Techno-economic analysis of a biorefinery plant in Azores Islands

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Abstract

Biomass is the only carbon-based material, besides fossil fuels, that can store energy in chemical bonds. Hence, the development of biorefineries to process biomass and obtain energy, fuels and chemicals becomes pivotal. The objective of this study is to analyse the technical and economic viability of installing a biorefinery plant in the Archipelago of Azores. These islands have a significant amount of woody biomass, namely *Pittosporum undulatum*, an invasive species with no commercial use. Therefore, a biorefinery plant based on woody biomass gasification is proposed to produce energy, fuels and chemicals which are currently obtained using non-renewable sources. The routes analysed in this study include hydrogen, methanol and Fischer-Tropsch (FT) fuels synthesis. The Aspen Plus software is used to model the biorefinery, estimate its production potential and determine its most viable configuration. The FT-synthesis route seems to be the most viable solution for the Azorean context as there is currently a market for its fuel products. However, the future energy transition in these islands will translate into a new energy demand, hence, hydrogen and electricity can be the preferred biorefinery outputs. The production of hydrogen is the most economically viable solution, followed by methanol and FT-fuels synthesis. The estimated production cost of hydrogen in the proposed installation in Azores is about 60% of its foreseen market value for 2025. The results for the production costs of FT-fuels and methanol show that these would be two to three and eleven times their market value of 2020, respectively.

Keywords: woody biomass; gasification; biorefineries; biofuels; islands.

1. Introduction

The development of renewable and more sustainable ways of production, storage and usage of energy has been the focus of an increasing amount of research over recent decades. The scarcity of fossil fuels and its inherent price volatility, in addition to the environmental problems related to its use, are some of the core problems that led the research and development of new sources and technologies to process energy.

Biomass has been exploited as energy source since the early stages of the human life and in 2017 still represented 55.6% of the primary energy produced worldwide [1]. Besides its ease of access and use, biomass is also the only natural carbon-based material, apart from fossil fuels, that can be used for energy purposes. Following this, the production of energetic chemicals and electricity through biomass has reached worldwide interest [2].

Against this background, the development of biorefineries has received growing attention over the last decades. The International Energy Agency (IEA) defines a biorefinery as 'an integrated production plant using biomass feedstock to produce a range of value-added products', bioproducts (chemicals, fuels, etc.) and bioenergy (heat and power). The fundamental driver for these plants is the deconstruction of some of the molecular structures of raw biomass to obtain simpler molecules that after some chemical processing can generate products with similar characteristics of those produced in conventional refineries (fuels, chemicals and/or energy). One of the goals of the European Union (EU) directive 2015/1513 is to favour the development of second-generation biorefineries, fuelled by non-edible biomass, over the first-generation, that relies mostly on edible material.

Biorefineries can be divided into two divergent routes, according to the type of material processing techniques: biochemical and thermochemical. The main biochemical paths comprehend the enzymatic or chemical hydrolysis of the feedstock prior to its reforming to other chemical materials. These routes are currently the most exploited ones, mostly due to the high number of running bioethanol facilities around the world at commercial scale [3]. The thermochemical routes, however, are becoming more important. These routes also present a wide range of possibilities. The most important consist of gasification, pyrolysis and direct burning of syngas and its further processing. These thermochemical paths require a number of material treatments primarily controlled by heat that promotes the breakdown of molecules and later the synthesis of other chemical products. Although mature technology is not yet fully available, there are already plants running at commercial scale [4-7].

1.1. Literature review

Biomass is used in many areas (construction, agriculture, energy, etc.) due to its favourable chemical and structural characteristics. Biomass is set to become an even more vital part of the global economy. The focus of the present study is its chemical precursor ability, so the biomass' carbon structure becomes its most significant characteristic. The Joint European Biorefinery Vision for 2030 [5] sets some of the targets for the European bioindustry for 2030, forecasting that 30% of the chemical production will be bio-based, while 25% of the fuels consumed will be biofuels. To do so, one of the ways is the implementation of biorefineries as assessed in Frey and Fichtl [6]. This work emphases the importance of the biorefineries in terms of sustainability and their present ability to produce a large span of products that are currently obtained by other means.

Biorefineries also differ on the feedstock materials and thereby arises the need for the categorization of the plants as first-, second- and third-generation plants, whose feedstocks are edible food crops, lignocellulosic material and microalgae, respectively, as stated in Cherubini [7]. Due to the fuel versus food debate, the direction seems to be the second- and third-generation plants, although the latter still presents development challenges [8].

Ghatak [9] presents the current possibilities for biochemical and thermochemical processes and the future directions on the development of viable and sustainable biomass utilization techniques. The author recognizes gasification and pyrolysis as the most prominent routes in the thermochemical spectrum. Nevertheless, the differences between both are notorious. The advantages of gasification over pyrolysis are: the synthesis gas (syngas) holds higher energy and also higher hydrogen content [10]; destruction of less material [10]; less NO_x and SO_x production [11]; chemical structure similarities between syngas and natural gas enable the possibility of following already mature processes used for natural gas processing to synthetize other chemical structures.

