3	1.00
Air gasifier	337.0	298.2	101.3	-
Syngas	505.6	298.2	101.3	0.69
Ash and char	75.6	298.2	101.3	0.31
Air ICE	5291.4	298.2	101.3	-
Electricity	-	298.2	101.3	0.24
Exhaust gas	5727.0	623.2	101.3	0.45

For the gasification system’s nominal capacity of 1.0 MW_{th}, with a gasifier energy efficiency of 68.5% and a biomass LHV of 14.4 MJ/kg, the estimated biomass consumption is approximately 244.2 kg/h. Given that the gasification system operates for 8,000 h annually, the total annual consumption of acorn waste is 1,959,184 kg, representing about 10.4% of the total biomass available in the municipality of Portalegre. Since approximately 55% of this biomass (equivalent to 10,403,280 kg) is unused, there is a substantial supply of acorn waste that can be effectively utilized for this purpose.

Figure 5 Sankey diagram illustrating the main energy flows of the integrated downdraft gasification–ICE-G) system operating with acorn waste at a nominal thermal input of 1.0 MW.

For simplification, the diagram focuses on the primary energy flows, including those within the biomass gasification system and the ICE-G used for electricity generation. The diagram reveals that the output energy is significantly lower than the input energy. Since energy cannot be created or destroyed, this discrepancy is due to substantial energy losses in the form of thermal, kinetic, sound, and other forms

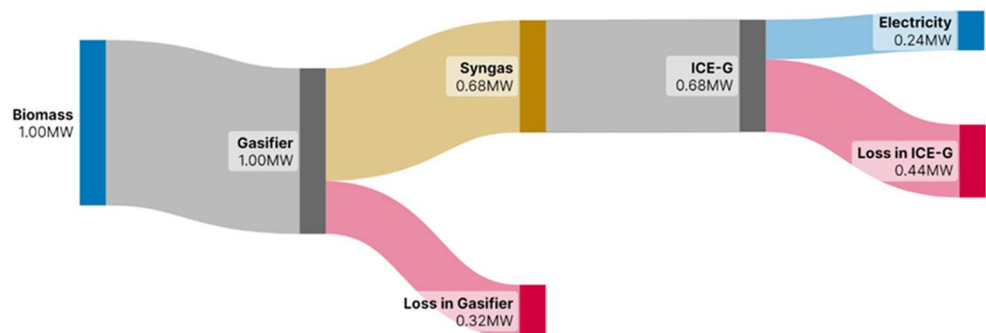
of energy that are not directly utilized. However, some of this “lost” energy, particularly thermal energy, can be recovered and reused within the gasification unit for various processes, such as biomass drying. Ultimately, electrical energy is the only form of energy sold to the grid to generate revenue.

During the gasification process, the energy contained in the acorn waste is converted into thermal and chemical energy in the form of syngas. The primary energy losses in this process, constituting 31.5% of the gasification system total losses, are due to thermal energy and discharged solids (ash and unconverted carbon). The syngas is then used as fuel in the ICE-G for electricity generation, where energy losses account for 44.5% of the total, primarily due to thermal energy loss in the exhaust gases and inefficiencies in the ICE-G. The overall efficiency of the proposed system is 24%, which aligns with the efficiency range reported in the literature, approximately 25% [60–62].

From an energy and environmental perspective, the performance of acorn-derived syngas was compared directly with that of natural gas (NG) on a mass basis, as both fuels can be used to generate electricity in the ICE-G system. Owing to its substantially higher LHV (46.0 MJ/kg), 1 tonne of NG can produce approximately 4.95 MWh of electricity, whereas 1 tonne of acorn-derived syngas yields roughly 0.65 MWh, reflecting the lower energy density of syngas generated from biomass gasification.

In terms of CO₂ emissions, producing 1 MWh of electricity with NG in the ICE-G results in approximately 0.47 tonnes of CO₂ emissions. In contrast, generating 1 MWh of electricity using syngas from the gasification of acorn waste in the ICE-G emits around 1.0 tonne of CO₂. Although CO₂ emissions are higher when using acorn waste compared to

Fig. 5 Sankey diagram illustrating the main energy flows of the integrated downdraft gasification–ICE-G) system operating with acorn waste at a nominal thermal input of 1.0 MW



NG for the same energy output, the advantage of biomass lies in its classification as carbon-neutral within the global CO₂ balance. Consequently, despite its lower specific energy content, syngas produced from acorn waste represents a renewable and climate-compatible alternative to fossil-based NG.

