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Techno-economic analysis of forest biomass blends gasification for small-scale power production facilities in the Azores

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ABSTRACT

The present work assesses the energetic valorisation of forest biomass blends in the archipelago of the Azores, to do so, a multiphase 2-D Eulerian-Eulerian model was employed to simulate forest biomass gasification in a pilot-scale fluidized bed reactor. The numerical model was validated under experimental gasification runs performed in a 250 kW_{th} quasi-industrial biomass gasifier. The potential use of the produced syngas as a complementary energy source for small-scale power production in the Azores was assessed based on the results. The exergy efficiency and tar production of the process were determined. A techno-economic study combining the net present value (NPV), internal rate of return (IRR), and payback period (PBP) followed by a Monte Carlo sensitivity analysis was comparatively performed for two distinct application sizes (100 and 1000 kW) so to gauge which unit size carries enhanced operative feasibility and foresee the main investment risks in conducting forest biomass blends gasification for power production in small facilities. Results revealed that the 100 kW unit was economically impracticable under current market conditions, while the 1000 kW unit showed to be economically feasible with an NPV of 486 k€, IRR of 17.44% and PBP of 7.4 years. The sensitivity analysis predicted a higher risk of failure in the NPV, being highly sensitive to the electricity sales tariff and electricity production. Indeed, forest biomass gasification projects carry great potential when applied to small facilities with economic viability in some economies of scales, withal, special concerns must always be considered regarding the project attractiveness to potential investors.

1. Introduction

Decades of worldwide dependence on fossil fuels foreshadowed a boom in renewable energy sources. The sounding climate change effects call out for an ecological emergency, with global leaders being urged to take sweeping measures to mitigate global carbon emissions. The urgency has never been greater and climate actions towards renewable and sustainable energy promotion are one of the hottest topics [1].

The production of useful energy from renewable sources provides an important contribution to the Azorean primary energy representing nearly 40% of the electricity generation, mainly coming from geothermal sources, followed by wind, hydroelectric and biomass (residual). The use of forest biomass as an energy resource in the archipelago offers a complementary solution to the current energy infrastructure [2]. Biomass gasification has become an attractive energy conversion process due to its high-efficient power production and enhanced environmental performance, aiding to fulfil the increasingly stringent energy demands while mitigating climate change and its impacts [3,4]. The Azorean forest stands and woodlands provide several wood species with high potential for energetic valorisation. Located in the middle of the northern hemisphere of the Atlantic Ocean, the Azores archipelago incorporates a total of nine islands being São Miguel the largest and also the most populated with a total area of 745 km^2 and 137,856 inhabitants. In São Miguel there are around 11 forestry species, out of which the most dominant are *Cryptomeria japonica*, *Pittosporum undulatum* and *Acacia Melanoxylon*, as shown in Fig. 1. Out of

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Nomenclature

β	gas-solid interface drag coefficient
$C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$	constants
C_p	specific heat capacity [$\mathrm{Jkg^{-1}K^{-1}}$]
G_n	turbulence kinetic energy [$\mathrm{m^2s^{-2}}$]
h_{pq}	heat transfer coefficient between the fluid phase and the solid phase [$\mathrm{Wm^{-2}K^{-1}}$]
k	thermal conductivity [$\mathrm{Wm^{-1}K^{-1}}$]
m	biomass flow into the gasifier [$\mathrm{m^3s^{-1}}$]
p	gas pressure [$\mathrm{kgm^{-1}s^{-2}}$]
Q_{pq}	heat transfer intensity between gas and solid phases [$\mathrm{Wm^{-2}sr^{-1}}$]
q_q	heat flux [$\mathrm{Wm^{-2}}$]
qth	specific enthalpy [$\mathrm{Jkg^{-1}}$]
S_n	source term
T	temperature [K]
U	mean velocity [$\mathrm{ms^{-1}}$]
v	instantaneous velocity [$\mathrm{ms^{-1}}$]
Y_m	contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate

Other symbols

α	volume fraction [$\mathrm{m^3m^{-3}}$]
ρ	density [$\mathrm{kgm^{-3}}$]
φ_{ls}	energy exchange between the fluid phase and the solid phase [$\mathrm{kgm^2s^{-2}(kgm^2s^{-2})^{-1}}$]
k_{Θ_a}	diffusion coefficient [$\mathrm{m^2s^{-1}}$]
$k_{\Theta_a}\nabla\Theta_s$	diffusion energy [$\mathrm{m^2s^{-1}(m^2s^{-1})^{-1}}$]
$(-P_s\bar{I} + \bar{\tau}_s){\sim}\nabla(\overrightarrow{v_s})$	generation of energy by the solid stress tensor
γ_{Θ_a}	collisional dissipation of energy [$\mathrm{Wm^{-3}}$]
τ	tensor stress [$\mathrm{kgm^{-1}s^{-2}}$]
μ	viscosity [$\mathrm{kgm^{-1}s^{-1}}$]
γ_c	stoichiometric coefficient [moles of *i*.moles of basis species^{-1}]

Subscripts

g	gas phase
s	solid phase
i	component

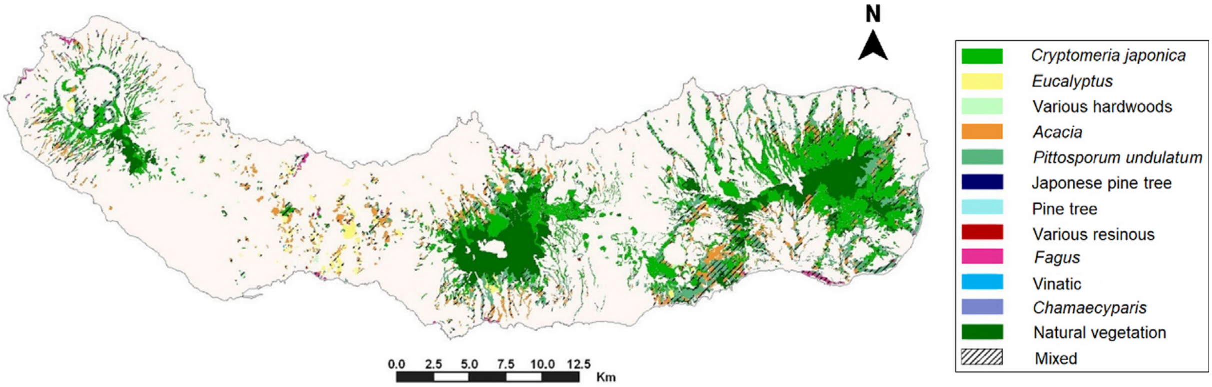

Fig. 1. Distribution of forested areas and its various species on the island of São Miguel, Azores [5].

these three, in São Miguel Island, *Cryptomeria japonica* is the most abundant, occupying circa 51.6% of the forest, followed by *Pittosporum undulatum* (22.7%) and *Acacia Melanoxylon* (17.9%) [5]. Invasive wood species are a current threat to the Azorean biodiversity conservation, altering plant community composition and structure. *Pittosporum undulatum* is the most widespread invasive species occupying up to 49% of the whole forested area in the Azores archipelago [6].

The biomass fuel potential of the main forest species in São Miguel Island was studied by Simas [5]. The author considered two distinct scenarios, one addressing by-products of the local timber industry jointly with some forest biomass, while the other estimated the total biomass potential from the main dominant forest species. Results showed that São Miguel revealed a biomass production capacity of 12,489.56 t/year and 37,461.85 t/year and energetic potential of 166,810.33 GJ/year and 532,854.08 GJ/year, according to each scenario.