The major challenge of the gasification technology is the equipment costs that can become prohibitive for most of the projects. Puig-Arnavat et al. [12] evaluated the performance of gasification technologies in terms of efficiency and produced gas. Fluidised-bed reactors seem to be more suitable for this process than entrained-flow, fixed-bed and stage gasification reactors. The most important features of fluidised-bed reactors for gasification are: high conversion efficiency; flexibility and ease of operation; high fuel flexibility in terms of size and type; possibility of large-scale capacity; very good scale-up potential; good temperature control and high reaction rates.

Steam is the most suitable choice for the gasification agent, according with the work of Kalinci et al. [13] that reviewed and evaluated the biomass-based hydrogen synthesis processes. This work states that steam as gasification agent allows to produce more combustible gases (namely hydrogen and carbon monoxide) and consequently a syngas with a higher heating value. Moreover, the utilization of steam is substantially cheaper than the oxygen or air utilization as gasification agent.

National Renewable Energy Laboratory (NREL) [14] extensively analysed the possible chemicals production technologies in biorefineries through the syngas processing. A comprehensive techno-economic analysis reported the major features of the technologies considered and identified hydrogen and methanol as the most prominent chemical products to pursue.

The model presented in Pala et al. [15] describes biomass steam gasification in a fluidised-bed gasifier through six phases in order to replicate the real gasification occurring processes. Different process conditions are tested and the model results are compared with experimental data obtained from the gasification of different biomass. The comparisons show that the model data agree reasonably well with the experimental data in terms of quantities and trends. Small deviations were observed in the predictions of the production of hydrogen and methane [15].

Marcantonio et al. [16] studied the gasification of hazelnut shells in a circulating bubbling fluidized-bed gasifier using a quasi-equilibrium approach developed in Aspen Plus. The unit integrated a water-gas shift (WGS) reactor to increase the hydrogen content in the outlet stream. The authors simulated the WGS reactor using two WGS reactors, one at higher temperature and another at lower temperature, because this reaction is moderately exothermic and tends to shift to the reactants side at high temperature. The authors concluded that the mole fraction of hydrogen increased about 50% with the integration of the WGS reactor and that the model developed was in good agreement with experimental data report in the literature [16].

Ortiz et al. [17] modelled a methanol production plant based on the syngas resulting from the reforming of glycerol. The objective was to maximize the overall process efficiency in terms of total net power and methanol production, under the constraint of making the overall process energy self-sufficient. The obtained model results could reproduce well the experimental data and model results from the literature [17].

Pondini [18] modelled the FT-fuels synthesis using Aspen Plus with different plant configurations and correlations from experimental data. This work's focus was to evaluate the plant's performance in terms of products' quality and quantity as a function of the process operating conditions. The results obtained could predict satisfactory the reality [18].

1.2 Present contribution

The aim of this study is to assess the viability of installing a biorefinery plant in the Archipelago of Azores, using as feedstock existing non-valued *Pittosporum undulatum* woody material. The installation of such infrastructure in these islands not only would improve the region external independency on fuels and chemicals products but also would enhance their price reduction. Moreover, associated with the biorefinery activities, social and economic development of the region would be expected [6,19]. Azores already presents a large share of renewable energy production, 36.6% [20], and a number of studies already considered the increase of the renewable energy penetration in the Archipelago [21]–[25].

In this study, biomass gasification was chosen for the synthesis of different chemical products (liquid fuels and materials), since this is the most appropriate technology for woody biomass. This study focused three paths after the gasification process: hydrogen, methanol and FT-fuels synthesis. The choice of these products considered the current and expected future market demands and also the arguments of NREL [14] that considered the hydrogen and methanol syntheses the most promising paths. The proposed plants are modelled using Aspen Plus and each product cost of production is estimated considering the capital and operational expenditures (CAPEX and OPEX).

2. Materials and methods

2.1 Aspen Plus

The Aspen Plus V9 software was chosen to model the operation of the three proposed plants (hydrogen, methanol and FT-fuels). This software is a powerful tool to design and predict real performance of chemical plants in most industry fields, being already highly implemented in the petrochemical industry.

All components that are involved in the processes must be defined. Therefore, besides the conventional components, the chemical composition of biomass and ashes, need to be defined. Then, the property method, is selected. The fluid dynamic package chosen was the Peng-Robinson with Boston-Mathias function (PR-BM), since it is indicated for refinery or petrochemical plants' applications [15], [26], [27]. Finally, the plant flowsheet is designed using operation blocks and material streams connecting each block. At this point, the properties of the feed streams (flow rate, composition and thermodynamic conditions) are defined based on the biomass resources.

For modelling purposes, the following assumptions are made:

- Processes are in steady state;
- Pressure and temperature conditions are uniform inside the reactor units;
- Tar formation is not considered;
- Char only contains carbon and ash;
- Drying, pyrolysis, partial oxidation and gasification are instantaneous processes;
- Gasification products consist of hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), nitrogen (N_2), water (H_2O), ammonia (NH_3) and hydrogen sulphide (H_2S) only.