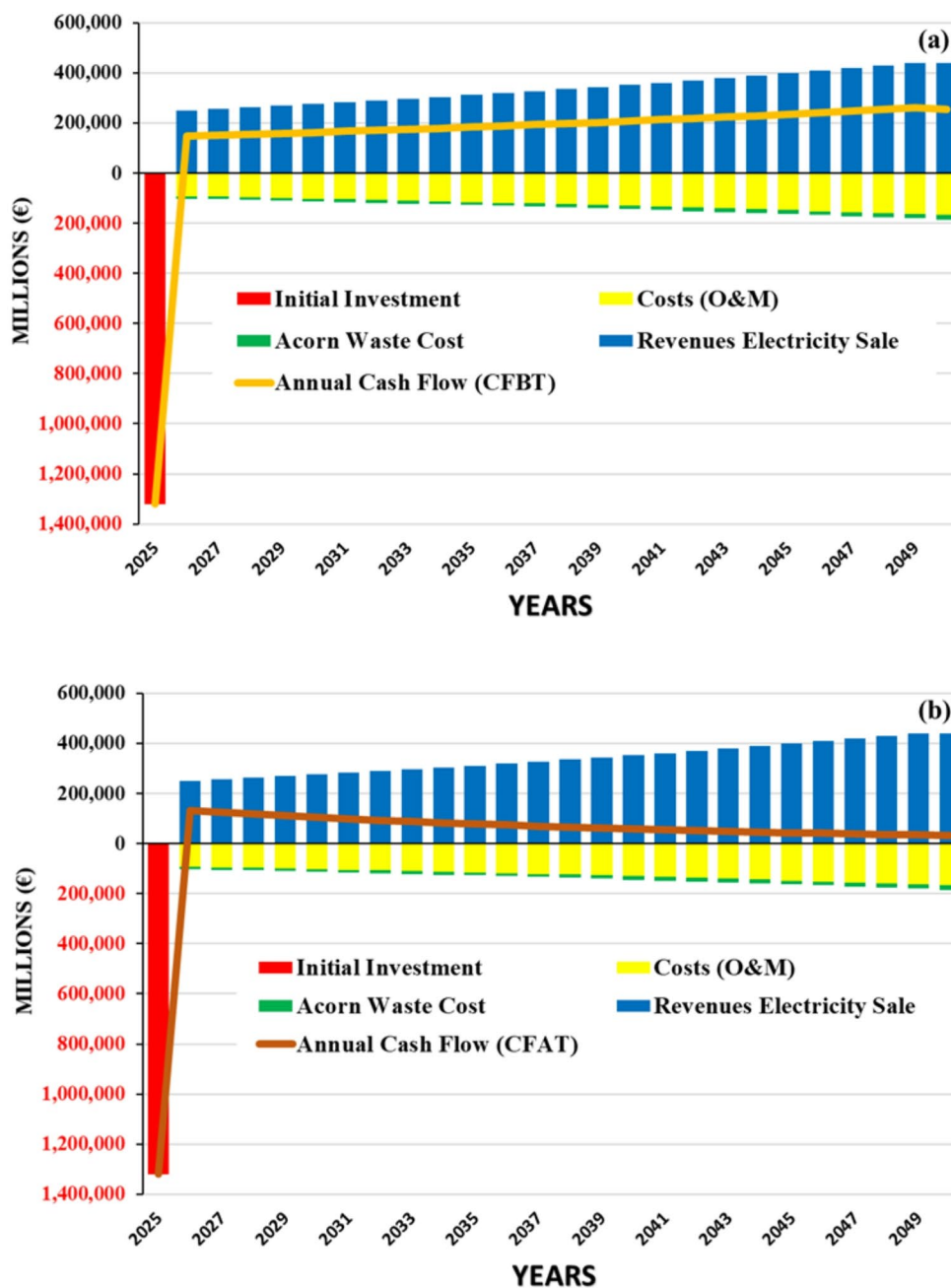
Figure 6 Cash-flows related to the initial investment that presents annualized costs and income throughout the useful lifetime of the system: (a) Pre-tax cash flow (CFBT) and (b) Post-tax cash flow (CFAT).

The initial investment, occurring in year 0, is approximately 1.32 M€, representing the substantial costs necessary to establish the system. The proposed system is

projected to have a 25-year operational lifespan. In the first year of operation, the project after-tax cash flow becomes positive as revenue generation begins. Revenue primarily comes from electricity sales, while expenses include O&M costs, personnel, structural costs, and biomass procurement. The system is expected to generate approximately 1,918.0 MWh/year throughout its operational life, resulting in average annual revenues exceeding 0.34 M€.