Lourenço et al. [6] assessed the distribution of the most important woody plant invader in the Azores, *Pittosporum undulatum*. Main assumptions point out that its heating value and chemical composition makes it a good feedstock to be used in combustion or gasification processes. Also, the usage of *Pittosporum undulatum* biomass for useful energy production may trigger the gradual and sustainable cutting of this invader and its further replacement by endemic species.

Silva et al. [7] determined the biomass valorisation of *Pittosporum undulatum* in the Azores, it was found that considerable amounts of woody biomass are available in three Azorean islands (São Miguel included) and there is a need to control these non-indigenous plants by developing renewable energy projects. Furthermore, control actions valorise *Pittosporum undulatum* for biomass energy projects assigning its high potential for energetic valorisation due to its low ash content and high calorific value.

A set of gasification experiments with *Cryptomeria japonica* biomass were conducted by Ogi et al. [8]. Main results demonstrated that *Cryptomeria japonica* revealed good gasifying performance with the produced syngas showing suitability for catalytic liquid fuel synthesis and low tar yields.

Biomass-to-energy systems can be distinguished by distinct economies of scale, among these, biomass small-scale solutions earned increased interest over recent years [9]. Small-scale energy systems showed to be more feasible and cost-effective to install in certain regions rather than conventional large-scale systems [10]. This is true as these systems play a significant role in providing energy access to decentralized areas and/or rural households communities, particularly in developing countries, bearing alternative electric power solutions to communities where connection to the central grid is economically unfeasible [11,12].

The use of small-scale biomass gasification systems works effectively when biomass feedstock is locally available, avoiding the complex operation logistics of larger units, reducing fuel supply transportation costs while providing electric power to the surrounding areas.

Therefore, in decentralized areas with biomass readability such as in São Miguel Island, small-scale biomass power technologies could be a potentially sustainable solution for addressing the required local energy needs as well as manage the attendance of plant invaders.

Thus, the goal of this paper is to assess the gasification of forest biomass blends residues and its techno-economic viability in small-scale gasification facilities in São Miguel Island, Azores. The contributions of this work rely on a thorough application analysis of these feedstock's in this particular region on quasi-industrial conditions in a 250 kW_{th} bubbling fluidized bed reactor. For this purpose, experimental gasification runs gathered from a quasi-industrial biomass gasifier were employed to validate the computational fluid dynamics (CFD) mathematical model. The exergy efficiency and tar production of the process were evaluated. A techno-economic evaluation alongside with a Monte Carlo sensitivity analysis was comparatively performed on two distinct small-scales (100 and 1000 kW) so to determine the application size that carries greater potential from an economic standpoint. Lastly, an environmental and policy assessment is addressed endorsing the impacts and prospects in deploying a small-scale gasification system as compared to conventional diesel generators.

1.1. *Small-scale energy systems for decentralized electrification*

According to the World Bank Group [13], about 840 million people worldwide do not have regular access to electric power. A significant portion of this number refers to people living in decentralized areas in which the demand for national grid electrification does not justify the investment [14]. The International Energy Agency (IEA) points out that as much as half of the electricity access to these communities will need to arrive from off-grid solutions [15].

Conventional diesel generators are commonly applied for decentralized electrification solutions. However, in such cases, electric power production may fare expensive due to high diesel fuel costs, hampered by fuel prices fluctuations and additional costs related to fuel transportation to remote and isolated sites [14].

Renewable energy sources are proving to be a clean, reliable and efficient option for decentralized electrification, not requiring regular fuel supply and being cost-competitive with diesel generators [16]. With the technology maturation, several small-scale off-grid solutions can be found such as biomass-fuelled systems, small wind generators, solar photovoltaic (PV), small hydropower, hybrid systems or even fuel-cell based systems [17]. Throughout this section, special concern will be delivered to biomass, wind and solar PV systems.

Small wind generators can be found commercially available delivering an energy output as a function of the average wind speed. Yet, whereas wind power generation has proven its effectiveness at large commercial scales, the same does not apply to small-scale whose performances often fall behind expectations [18].

Solar PV is one of the available solutions for decentralized electrification. These sorts of systems can be utilized for any electrical application in decentralized areas both in developed or developing countries. However, solar PV is highly dependent on site and weather (solar irradiance and sunshine hours) and in load demand [19].

Biomass is a key source of renewable energy and biomass-generated electricity can be very competitive whenever affordable feedstocks are locally available [20]. According to REN21 Report [21], in 2018 the global bioenergy electricity capacity (traditional biomass included) was set around 130 GW and may increase up to 35% of the world's primary energy by 2050 [22]. Furthermore, in IRENA's vision for 2030, biomass will contribute to the global renewable energy consumption with the largest share as compared to wind and solar PV with approximately 77.3 EJ/year as described in Fig. 2. The values in the grey circles depict the approximate growth in the global renewable energy use by resource from 2010 to 2030 in EJ/year.

Small-scale biomass gasification systems became popular for off-grid purposes due to its cost-effectiveness and high plant load factor. One of the constraints in these systems is requiring uninterrupted feedstock supply throughout its project lifetime, which may concern less far willing investors. Biomass-based systems provide an important asset particularly in rural areas where additional residues from agricultural and timber industry are also easily accessible. Plus, biomass exploration provides a helping hand towards wildfire hazards reduction by promoting forest biomass harvesting and cleaning in over-grown areas [24]. These units have already proved their suitability for power generation in provincial household clusters being already widely used for rural electrification solutions. In fact, for decentralized communities requiring low electrical load demand, biomass gasification systems proved to be more cost-competitive than solar PV or even grid electrification [25].

Concerning the current status of bioenergy in Portugal (the Azores included), biomass provides about 13% of the total primary energy consumption, about 50% of the total renewable energy share, contributing with a total electrical power of 2.8 TWh in 2018 [26,27]. Economy-wise the technologies based on renewable energy for electricity production with greater impact on the Portuguese Gross Domestic Product (GDP) are solar and wind, once these sectors dispose of factories operating and developing on these systems further promoting these renewable sectors growth, as depicted in Fig. 3. Still, to attract private investors, the Portuguese Government has established a favourable tariff for energy generated from biomass, around 121.34 €/MWh, the second-highest tariff on renewable energies production, being preceded by solar PV with about 291.20 €/MWh and followed by wind with 97.55 €/MWh [28]. As for small-scale off-grid solutions allocation, since 2014 thanks to the publishing of the Decree-Law n°. 153/2014, set to promote the installation of small-scale units (up to 1 MWe) for prosumers and small to medium-sized businesses, solar PV has been leading the way in the Portuguese energy market with an installed capacity of about 252 MWe in this scale range [29].

Choosing the most appropriate technology is a pivotal deed in which one must weigh in several practical considerations such as, technology maturity and standardization, yearlong resources adequacy, stable feedstock supply (biomass-fuelled systems), user-friendliness, access to maintenance and repair, to name a few [19]. Given the load demand, location characteristics and the wood plant invaders paradigm of the São Miguel Island, scattered autochthonous communities, or even small businesses, may indeed benefit from biomass-fuelled small-scale solutions, mostly thanks to free and easy access to local biomass through short supply chains capable of ensuring continuous energy feed regardless of climatic conditions on the short-to-medium term.