Figure 1 shows the plants different paths and their common processes. The three plant configurations comprise four distinct stages: gasification, syngas adjustment, product upgrading and its recovery and energy recovery.

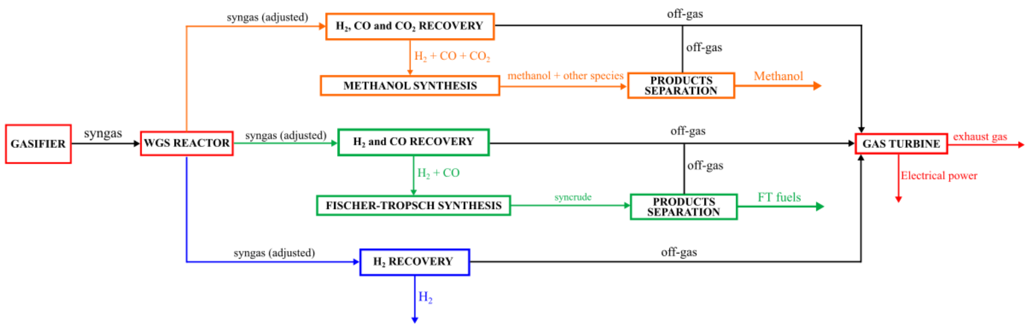

Figure 1. Simplified block diagram of the three plant configurations.

2.2 Gasification, WGS reactor, products separation and energy recovery modelling

The modelling of the steam gasification unit followed essentially the work of Pala et al. [15]. Although usual designs ensure the drying of the biomass prior gasification this is not considered in this model. Figure 2 presents the flowsheet section of the gasification modelling. Since Aspen Plus does not present a pre-set gasifier model, the gasification stage is simulated by imposing the main steps and inherent reactions that occur in a real fluidised-bed gasifier with steam injection.

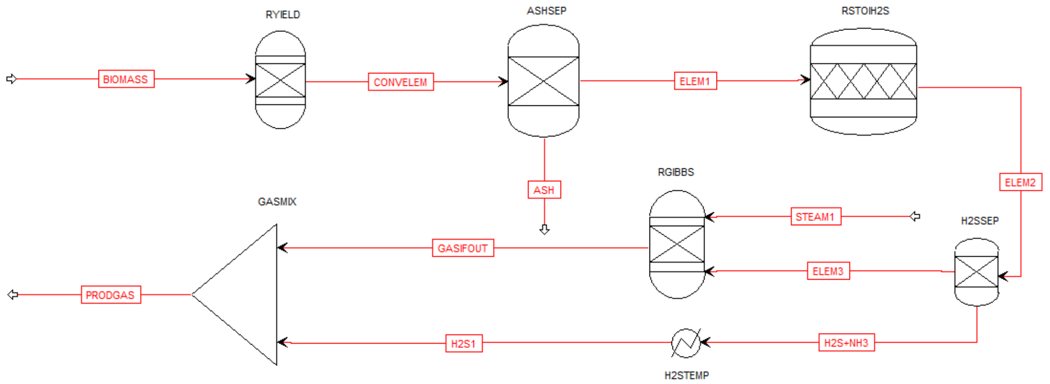

Figure 2. Flowsheet section of the gasification modelling in Aspen Plus.

The adjustment of the syngas H_2/CO ratio to its most appropriate value for each of the three processes is performed in the WGS reactor. To this end, two equilibrium reactors (LTWGSR and HTWGSR) are used, as carried out by Marcantonio et al. [16]. These reactors operate at different temperatures, at 200 ºC (LTWGSR) and 400 ºC (HTWGSR). Figure 3 presents the flowsheet section of the WGS reactor in Aspen Plus.

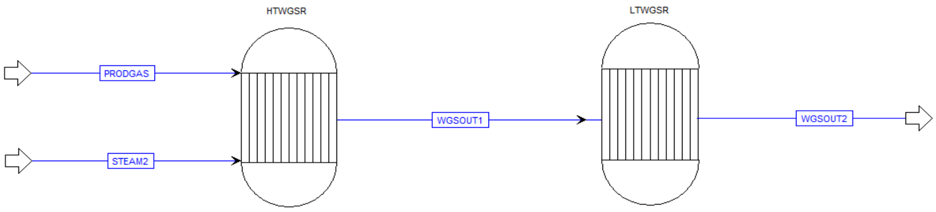

Figure 3. Flowsheet section of the WGS reactor modelling in Aspen Plus.

Since the Aspen Plus software does not have a separation unit that operates as a PSA reactor, it is required the use of a simplified separator by specifying a recovery capability identical to that of a real PSA reactor (Figure 4). The PSA reactor for H_2 recovery capacity is based on the values indicated by Sentis et al. [28], while for CO and CO_2 capture is based on the values specified by Ortiz et al. [17]. The PSA power consumption is estimated based on the study of Ishibashi et al. [29], who considered that a the consumption of 0.62 kW per kg of recovered CO_2.