From the first year onward, cash flows are projected to increase steadily as revenues outpace expenses, both of which grow at the inflation rates set over the system's

Fig. 6 Cash-flows related to the initial investment that presents annualized costs and income throughout the useful lifetime of the system: (a) Pre-tax cash flow (CFBT) and (b) Post-tax cash flow (CFAT)



lifetime. Revenue growth underscores the importance of electricity sales prices in driving positive incremental cash flow. The financial analysis indicates that this system will be debt-free by the end of the 8th year of operation based on CFBT, and by the 14th year based on CFAT. Excluding the initial investment, which is reflected only during the investment period, O&M costs (crucial to keeping the system operational) account for approximately 90% of the total annual expenses, with acorn waste acquisition comprising the remaining 10%. This distribution of expenses is due to the high initial investment and the fact that O&M costs are calculated as a percentage of this investment.

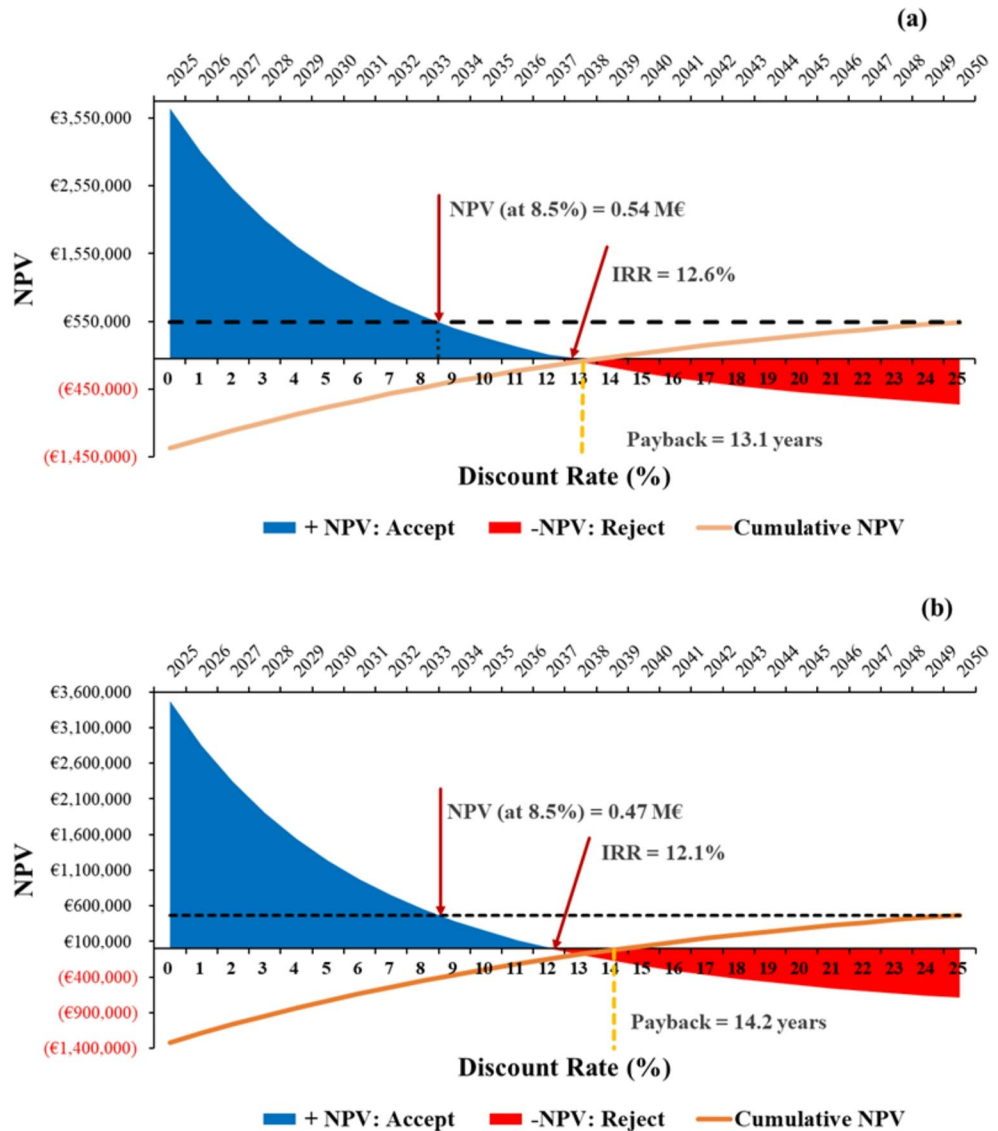
The economic viability of the project was assessed by analyzing key indicators, including NPV, LCOE, IRR, and payback. Figure 7 presents the results of this analysis.

The NPV was evaluated across a range of discount rates (0 to 25%) to determine the feasibility of the project.