Positively, off-grid small-scale renewable energy solutions do have the potential to mould the way we grasp the power sector, with main assets lying within its inferior set-up capital, suitability for rapid development and easiness in reaching last-mile customers, as opposed to grid extension solutions.

2. Experimental setup

The gasification experiments were conducted in a quasi-industrial

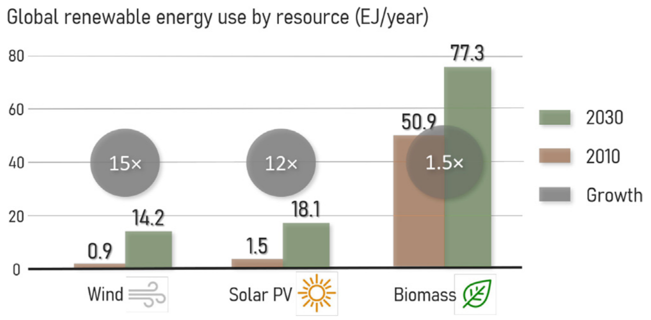

Fig. 2. Global renewable energy consumption prediction for 2030 [23].

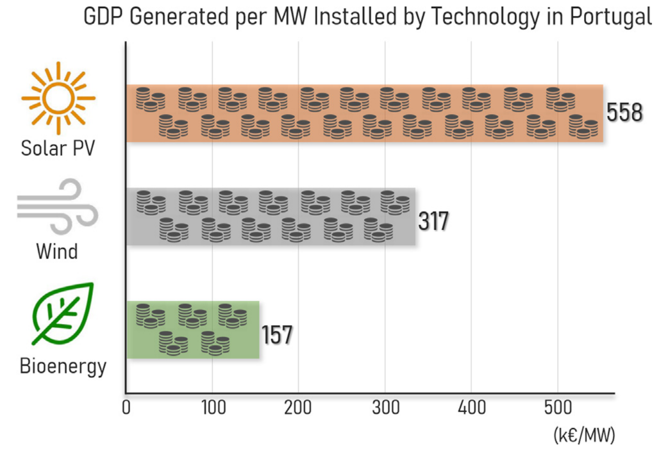

Fig. 3. Renewable energy technologies for electricity production with greater impact on the Portuguese economy [30].

gasification plant located in the Alentejo region at the Polytechnic Institute of Portalegre, Portugal. The proximate and elemental analyses of the used feedstocks are shown in Table 1. The experimental gasification runs were performed with forest residues and vine-pruning since their chemical compositions are very similar to *Cryptomeria japonica*'s, allowing to attain the proper trends so to further validate the mathematical model developed to deal with this Azorean feedstock. *Cryptomeria japonica* was selected to validate the model once it embodies the majority of the forest biomass blend to be considered in the Azorean scenario. The experimental apparatus is depicted in Fig. 4a and b.

The unit carries a 250 kW_{th} bubbling fluidized bed gasifier, 0.5 m wide and 4.15 m height, thermally isolated by a ceramic refractory material coating its interior. Biomass feedstock is delivered into the reactor at a height of 0.4 m from distributor plate, a preheated airflow is delivered within the reactor through a set of diffusers in the distributor plate. The bed has a static height of 0.15 m and is composed of 70 kg of dolomite (calcium magnesium carbonate $CaMg(CO_3)_2$) ranging in size between 0.3 and 0.7 mm. The dolomite use as bed material is considered advantageous once it is cheap and exhibits catalytic tar cracking and anti-sintering properties. The reactor operates under atmospheric pressure with a maximum feedstock rate of 70 kg/h and at the bottom of the reactor a set of diffusers deliver an approximate flow of 70 m^3/h of preheated air at 350 K. The gas-cooling system is composed by two heat exchangers, the first cools the syngas to 570 K using a co-current air flow entering the unit, while the second cools the syngas to about 420 K by forced flow of air from the exterior. The black carbon and ash particles produced during the gasification process are collected into a bag and a condenser is used to withdraw the liquids from the syngas by cooling it to room temperature in a tube heat exchanger. Gas sampling bags are used to collect the syngas samples at the condenser outlet once the gasification process reaches steady-state operation. Syngas samples are then analysed in a gas chromatograph within one hour after collection. Additional details on all remaining components are fully addressed in [31,32].

3. Mathematical model

The implemented 2-D Eulerian-Eulerian mathematical model was firstly developed by Silva et al. [31]. Complex phenomena concerning the gasification process for the fluidized bed reactor is simulated by means of a multiphase (gas and solid) model within the ANSYS Fluent framework. The gas-phase was considered as a continuum, and the solid phase was modelled following a Eulerian granular model. Interactions between phases were modelled as well, with both phases exchanging heat by convection, momentum (due to drag between phases), and mass (given the heterogeneous chemical reactions). To appropriately describe the hydrodynamic phenomena within the fluidized bed reactor the standard k-ε turbulence model is applied. The heat transfer between the solid and gas phases, the viscous dissipation, and the expansion work is described by the energy conservation equation. In the chemical reaction model, the kinetic/diffusion surface reaction model portrays the heterogeneous reactions, and the finite-rate/eddy-dissipation model is used to describe the homogeneous gas-phase reactions. Table 2 summarizes the main governing equations for both gas and solid phases and the hydrodynamic model. Table 3 provides the devolatilization model, main chemical reactions and reaction rates coefficients (based on the Arrhenius law) in the chemical model. Since the present model has already been extensively documented in recent literature published by the research group, only key points will be highlighted. Further details on the model can be found elsewhere [31,33].

4. Results and discussion

4.1. Model validation

To validate the model a total of six gasification experiments, three using forest residues and three using vine-pruning as fuels, were performed with atmospheric air being used as gasification agent. Table 4 shows the operating conditions and syngas analysis for the six experiments used to validate the numerical model. The remaining syngas fraction respects to nitrogen (N_2) yet it is not here shown for the sake of simplification. As the research group already possessed a broad set of experimental data for forest residues and vine-pruning gasification, previously thoughtfully employed to validate numerous works [31], and given the chemical similarity between the considered biomass feedstocks, it is then feasible to validate the numerical results obtained from the simulation of *Cryptomeria japonica* gasification with the experimental data of forest residues and vine-pruning. Nevertheless, despite the overall chemical similarities, a slight difference was measured for the ashes in the elemental analysis between *Cryptomeria japonica* and vine-pruning (Table 1).

Fig. 5 presents the relative deviations between the experimental forest and vine-pruning residues and numerical *Cryptomeria japonica* syngas species. Results show that the mathematical model was capable to correctly predict the syngas compositions for the six experiments. A maximum error of 20% was delimited within the dashed lines, which is a reasonable margin for such a complex process as biomass gasification in a quasi-industrial fluidized bed reactor [31]. The largest deviations were measured for the smaller fractions, methane gas (CH_4), around 19%, such behaviour is justifiable once smaller fractions tend to favour higher relative errors. For simplification purposes, only six experiments were considered here, once the mathematical model applied in this study has already been thoroughly validated concerning the syngas compositions from multiple gasification agents and feedstocks at various operating conditions, strengthening the accurate predictability of the mathematical model in a broad range of applications [34,35].

Table 1
Biomass feedstock's properties.