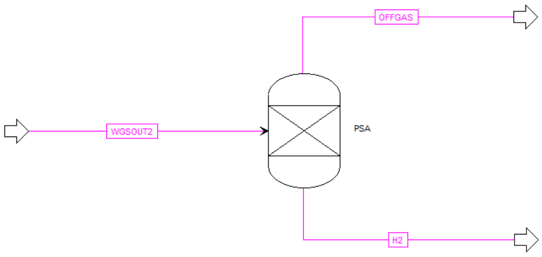

Figure 4. Flowsheet section of the PSA reactor modelling for hydrogen recovery in Aspen Plus.

The Aspen energy analyzer (AEA) tool provides the most suitable ways to recover heat from the different streams and estimate the available energy savings in the plants. Also, steam and gas turbine systems are implemented to recover power from the plant to cover its power needs and, if exceeded, to be sold to the power grid and be source of revenue.

Aspen Model Analysis Tools are used in the design phase, namely the Optimization tool. The three plant configurations are established to attain the best results according to the settled goals. These goals are as follows:

- To maximize the products yield (hydrogen, methanol and FT-fuels) in each plant;
- To attain maximum energy efficiency for all processes;
- To reduce the water consumption and, if possible, not to consume more than the produced one;
- To promote the self-sustainability of the plant regarding energy consumption;

2.3 Hydrogen synthesis

This plant requires a unique PSA unit for the hydrogen recovery after the WGS reactor. The remaining syngas is then directed to a gas-turbine to produce power. Prior to the combustion of the syngas, water is removed from the stream. Some of it is then redirected to the system being injected as steam in preceding units, namely, in the gasifier and WGS reactor.

2.4 Methanol synthesis

To produce methanol (CH_3OH), the stream leaving the WGS reactor goes into a series of three PSA reactors, each promoting the recovery of H_2, CO and CO_2. To maximize the methanol yield, the $\frac{[H_2]-[CO_2]}{[CO]+[CO_2]}$ has to be equal to 2-2.1 [17]. The resultant mixture is then compressed and fed to a stoichiometric reactor so that the synthesis occurs, following [30].

The resultant stream consists of new formed species (methanol, ethanol, dimethyl ether and water) and unconverted species (CO, CO_2 and H_2). The separation of the methanol occurs through a distillation column and a flash separator. The off-gas, mixed with the unabsorbed syngas, is directed to a gas turbine to produce electricity.

2.5 FT-fuels synthesis

In this plant, after the syngas H_2/CO adjustment in the WGS reactor, two PSA reactors are designed to recover separately the H_2 and the CO and then mix them. The H_2/CO molar ratio must be close to 2.15, as indicated by van Steen and Claeys [31], to maximize the hydrocarbons yield. The resultant stream is fed to a reactor block where the FT synthesis occurs. To model the complex hydrocarbons synthesis that occurs in the FT reactor the following additional assumptions are considered:

- The Anderson-Schulz-Flory (ASF) ideal product distribution model [32], the alpha parameter correlation [33] for a cobalt-based catalyst, and the olefin/paraffin (O/P) distribution [34] are used;
- FT products are only paraffins, olefins, water and unconverted syngas;
- Highest hydrocarbon carbon number is thirty (C_{30});

To estimate the composition of the stream leaving the FT reactor, a CALCULATOR block is designed in an Excel flowsheet. This flowsheet calculates the reactor outlet stream according to ASF and O/P distributions.

After synthetized, this syncrude stream is directed to a system of separators, namely a three-outlet flash separator and three distillation columns. This system allows to separate the hydrocarbons in light gases (C_1-C_4), gasoline (C_5-C_{10}), kerosene (C_{10}-C_{13}), diesel (C_{14}-C_{20}) and waxes range (C_{21}-C_{30}), as considered in Pondini [18].

The waxes produced are conducted to a hydrotreatment unit where their hydrocracking is performed to increase the desired higher diesel yields. This hydrotreatment occurs in a reactor by injecting H_2, separated from the PSA outlet stream. The off-gas stream is then fed to a gas turbine for power production.

This plant is designed to produce the maximum amount of fuels possible with the available biomass. Since it produces three different liquid fuels and from kerosene has a quite low demand in Azores (about 135.3 ton/year), two scenarios are considered. The first scenario considers the use of the excess kerosene produced in relation to the demand for power production within the plant. The second considers the exportation of this excess kerosene.

2.6 Energy and exergy efficiency analysis

The energy and exergy efficiencies of the plants are also estimated. The energy efficiency is defined as:

$$\eta = \frac{\dot{E}_{\text{output}}}{\dot{E}_{\text{input}}} \times 100\% \qquad (1)$$

where $\dot{E}_{\text{output}}$ is the sum of the power produced and the synthetized products heating value ($\dot{m}_{\text{chemical}} \times LHV_{\text{chemical}}$), and $\dot{E}_{\text{input}}$ is the sum of the consumed power and the heating value of the fed biomass ($\dot{m}_{\text{biomass}} \times LHV_{\text{biomass}}$). *LHV* is the lower heating value. Its values for the chemical products are taken from [35].