A project is considered viable if its NPV is greater than zero, otherwise, it is rejected. The analysis shows that as the discount rate increases, the NPV decreases, indicating an inverse relationship between NPV and the discount rate. With an 8.5% discount rate, the projected NPV is 0.54 before tax and 0.47 M€ after tax. The IRR, the discount rate at which NPV equals zero, is 12.1% before tax and 12.6% after tax, showing only a slight difference of 0.5%. The LCOE, representing the total fixed and variable costs of electricity generation, is 0.10 €/kWh, which is lower than the electricity sales price of 0.12 €/kWh, indicating economic viability. Finally, the payback period (e.g., when the accumulated cash flow becomes positive) is 13.1 years before tax and 14.2 years after tax.

The economic indicators reveal that the project has a positive NPV, an IRR exceeding the discount rate, an LCOE lower than the sales value of electricity, and a Payback

Fig. 7 Financial indicators (NPV, IRR and payback) throughout the useful lifetime of the system: (a) Pre-tax cash flow (CFBT) and (b) Post-tax cash flow (CFAT)



shorter than the useful life of the system, affirming its economic viability. However, according to the World Bank Group's criteria for international financial cooperation, typical benchmarks for biomass projects suggest that the NPV should be positive, the IRR should exceed 10%, and the payback should be less than 10 years [39]. Although this project appears attractive to investors, the payback of 13.1 years slightly exceeds the World Bank's recommended 10-year threshold for biomass power generation projects. A longer payback tends to reduce the attractiveness for investors. It is also important to note that these criteria may vary depending on the specific conditions of each country and the economic evaluation methodology applied. A summary of the main results of this techno-economic evaluation is presented in Table 5.

Beyond the economic indicators discussed above, the proposed gasification system also presents relevant long-term sustainability and environmental implications. The valorization of acorn waste contributes to improved residue management in *Montado* systems, where uncollected biomass can accumulate and increase environmental pressures, including wildfire risk and nutrient losses. As a decentralized energy solution based on locally available biomass wastes, the system supports circular economy principles by improving resource efficiency, reducing transport-related emissions, and avoiding competition with food and feed resources [63]. Similar residue-based bioenergy systems have been identified in the literature as effective pathways for enhancing regional sustainability and promoting renewable energy deployment in rural areas [64, 65]. Although a detailed environmental life cycle assessment was beyond the scope of this study, the combined energy, economic, and CO₂ balance results indicate that acorn waste gasification has the potential to contribute positively to long-term sustainability objectives when integrated into regional bioenergy strategies [66].

Table 5 Summary of key techno-economic performance indicators for the acorn waste gasification system

Items	Acorn waste
Total capital cost (M€)	1.32
NPV _{CFBT} (M€)	0.54
NPV _{CFAT} (M€)	0.47
LCOE (€/kWh)	0.10
IRR _{CFBT} (%)	12.58
IRR _{CFAT} (%)	12.09
Payback _{CFBT} (Years)	13.14
Payback _{CFAT} (Years)	14.21

Conclusions and Future Prospects

Acorns are the fruit of several oak species and are traditionally used for animal feeding; however, a substantial fraction remains unused. In the Alentejo region of Portugal, approximately 45% of annual acorn production is left in the field, representing an underutilized biomass resource with potential for energy recovery.

In this study, the feasibility of converting acorn waste into electricity through fixed-bed gasification coupled with an internal combustion engine was assessed. The work combined physicochemical characterization, gasification experiments, mass–energy flow analysis, and a techno-economic assessment. The results demonstrate that acorn waste can be successfully gasified using air as the gasifying agent, producing a syngas suitable for electricity generation. Increasing gasification temperature improved process performance by reducing tar and char formation and enhancing cold gas efficiency, while methane concentrations remained stable and favourable for engine-based power generation.

From an energy and economic perspective, the proposed system achieved an overall electrical efficiency of 24% and showed economic viability, with a positive net present value, an internal rate of return exceeding the discount rate, and a levelized cost of electricity below the assumed sales price. These results indicate that acorn waste gasification can represent a technically and economically viable option for decentralized electricity production based on locally available biomass wastes.

Despite this potential, the practical deployment of such systems is strongly influenced by biomass mobilization and logistics. Acorn wastes are spatially dispersed across agro-silvo-pastoral landscapes, making collection, handling, and transport critical factors affecting both economic performance and environmental outcomes. Future research should therefore focus on optimized supply-chain configurations, decentralized or modular gasification concepts, and integrated residue management strategies that minimize transport distances and operational costs.

From a broader perspective, the valorization of acorn waste aligns with national and European policy objectives related to renewable energy deployment, circular economy principles, and the sustainable management of forest and agro-forestry systems. Supportive policy frameworks that encourage the use of endogenous biomass wastes, together with incentives for decentralized bioenergy solutions, could facilitate the practical implementation of acorn waste gasification and similar residue-based energy pathways.

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Data Availability Data are available from the corresponding author upon request.

Declarations

Competing Interests The authors have no relevant financial or non-financial interests to disclose.

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