Biomass properties	*Cryptomeria japonica*	*Forest residues*	*Vine-pruning*
Proximate analysis (%)			
Moisture	9.33	10.30	11.80
Ash	0.43	0.20	2.10
Volatile matter	78.13	75.80	73.60
Fixed carbon	12.11	13.70	12.50
Elemental analysis (%, dry basis)			
C	50.63	43.00	41.30
H	6.06	5.00	5.50
N	0.09	2.40	2.60
O	43.22	49.60	50.60

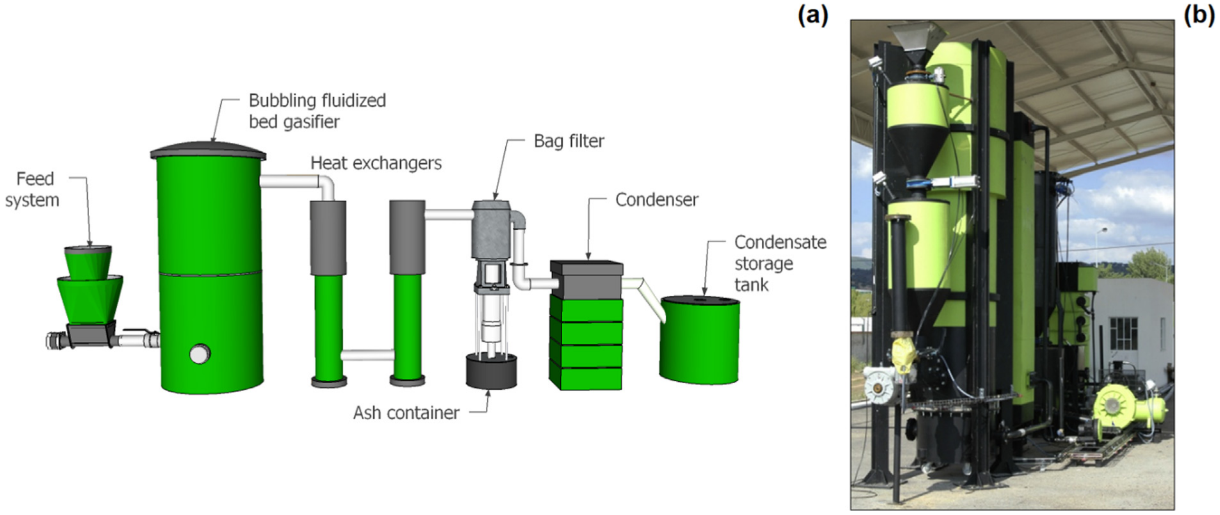

Fig. 4. Gasification unit description: (a) schematics of the biomass gasification plant, and (b) photograph of the installation.

Table 2
Conservation equations and hydrodynamic model for both gas and solid phases.

Conservation equations
Energy (gas phase):
$\frac{\partial(\alpha_q \rho_q h_q)}{\partial t} + \nabla(\alpha_q \rho_q \vec{v_q} h_q) = -\alpha_q \frac{\partial(p_q)}{\partial t} + \bar{\tau_q}\colon \nabla\vec{v_q} - \nabla\vec{q_q} + S_q + \sum_{p=1}^{n}(\vec{Q}_{pq} + \dot{m}_{pq} h_{pq})$
Mass (gas phase):
$\frac{\partial(\alpha_g \rho_g)}{\partial t} + \nabla\bullet(\alpha_g \rho_g v_g) = S_{gs}$
Momentum (gas phase):
$\frac{\partial(\alpha_g \rho_g v_g)}{\partial t} + \nabla\bullet(\alpha_g \rho_g v_g v_g) = -\alpha_g \nabla p_g + \alpha \rho_g g + \beta(v_g - v_s) + \nabla\bullet\alpha_g \tau_g + S_{gs} U_s$
Energy (solid phase):
$\frac{\partial(\alpha_p \rho_p h_p)}{\partial t} + \nabla(\alpha_p \rho_p \vec{v_p} h_p) = -\alpha_p \frac{\partial(p_q)}{\partial t} + \bar{\tau_p}\colon \nabla\vec{v_p} - \nabla\vec{q_p} + S_p + \sum_{p=1}^{n}(\vec{Q}_{pq} + \dot{m}_{pq} h_{pq})$
Mass (solid phase):
$\frac{\partial(\alpha_s \rho_s)}{\partial t} + \nabla\bullet(\alpha_s \rho_s v_s) = S_{sg}$
Momentum (solid phase):
$\frac{\partial(\alpha_s \rho_s v_s)}{\partial t} + \nabla\bullet(\alpha_s \rho_s v_s v_s) = -\alpha_s \nabla p_s + \alpha \rho_s g + \beta(v_g - v_s) + \nabla\bullet\alpha_s \tau_s + S_{sg} U_s$
Hydrodynamic model
Kinetic energy:
$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}\bullet(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\right] + G_k + G_b - \rho\varepsilon - Y_M + S_k$
Dissipation rate:
$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_i}\bullet(\rho\varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + G_{3\varepsilon} G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + S_\varepsilon$
Granular Eulerian model:
$\frac{3}{2}\left[\left(\frac{\partial(\rho_s \alpha_s \Theta_s)}{\partial t} + \nabla\bullet(\rho_s \alpha_s \vec{v_s} \Theta_s)\right)\right] = (-P_s \bar{I} + \bar{\tau_s})\colon \nabla(\vec{v_s}) + \nabla\bullet(k_{\Theta a} \nabla(\Theta_s)) - \gamma_{\Theta a} + \varphi_{ls}$

4.2. Exergy efficiency and tar content

An exergy analysis conjoins energy, environment and sustainable development, being employed to target opportunities for process improvement and assess distinct process alternatives. Thus, to better understand the effects of substrate and operational parameters on the reactor performance the exergy efficiency of syngas and tar were determined and calculated as follows [36]:

$$\varepsilon_{syngas} = \frac{Ex_{syngas}}{Ex_{biomass} + Ex_{steam} + Ex_{heat}} \tag{1}$$

$$\varepsilon_{tar} = \frac{Ex_{tar}}{Ex_{biomass} + Ex_{steam} + Ex_{heat}} \tag{2}$$

where, ε_{syngas} and ε_{tar} are the syngas and tar exergy efficiencies, respectively, and Ex is the exergy rate.

Fig. 6 illustrates the calculated exergy efficiency and tar content for various reactor operating temperatures. Results show that gasification temperature has a strong influence on both exergy efficiency and tar content. Exergy traduces the quality of energy and is defined as the amount of energy available to be used [37]. Here, its analysis may be used to measure the efficiency of the gasifying unit by allowing to identify the maximum theoretical capability of energy system performance. The exergy efficiency increases with the gasification temperature, as both endothermic reactions and gaseous products yield come enhanced. The tar concentration in the producer gas comes gradually reduced with the temperature increase, promoting tar decomposition and reforming, while lower temperatures promote tar condensation. These results are consistent with the current literature [38]. The forest residues and vine-pruning gasification process showed a reasonable exergy efficiency, around 50 to 67%, making this process fit to produce syngas for electricity production in small facilities. For simplification purposes, additional details concerning the employed exergy model can be found in [39].