The exergy efficiency is defined as:

$$\varepsilon = \frac{\dot{Ex}_{\text{products}}}{\dot{Ex}_{\text{biomass}}} \times 100\% \qquad (2)$$

where $\dot{Ex}_{\text{products}}$ is the sum of the exergy rate of the products, each calculated by multiplying their specific exergy (kJ/kg), taken from the Aspen Plus results, by their mass flow rate (kg/h), and $\dot{Ex}_{\text{biomass}}$ is the (chemical) exergy rate of the input biomass given by:

$$\dot{Ex}_{\text{biomass}} = \beta \times LHV_{\text{biomass}} \times \dot{m}_{biomass} \qquad (3)$$

where [36]:

$$\beta = \frac{1.044 + 0.016\frac{X_{\text{H}}}{X_{\text{C}}} - 0.3493\frac{X_{\text{O}}}{X_{\text{C}}}\left(1 + 0.0531\frac{X_{\text{O}}}{X_{\text{C}}}\right) + 0.0493\frac{X_{\text{N}}}{X_{\text{C}}}}{(1 - 0.4124)\frac{X_{\text{O}}}{X_{\text{C}}}} \qquad (4)$$

2.7 Cost analysis

The total investment cost of each equipment ($Cost_{\text{NEW}}$) is estimated using the following equation [28], [37]:

$$Cost_{\text{NEW}} = Cost_{\text{REF}} \times \left(\frac{Scale_{\text{NEW}}}{Scale_{\text{REF}}}\right)^{fs} \times \frac{CEPCI_{2018}}{CEPCI_{\text{REF}}} \qquad (5)$$

This value is based on the cost of the equipment available in the literature, $Cost_{\text{REF}}$. To consider the difference in scales of the equipment used in this work ($Scale_{\text{NEW}}$) and that in the literature ($Scale_{\text{REF}}$), a scaling factor (f_S) is considered. Finally, to adjust the estimation of the costs, the Chemical Engineering Plant Cost Indexes (CEPCI) from the case considered in the literature ($CEPCI_{\text{REF}}$) and the most recent value ($CEPCI_{2018}$) are considered [38].

To obtain the CAPEX, the investment cost of each equipment is multiplied by the installation factor (f_{I}), i.e.:

$$CAPEX = Cost_{\text{NEW}} \times f_{\text{I}} \qquad (6)$$

which considers the costs associated with the site installation of the equipment.

The OPEX are estimated using the following equation:

$$OPEX = O\&M + BC + EC \qquad (7)$$

where O&M are the operation and maintenance costs (4% of the total investment costs), BC are the biomass costs (including transportation), and EC are the costs related to the electricity demand of the plant.

The fuel production cost (*FPC*) in each plant is calculated through:

$$FPC = \frac{CAPEX\,.\,CRF\ + OPEX - ER}{FP} \qquad (8)$$

where *ER* are the electricity revenues from the selling of the excess electricity to the power grid, *FP* is the yearly fuel production, and *CRF* is the capital recovery factor used to annualize the investment costs, i.e.:

$$CRF = \frac{i \times (1+i)^l}{(1+i)^l - 1} \qquad (9)$$

where i is the discount rate (10% [39]) and l is the equipment lifetime (20 years [40]). Table 1 presents the values to estimate the *OPEX* and the *ER*. For the *EC*, the power tariffs of Azores are considered, for *ER*, the tariff of Continental Portugal for the selling of power produced from biomass to the grid is considered.

Table 1. Tariffs considered to estimate *OPEX* and *ER*.

Cost category	Tariff	Source
Raw biomass + delivery (by land)	20 €/ton	[30]
Biomass maritime transportation	58.24 €/ton	[45]
Power purchased from the grid	0.0941 €/kWh	[32]
Power sold to the grid	0.0855 €/kWh	[46,47]

Although three different fuels are synthetized in the FT-fuels plant, the same approach is used. This way the resultant *FPC* is the minimum selling price for the three synthesized fuels, which would make the plant economically viable if all were sold at the same price.

Since the tariffs for the purchase of the biomass and its transportation can vary significantly, a sensitivity analysis is carried out with these variables. In this analysis, the variables range from 50% to 150% of the reference values. Furthermore, it is also analysed the possibility of the biorefinery implementation in other islands. In addition, a sensitive analysis is performed for some of the PSA performance variables that affect the production and the costs of the synthetized products. The influence of the PSA hydrogen recovery is evaluated, using the reference value (70%) and the value referred by Gutiérrez Ortiz et al. [17] (95%). The PSA reactors' power consumption influence is also evaluated, ranging from 50% to 150% of the considered reference value.

3. Case study

The present work examines the possibility of installing a biorefinery plant in the Archipelago of Azores, making use of its endogenous resources and providing consumable products for the islands or for exportation.