5. Techno-economic analysis

5.1. Methodology

A techno-economic analysis is developed to assess the economic feasibility from an investor point of view of this project along a predefined lifetime period. As an endeavour to bring this analysis as close as possible to a real practical application, this study was built based on literature review concerning investment projects in small gasification facilities [24,40,41]. The dairy industry has a decisive impact on the economy of the island, given its volume of sales, exports and also the high number of workers in the sector [42]. Therefore, two proposed unit sizes one with 100 kW and the other with 1000 kW are comparatively addressed so to evaluate which unit size is more economically feasible in this application. These small-scale gasification plants are lodged within a dairy industry located near a forest landing for higher biomass availability with impact on transport costs and profitability of the supply operation. A near existing power line to connect the unit to the grid is also assumed. A capital cost of 1760 €/kW is assumed for the 100 kW unit, while a capital cost of 1320 €/kW is assumed for the 1000 kW, as a result of economies of size relating to the deployment of a larger unit [40]. The two projects are considered to extend to a total of 10 years lifetime (start-up phase in 2019 for initial investment and deployment, and an operation phase from 2020 to 2029). The plants' lifetime is set to 10 years once according to the manufacturer major plant refitting will probably be necessary after 10 years [40]. A feedstock supply plan scenario established with local forest producers and

Table 3
Chemical reactions model.

$Biomassdevolatilization \rightarrow char + volatiles + watersteam + ashVolatiles \rightarrow \alpha_1CO + \alpha_2CO_2 + \alpha_3CH_4 + \alpha_4H_2 Reactionrate: r_1 = A_i exp\left(\frac{-E_i}{T_S}\right)(1 - a_i)^n$	
Homogeneous reactions:	Arrhenius reaction rate:
$CO + 0.5O_2 \rightarrow CO_2$	$r_2 = 1.0 \times 10^{15} exp\left(\frac{-16000}{T}\right) C_{CO} C_{O_2}^{0.5}$
$CO + H_2O \rightarrow CO_2 + H_2$	$r_3 = 5.159 \times 10^{15} exp\left(\frac{-3430}{T}\right) T^{-1.5} C_{O_2} C_{H_2}^{1.5}$
$CO + 3H_2 \leftrightarrow CH_4 + H_2O$	$r_4 = 3.552 \times 10^{14} exp\left(\frac{-15700}{T}\right) T^{-1} C_{O_2} C_{CH_4}$
$H_2 + 0.5O_2 \rightarrow H_2O$	$r_5 = 2780 exp\left(\frac{-1510}{T}\right)\left[C_{CO}C_{H_2O} - \frac{C_{CO_2}C_{H_2}}{0.0265 exp\left(\frac{3968}{T}\right)}\right]$
$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	$r_6 = 3.0 \times 10^{5} exp\left(\frac{-15042}{T}\right) C_{H_2O} C_{CH_4}$
Heterogeneous reactions:	Arrhenius reaction rate:
$C + 0.5O_2 \rightarrow CO$	$r_7 = 596 T_p exp - \left(\frac{1800}{T}\right)$
$C + CO_2 \rightarrow 2CO$	$r_8 = 2082.7 exp - \left(\frac{18036}{T}\right)$
$C + H_2O \rightarrow CO + H_2$	$r_9 = 63.3 exp - \left(\frac{14051}{T}\right)$

Table 4
Experimental operating conditions and syngas analysis.

Gasification run	*Forest residues*			*Vine-pruning*		
	1	2	3	4	5	6
Temperature (K)	1088	1088	1063	1063	1063	1088
Biomass feed rate (kg/h)	63	74	63	25	55	55
Air flow rate (Nm^3/h)	94	98	98	52	40	40
Syngas flow rate (Nm^3/h)	106	94	100	107	108	102
Syngas fraction (dry basis)						
H_2	8.2	8.4	7.6	5.1	10.4	12.7
CO	18.6	18.0	17.9	8.3	11.7	14.1
CH_4	4.6	4.4	4.4	1.1	2.4	2.3
CO_2	16.7	17.1	17.1	16.5	20.1	17.9

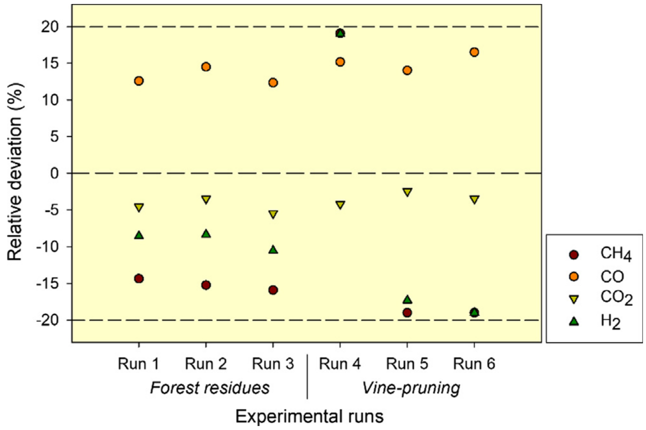

Fig. 5. Experimental and numerical syngas component (CH_4, CO, CO_2, H_2) fraction relative deviation.

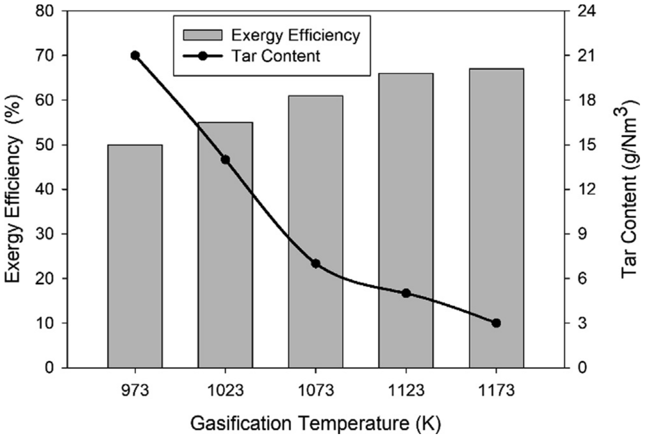

Fig. 6. Influence of temperature on calculated exergy efficiency and tar concentration in the producer gas.

associations is assumed. This strategic partnership is important given the direct influence to the development of biomass and forest management in the region (specifically in the control of the invader species *Pittosporum undulatum*) further ensuring the future supply to the small-scale plant. Forest biomass harvesting and collection is assumed to occur mainly by cut-and-chip process on-site, followed by direct transportation to the plant for storage and processing at a cost of 35 €/ton (including transportation expenses) [24]. The small-scale plants will operate by consuming residual forest biomass blends up to a minimum of 90% of the total fuel burned, however, other timber industry wastes or agriculture/natural vegetation wastes may also complement the forestry blends primary fuel. The use of forest biomass blends gasification allows increasing the supply efficiency while avoiding feedstock disruption. The plants' provisioning policy will be directed preferentially to blends of *Cryptomeria japonica*, *Pittosporum undulatum* and *Acacia Melanoxylon*. An average consumption of 1132 tons/year for the 100 kW unit and 11,324 tons/year for the 1000 kW unit are estimated, with an electric power output of 787 MWh/year and 7876 MWh/year, respectively, all considering a baseload annual operation time of 7160 h (in accordance with the literature for forest biomass gasification in small-scale gasification systems) [40]. The operation of both units is assumed to be monitored by workers already performing other tasks, therefore neither units require dedicated labour allowing to save on employees related costs, identical assumptions can be found assumed in the literature [40]. Most of the electrical energy generated is used to reduce the primary energy demands, but 45% of the production is assumed to be sold to the national grid for profitability purposes. In this study no heat sales are considered, all produced thermal power is assumed to be used for biomass drying and producing additional electricity by means of an intern heat recovery system.

Table 5 details the economic assumptions used to build the spreadsheet-based economic model developed to calculate the project's net present value (NPV), internal rate of return (IRR) and payback period (PBP). These three methods are important common indicators in investment decisions [41]. The considered cash flows for costs and revenues calculations were: initial investment (equity and borrowed

Table 5
Economic assumptions for the 100 and 1000 kW small-scale gasification plants [24,40,41].

Economic parameters	100 kW unit	1000 kW unit	Observations
Discount rate (%)	10	10	–
Inflation rate (%)	1.6	1.6	Inflation rate applied in 2020.
Equity capital (30%) (k€)	52	396	Values applied during the investment period. Comprises costs related to credit opening, whole plant equipment acquisition (gasifier, turbine, producer gas cleaning system) and electric power line construction.
Borrowed capital (70%) (k€)	123	924	
Amortizations (k€)	11	88	Amortizations value in 2020. Comprises the regular debt payment throughout the plant lifetime and insurance.
O&M costs (k€)	12	92	Value applied in 2020 (7% of the capital cost (equity and borrowed)). Comprises all consumption costs with the facility, namely forest biomass transportation to the dairy industry, biomass pre-treatment, ash transport and deposition into landfill, and maintenance of the equipment and facility.
Total annual costs (k€)	24	181	Value for 2020.
Power output parameters			
Electricity production (MWh/year)	787	7876	Considering the baseload operation time of 7160 h.
Electricity sold to the grid (MWh/year)	354	3544	45% of the total electricity production is sold to the grid.
Electricity sales tariff (€/MWh)	121.34	121.34	Tariff applied in 2018.
Revenues			
Annual revenue (k€/year)	42	430	Revenues from electricity sales to the grid in 2020.

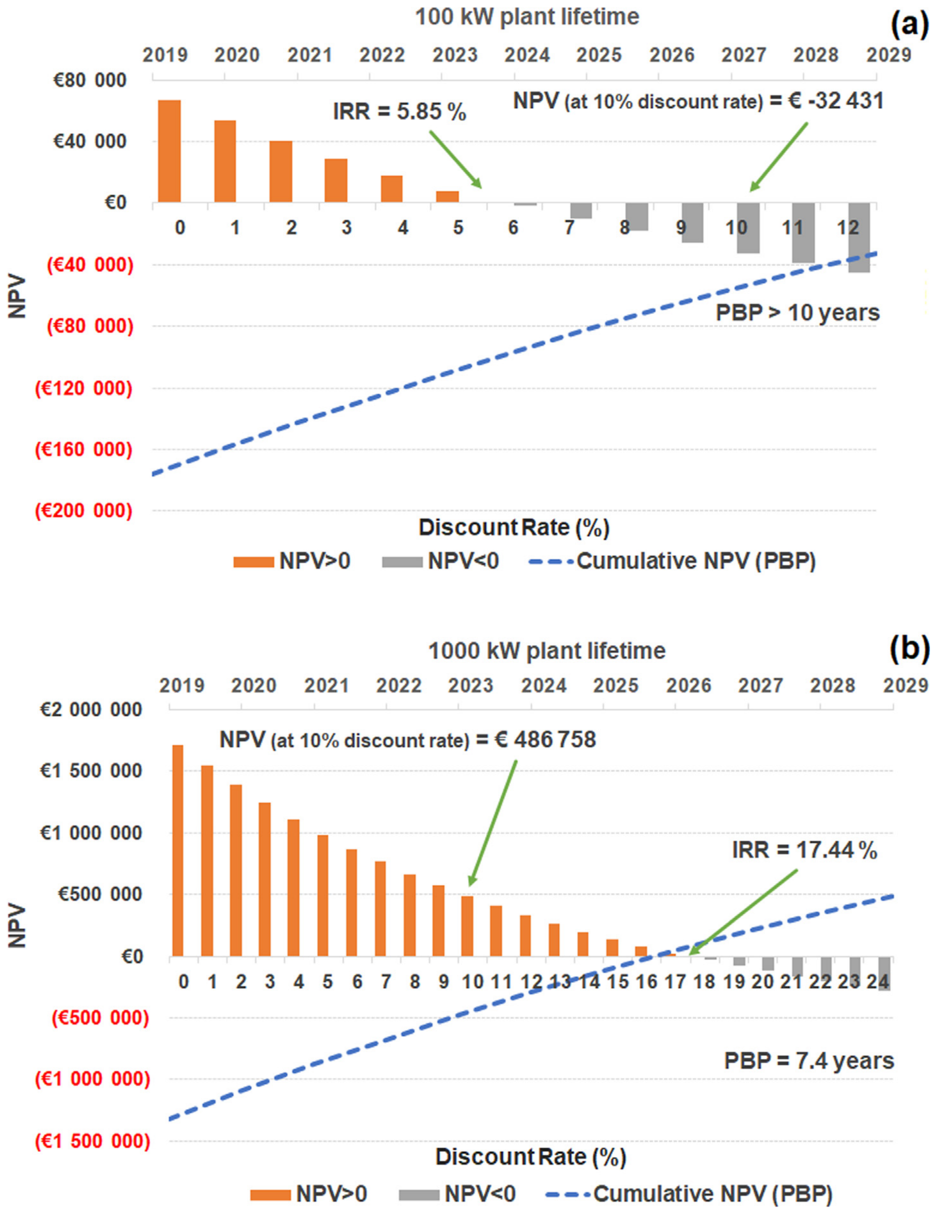

Fig. 7. NPV profile variation as a function of the discount rate, IRR and PBP given out by the cumulative NPV for the: (a) 100 kW plant and (b) 1000 kW plant.

capital); amortizations; O&M costs (includes biomass processing and transportation costs); and revenues from electricity sales to the grid. All cash flows, except the initial investment occurring only in the start-up phase of the project, extend throughout the 10 years lifetime of the project, with all costs and revenues being updated to the year they correspond to. The total annual cash flow is given by the sum of all the costs and revenues for each year. The annual revenue is given by multiplying the annual electricity production by electricity sales tariff in the same year. The annual cash flow is resolved by balancing the total annual costs, revenues, and electricity savings. A discounted cash flow is determined by dividing the annual cash flow in each year by the unity plus the calculated discount rate elevated to the relating year. Lastly, the cumulative NPV is determined to provide the present worth of negative and positive investment cash flow. All the analysis is performed at current prices, revenues, and current value-added taxes rates. The implemented inflation rates for 2020 and 2021 are based on the forecasts provided by the Bank of Portugal. After 2022 the applied inflation rate is the calculated average of the last 10 years. All implemented tariffs and prices progression along the project lifetime are amended in agreement with the Consumer Price Index provided by the National Statistical Institute of Portugal. Amortization rates are in accordance with the straight-line method, and all interest rates considered result from the quotations provided by Portuguese banking for this type of projects.