3.1 Archipelago of Azores

In 2017, Azores produced 803 GWh of power, mostly in S. Miguel (55%) and in Terceira (22%). The islands are not interconnected. Power production is achieved mainly through fuel oil and diesel, but also from renewable sources (37%) [20]. In 2017, 96,301 ton of fuels were consumed for transportation in Azores, 67% of diesel and 33% of gasoline. Diesel is also predominantly used in the maritime transport, and kerosene in the air transport, with 169,122 litres consumed in 2017 [44]. In 2017, Azores had about 146,940 vehicles, of which 51% in S. Miguel [45]. Azores has no oil refinery, so all fuels are imported, distributed and sold to end-users.

The utilization of *Pittosporum undulatum* as feedstock for biorefineries is encouraged by the work of Lourenço et al. [24]. The authors estimated the Azores biomass potential of this specie and highlight the great opportunity of its use for energy purposes. This specie estimated available biomass is 129,988 tons per year in the archipelago.

3.2 Scenarios considered

This work considers the synthesis of different chemical products that have different uses and purposes. The estimated production of hydrogen will be used as fuel for a future scenario where hydrogen-fuelled vehicles replace the conventional fuelled ones, or at least part of them. Therefore, the hydrogen plant is desirable for a near future, where hydrogen can play an important role in the transportation sector.

The methanol finds its use as a fuel itself, but mostly as a chemical precursor and that is its most relevant feature. The methanol properties are similar to those of the liquified petroleum gas (LPG), having half the heating value of gasoline [14]. Since currently no methanol is consumed in the islands, the produced methanol will be exported. Nevertheless, the potential implementation of methanol-based industries in Azores might legitimate future projects, contributing for the economic development of the territory.

Finally, FT-fuels such as diesel, gasoline and kerosene are vital in the current energy context of the islands since these can replace fossil fuels in Azores. Since this plant produces simultaneously diesel, gasoline and kerosene, and this last fuel has a rather small demand in Azores, two scenarios are considered that differ in the way the excess kerosene produced is handled, as mentioned earlier. In this first scenario, the excess kerosene is used for power production within the plant, and in the second scenario, the excess kerosene is exported.

On the possibility of producing surplus electricity in the plants, since there is no interconnection between the islands' power systems, this electricity will be used only in the island where the biorefinery is installed.

4. Results

As mentioned earlier, the woody biomass used to feed the system is *Pittosporum undulatum*, an invasive species with no commercial use. In this sense, the chemical properties for the input in Aspen Plus environment follow the study of Borges Silva et al. [24]. The mass flow rate for the biorefinery plants is 16.25 ton/h. This value corresponds to the utilization of 130 kton per year, which obeys to a sustainable exploitation approach [24]. The estimation of the mass flow rate considers an annual load of 8000 hours, being the remaining hours of the year used for maintenance. Consequently, the biomass yearly costs amount to 9 M€ per year.

4.1. Modelling results

Table 2 presents the modelling results for the three plants for one year of operation.

The hydrogen synthesis plant is self-sufficient in terms of energy, according with the AEA tool. Also, this plant produces more electricity than it needs, allowing for the selling of the surplus electricity to the power grid. This surplus electricity, 50,645 MWh, can cover 23.9% of S. Miguel's yearly fossil fuel thermal power production. This value is about 11.7% of the total yearly power production of this island. Hence, this island is a suitable location for the proposed plant. In addition, this island has the second highest biomass resource of the nine islands of the Archipelago of Azores (c.f. section 3.1). To assess the possible impact on the transport sector of the yearly hydrogen production of the plant, an evaluation is carried out considering the travelled distance by all the existing light-duty vehicles. For this, the current yearly distance travelled by the light-duty vehicles in Azores is estimated. Data from 2017 is used and the travelled distance/vehicle/year is taken from Baptista et al. [25]. The travelled distance per kg of hydrogen is considered 82 km, based on estimates of NREL [46]. Hence, 16% of the current travelled distance by all light-duty vehicles would be covered by the produced hydrogen.

The methanol synthesis plant can be self-sustainable in terms of cooling and heating needs according with the AEA tool. In contrast with the hydrogen plant, this plant requires power from the grid. The power produced by the plant is only able to cover 97% of the plant's power demand. The power acquired from the grid is marginal (1%) when compared with the power consumption in the island.

According with the AEA tool, the FT-fuel synthesis plant is self-sustainable in terms of heating but not in terms of cooling needs. It requires 8.65 MW of cooling. In the first scenario, the plant can produce more electricity than it needs, while in the second scenario it requires power from the grid. The surplus electricity (Table 2), in the first scenario, can cover 11.2% of S. Miguel's yearly fossil fuel thermal power production. This value is about 5.5% of the total yearly power production of this island. For the second scenario, 0.3% of the island's current power consumed is required.The diesel and gasoline annual production covers 6.6% and 10.5% of the current Azores fuels' demand, respectively [47]. The first scenario allows for the complete replacement of the current kerosene demand in the islands, while the second scenario allows to exceed this demand and to produce a surplus of 4,153 ton of kerosene to export.