Fig. 7a and b, show the economic model results for the NPV, IRR and PBP calculations. The NPV method states that an investment should be accepted if the NPV > 0 and rejected if the NPV < 0. The IRR is the expected return rate offered by the project and is given by the moment at which the NPV equals to zero. The PBP is the year in which the cumulative cash flow turns positive providing the exact amount of time needed to recover the initial capital investments made. For the 100 kW small-scale gasification plant project the calculated NPV at the discount rate of 10% is negative and equal to −32 k€, the IRR rate is 5.85% and PBP is 13.8 years, thus, superior to the 10 years project lifetime (Fig. 7a). Concerning the 1000 kW plant project, the NPV resulted in 486 k€, the IRR in 17.44% and PBP in 7.4 years (Fig. 7b).

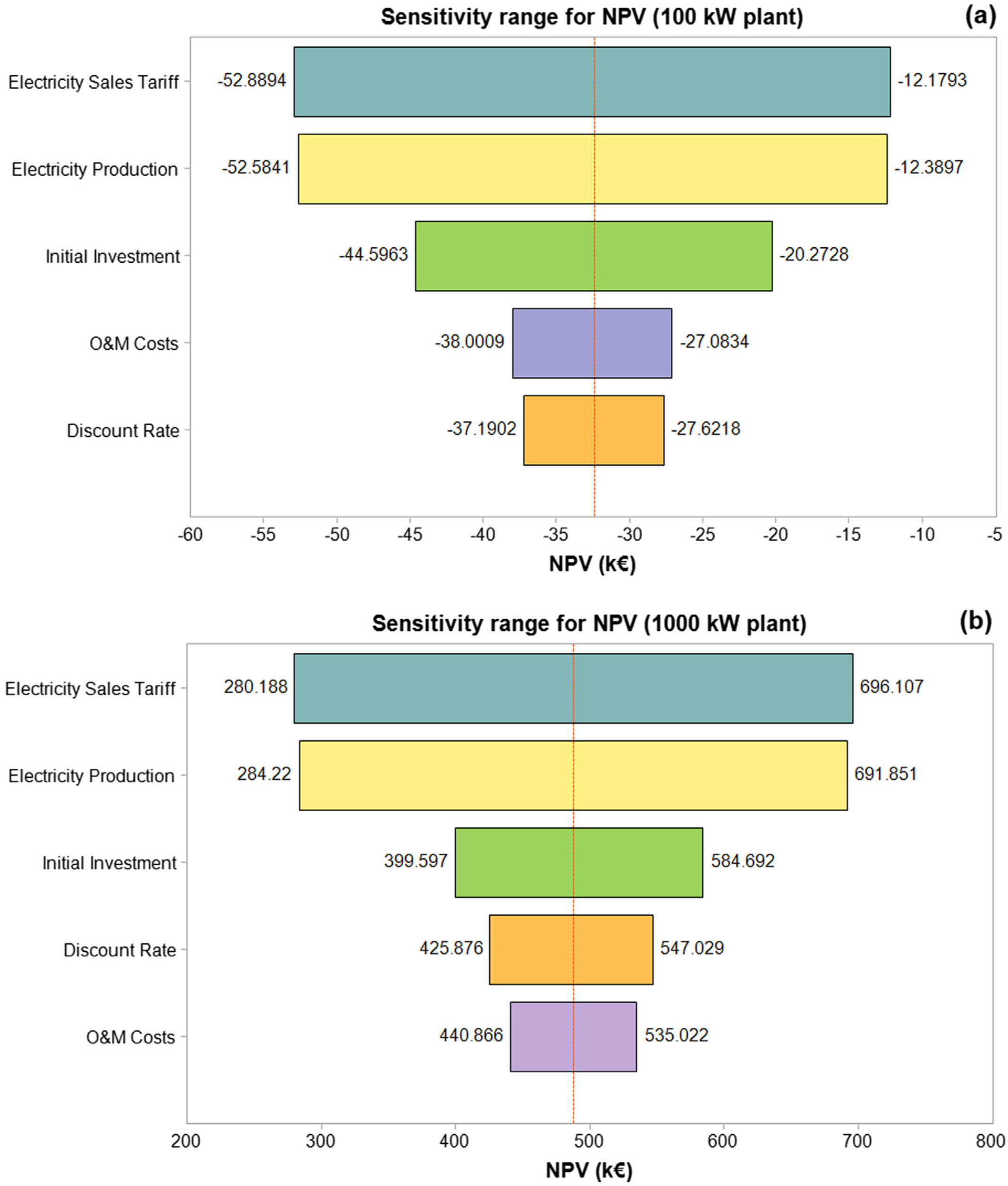

Fig. 8. Sensitivity analysis range to input variables for NPV: (a) 100 kW plant, (b) 1000 kW plant.

In general, the financial indicators clearly point out that only the 1000 kW project is economically feasible, by presenting a positive NPV, an IRR higher than the discount rate, and a PBP inferior to the plant lifetime. On the other hand, in this application, it is not economically feasible to put in operation a 100 kW plant, because it delivers a negative NPV, an IRR inferior to the discount rate and PBP superior to the project lifetime considered, as the cash inflows do not overcome the cash outflows, foreseeing negative future investment earnings. Focusing on the 1000 kW project, one must now look beyond these indicators and assess the attractiveness of the project from an investor standpoint. According to typical financial benchmarks for biomass projects present in the literature, the NPV must be positive, IRR greater than 10%, and PBP less than 10 years [41]. Indeed, these criteria may differ by country risk and project-specific conditions, notwithstanding, these will be brought into consideration for reference purposes. Given these assumptions, one may assess that the 1000 kW project successfully meets all main requirements for a biomass project be operated profitably.

5.2. Sensitivity analysis

To measure the risks associated with the project, a Monte Carlo sensitivity analysis is implemented within the economic model spreadsheet so to assess the most critical variables for the performance of the project. The variables that most affect the viability of the project are electricity sales tariff, electricity production, initial investment, discount rate and O&M costs. The five considered variables sensitivity bounds are defined as unfavourable or favourable by varying the baseline value up to a ± 10% range. The simulation is conducted for a total of 10,000 iterations. All other variables within the economic model are maintained unchanged during this analysis. A triangular distribution is considered for each variable due to its mathematical simplicity and ability to generate enough random samples, requiring the input of a minimum (favourable value), a mode (baseline value), and maximum (unfavourable value) [43]. Fig. 8a and b depict the NPV sensitivity analysis to each one of the considered critical variables for both units. For the sake of simplification, only the sensitivity analysis to the NPV is presented since the analysis showed that higher risks of investment loss are more likely to occur due to NPV failure. The wider bars in the tornado plot are the ones that require special concern, thus, from all considered variables, electricity sales tariff and electricity production are the ones that the NPV is more sensitive to. These two variables may greatly compromise the NPV as compared to the remaining variables. The sensitivity analysis shows that the 100 kW project is indeed condemned to failure, as a positive NPV would be unreachable even in the most favourable scenarios, while the 1000 kW project proved to be an investment that may be worth considering with no negative NPV values being foreseen even in a most pessimistic scenario. Unsurprisingly, for both 100 kW and 1000 kW facilities, electricity production and electricity sales tariff are the variables that carry greater impact over the NPV, as the calculated annual revenues (given by the product of the annual electricity production for the electricity sales tariff) are strongly dependent on these. The conditional mean given by the vertical red line points the previously calculated NPV values, –32 k€ for 100 kW and 486 k€ for the 1000 kW.

A set of final remarks must be addressed in order to better evaluate this investment project. Costs related to employees are not considered in this project which aids the viability of the investment for the 1000 kW plant. Regardless of the positive economic factors attained for the bigger unit, at least 45% of the generated electric power is considered to be sold to the national grid, contrarily, the viability of the project would be broadly hampered. In addition, the plant must be operated in an almost continuous fashion with an annual baseload of 7160 operating hours being considered, so to guarantee a sufficient power output production capable of maintaining the feasibility of the project. Here, the system output aspect is particularly crucial once the project NPV relies considerably on revenues coming from the electricity production and national electricity sales tariff (which comprises a certain uncertainty due to its dependence on energy market prices fluctuations and subsidies). Ultimately, the 1000 kW small-scale gasification plant proved to be a rather steady investment, yet, it is easily recognizable the tenuity and the risks associated with an investment of this type. In this manner, it is important to look beyond the numbers provided by the economic model, and assess each situation independently considering all potential factors that can easily reverse the initially predicted viability of the project.

6. Environmental and policy analysis

One of the main motivations behind gasification technology is that it aids meeting the world's growing demand for cleaner energy through exploiting a wide variety of feedstocks increasing resource efficiency while reducing climate change via CO_2 mitigation.

When assessing potential deploying sites for the system it is important to implement an overall energy plan and management scheme envisioning environmental and social issues assuring that the small-scale biomass gasification project is built sustainably. Diesel generators have been traditionally applied for off-grid electricity production in decentralized areas [44]. Such fossil fuel-driven engines emit NO_x, CO, unburned hydrocarbons and particulate matter, which contribute to air pollution and are particularly harmful to local inhabitants. A well operated and established biomass gasification system can produce far less GHG emissions since biomass is considered carbon-neutral, feedstocks arrive from renewable sources and most of the produced gas is used as fuel [45,46]. Fig. 9 compares the GHG emissions concerning CO_2, CH_4 and N_2O (nitrous oxide) produced annually by small-scale diesel generators and biomass gasification systems. Beyond question, biomass gasification systems contribute to a considerably lesser extent to the GHG burden as compared to diesel generators, bearing overall lower environmental impact.

Beyond the gaseous emissions, solid and liquid by-products resulting from the small-scale gasification systems operation must also be measured-in. Resulting ashes from forest biomass gasification must be properly managed, and among the options of valorisation, their use in construction materials or as fertilizers can be potential solutions, as it happens to ashes from biomass combustion [47]. In contrast, the condensates are the ones requiring additional precautions. Tar-containing condensates are rich in phenols and other remaining compounds of incomplete combustion process, whose amount depends on the fuel, reactor type and gas cleaning system, and are known for containing a wide range of toxic products. These pollutants can have undesirable environmental effects and should not be freely discharged, instead, they should be handled in an environmentally-friendly manner through suitable disposal waste streams avoiding environmental contamination

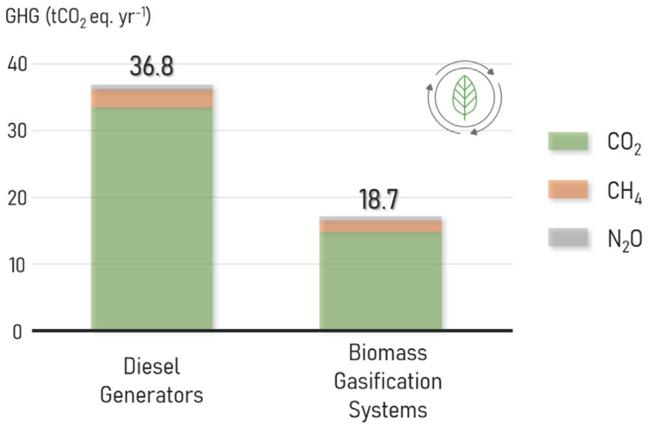

Fig. 9. Annual GHG emissions comparison between small-scale diesel generators and biomass gasification systems [45].

of soils and watersheds. Additional measures focusing on enhancing the reactors operating conditions through efficient and established operational methods will not only give support in improving the syngas yield but also promote tar production mitigation [48]. According to the literature, costs associated with these by-products disposal and treatment in small-scale systems may revolve around 14 k€ per year [49].

Policies and regulations for off-grid renewable solutions should envision a comprehensive approach so to establish an enabling ecosystem for deployment while maximizing socio-economic development. To effectively deploy off-grid solutions one requires fair financing structures and credit support to surpass the high upfront capital costs, as also acknowledging beforehand the implications arriving from uncertain policies and regulations, growing competitiveness with other technologies, and the lack of skilled personnel [50]. Therefore, for the sake of profitability, local governments must implement light-handed regulatory measures towards subsidiary support and feed-in tariffs to electricity from renewable sources while easing private-sector participants actions, thus benefiting small-scale biomass gasification power generation development. Although gasification technology is known for more than a hundred years and many manufacturers promise appropriate small-scale systems, its implementation remains somewhat limited mainly due to some challenges and difficulties arriving from high investment costs, several technical issues and lack of standardization [24]. For this transition, future concerns on this technology should commit to stimulating financial and research interest towards developing gasification technology to a wide commercial viability status.

Small-scale gasification systems for decentralized solutions do provide a window of opportunity for achieving global access to electricity being rapidly scalable, environmentally sustainable and tailor-made to local conditions, suiting as key for unlocking a sustainable future while uplifting the local economy in these locations [51]. Unequivocally, the concept of performing biomass gasification in decentralized areas to empower remote and sparse populations does reflect the promising nature of gasification systems assigning it a valuable and current application purpose.

7. Conclusions

The gasification process of residual forest biomass blends from São Miguel Island, in the Azores archipelago, was studied in a quasi-industrial fluidized bed reactor by employing a 2-D CFD model. The Cryptomeria japonica biomass residues employed in this work was similar to the species that can be found in São Miguel Island itself, which is one of the 9 islands belonging to the Azores archipelago. A set of gasification experiments were gathered from the fluidized bed reactor at different temperatures for validation purposes. The numerical model effectively predicted the acquired experimental data with generally good agreement. The exergy efficiency set around 50 to 67% proved that the process was fit to produce syngas for electricity production in small facilities. Based on these assumptions two different size facilities with 100 kW and 1000 kW small-scale gasification plants were proposed, located in a dairy industry. The techno-economic analysis showed that the 100 kW project was economically unfeasible under current market conditions, showing a negative NPV of –32 k€, an IRR of 5.85%, and PBP larger than the 10 years project lifetime, while the 1000 kW project showed to be economically feasible with an NPV of 486 k€, IRR of 17.44% and PBP of 7.4 years. The sensitivity analysis showed a higher risk of failure in the NPV, with electricity sales tariff and electricity production causing higher impact change over this method. Furthermore, the 100 kW showed to be unable to reach a feasible scenario, while a rather steady economical behaviour was foreseen for the 1000 kW project. Final remarks point that, forest biomass gasification projects carry great potential in small facilities applications in São Miguel with economic viability in some facility sizes, however, special concerns must always be measured in regarding the project attractiveness to potential investors. Environmentally-wise, small-scale gasification systems provided competing advantages as compared to conventional diesel generators, particularly in regards to GHG emissions. Furthermore, additional precautions must be measured-in concerning ash and tar disposal. Resulting ashes can be used in construction materials or as fertilizers, while tars should be handled through suitable waste streams avoiding environmental contamination of soils and watersheds. Finally, costs associated with these by-products disposal and treatment in small-scale systems may revolve around 14 k€ per year.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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