Table 2. Modelling results for the three plants.

Annual results	Hydrogen plant	Methanol plant	FT-fuels plant					
			First scenario			Second scenario		
Annual production (ton)	Hydrogen	Methanol	Gasoline	Kerosene	Diesel	Gasoline	Kerosene	Diesel
	5,485	11,201	3,320	135.3	4,184	3,320	4,288	4,184
CO_2 emissions (ton)	126,027	110,599	101,854			88,968		
Electricity consumed (MWh)	23,178	159,736	75,796			74,431		
Electricity produced (MWh)	73,823	154,186	99,634			72,953		
Surplus electricity (MWh)	50,645	-	23,838			-		
Electricity from the grid (MWh)	-	5,550	-			1,478		
Energy efficiency (%)	59	38	39			44		
Exergy efficiency (%)	14	26	34			35		

4.2. Economic analysis results

Table 3 shows the results of the economic analysis of the plants, presenting the *CAPEX*, *OPEX* and the *FPC* for each plant. The exploited biomass is the same for all plants and its associated costs amount to 9 M€ per year.

The *CAPEX* of the proposed hydrogen plant amounts to 129 M€, and the yearly *OPEX* amounts to 13 M€ per year. The revenues of the surplus power selling to the grid amount to 4.3 M€ per year. The *FPC* obtained for the hydrogen synthesis is 4.36 €/kg. This value is 48% to 60% of the United States hydrogen retail price (7.28 to 9.10 €/kg) foreseen for the 2020-2025 period [48]. This *FPC* for hydrogen results in a cost of 0.053 € per travelled km, considering the assumptions made above for the hydrogen fuel economy. Comparing to the current Azorean context, this represents 53% of the current cost for the light-duty gasoline vehicles (0.10 €/km).

The *CAPEX* of the proposed methanol plant amounts to 157 M€, and the yearly *OPEX* amounts to 14.49 M€ per year. In the last are already accounted the costs of the power acquisition to que grid (0.52 M€ per year). The *FPC* obtained for the methanol synthesis is 2.90 €/kg. This value is eleven times higher than the market price (0.273 €/kg) for the European region in 2020 [49].

The *CAPEX* of the proposed FT-fuels plant amounts to 201 M€ in the first scenario and to 203 M€ in the second scenario. The yearly *OPEX* amounts to 16.1 M€ in the first scenario and to 16.4 M€ in the second scenario. For the first scenario, the revenues of the surplus power selling to the grid amounts to 2 M€ per year. The *FPC* obtained for the FT-fuels synthesis is 4.91 €/kg in the first scenario and 3.39 €/kg in the second scenario. Both values are significantly higher than the Azores retail fuel prices (1.92 €/kg for gasoline, 1.55€/kg for diesel [50] and 0.53 €/kg for kerosene [51]).

Table 3. Economic analysis of the three plants.

Plant		Hydrogen	Methanol	FT-fuels	
				First scenario	Second scenario
CAPEX (M€)		129	157	201	203
OPEX	Operation and maintenance, O&M (%)	4			
	Biomass costs, BC (M€/year)	9			
	Electricity revenues, ER (M€/year)	4.3	-	2	-
	Electricity costs, EC (M€/year)	-	0.52	-	-0.14
FPC (€/kg)		4.36	2.90	4.91	3.39

4.3. Sensitivity analysis

Table 4 shows the results of the sensitivity analysis carried out on the price of purchasing biomass and its maritime transportation, the possibility of implementation in other islands of the archipelago and its impact on *FPC* for the three plants. All the values considered result in hydrogen production costs below its foreseen market value. For the methanol and FT-fuels plants, the resultant FPC is still higher than their market value.

Table 4. Sensitivity analysis concerning the biomass associated costs and possibility of implementation in other islands.

Biomass associated costs		Hydrogen plant		Methanol plant		FT-fuels plant			
						First scenario		Second scenario	
Price of biomass (€/ton)	Maritime transportation costs (€/ton)	FPC (€/kg)	FPC variation (%)	FPC (€/kg)	FPC variation (%)	FPC (€/kg)	FPC variation (%)	FPC (€/kg)	FPC variation (%)
10	29.12	3.54	-19	2.50	-14	4.32	-12	3.00	-12
	58.24	4.12	-5	2.78	-4	4.74	-3	3.27	-4
	87.36	4.71	8	3.07	6	5.16	5	3.54	5
20	29.12	3.78	-13	2.61	-10	4.49	-9	3.11	-9
	58.24	4.36	-	2.90	-	4.91	-	3.39	-
	87.36	4.94	13	3.18	10	5.33	9	3.65	8
30	29.12	4.01	-8	2.73	-6	4.66	-5	3.22	-5
	58.24	4.60	5	3.01	4	5.08	3	3.49	3
	87.36	5.18	19	3.30	14	5.50	12	3.76	11
Island		FPC (€/kg)	FPC variation (%)	FPC (€/kg)	FPC variation (%)	FPC (€/kg)	FPC variation (%)	FPC (€/kg)	FPC variation (%)
Santa Maria		5.00	12	2.97	2	5.07	3	3.46	2
São Miguel		4.44	-	2.90	-	4.91	-	3.39	-
Terceira		4.58	3	2.96	2	5.01	2	3.46	2
Graciosa		5.12	15	2.99	3	5.16	5	3.48	3
São Jorge		4.85	9	2.94	2	4.98	1	3.44	1
Faial		4.57	3	2.95	2	4.99	2	3.44	2
Pico		4.05	-9	2.67	-8	4.58	-7	3.18	-6
Flores		5.16	16	2.95	2	5.19	6	3.44	1
Corvo		5.34	20	3.00	4	5.31	8	3.49	3

The results presented in Table 5, in regard in the sensitivity analysis on the PSA performance, show that although a larger production capability would be possible for the three plants with a higher hydrogen recovery from the hydrogen PSA, only the hydrogen production costs would be below its market value. This would result in a hydrogen production of 7,444 ton per year, and a 28% current travelled distance in the archipelago being possible to make with that fuel.

Table 5. Sensitivity analysis concerning the PSA performance.

PSA performance		Hydrogen plant		Methanol plant		FT-fuels plant							
						First scenario				Second Scenario			
		FPC (€/kg)	Annual production (ton)	FPC (€/kg)	Annual production (ton)	FPC (€/kg)	Annual production (ton)			FPC (€/kg)	Annual production (ton)		
H_2 recovery (%)	Electricity consumption (kW/kg)		Hydrogen		Methanol		Gasoline	Kerosene	Diesel		Gasoline	Kerosene	Diesel
70	0.31	4.33	5,485	2.65	11,201	4.79	3,318	135.3	4,185	3.31	3,318	4,292	4,185
	0.62	4.36		2.90		4.91				3.39			
	0.93	4.39		3.17		5.03				3.48			
95	0.31	3.41	7,444	2.29	12,789	4.05	4,231		5,243	2.80	4,231	5,378	5,243
	0.62	3.44		2.52		4.17				2.89			
	0.93	3.47		2.76		4.29				2.98			

5. Discussion

Azores presents a wide variety of endogenous resources that are currently not exploited. In this sense, this work presents the techno-economic assessment of a biorefinery plant in Azores, taking advantage of available biomass resources, namely *Pittosporum undulatum,* to produce energy and chemicals.

Three different plants are assessed using Aspen Plus: hydrogen, methanol and FT-fuels synthesis plants. The results show that hydrogen plant can be economically viable, being its associated production costs (4.36 €/kg) lower than its projected market price for 2025 (7.28 to 9.10 €/kg). The utilization of hydrogen as transportation fuel would cover 16% of the currently travelled distance by light-duty vehicles in Azores and, consequently, would reduce the pollutant emissions on the islands from road vehicles. The hydrogen fuel economy is also expected to be more favourable than the actual gasoline one, being the cost per travelled distance 53% of the current one for gasoline. This plant presents the highest energy efficiency (59%), although the lowest exergy efficiency (14%) of the three plants. However, hydrogen still finds no relevant market demand in Azores. Its application is projected for the future where hydrogen takes part in the transportation sector. This biorefinery would also produce renewable electricity and is estimated to match up to 24% of the currently thermal power production in the S. Miguel.

It is important to highlight that the yearly produced electricity by the hydrogen plant is assumed to be sold to the grid in its totality, which may not be completely true. Since the analysis carried out in this study is not an hourly analysis, but a yearly analysis, there may be times when the power grid is not able to accept the electricity supplied by the plant. However, since a constant power production is being considered, because the biomass flow rate is constant, the supplied power can cover the base load of S. Miguel.

The production costs of methanol (2.90 €/kg) are about eleven times its market price (0.273 €/kg). Even though methanol finds the most varied span of utilizations, currently there is no market in Azores, being its exportation the most valid option. Nevertheless, the possibility of developing activities to synthetize other chemicals through methanol could be a good opportunity for Azores, that depends heavily on importations. In the case of the FT-fuels, although the estimates on the production would cover respectively 6%, 10% and 100% of the diesel, gasoline and kerosene current Azores' demand, the production costs are prohibitive for both evaluated scenarios (4.91 €/kg and 3.39 €/kg). The lower pollutant emissions (SO_x and NO_x) [11] when compared to the conventional fuels ones and the non-requiring of existing infrastructures modifications, are the most important features these fuels.

The sensitivity analysis results show that even for the most favourable cases, out of the three plants, only the hydrogen one would be economically viable. Although its production costs can decrease in the best scenario, methanol and FT-fuels plants would not yet achieve a production cost below its market value.

Besides being economically non-viable, both the methanol and the FT-fuels plants (in the second scenario) require power consumptions that would increase the power demand of Azores.

In regard to the CO_2 emissions of the plants, although the hydrogen plant produces the most CO_2 among the three, the further utilization of hydrogen as fuel is set to produce only water and heat, contrary to the combustion of the other produced materials (methanol or FT-fuels).

Being technologically feasible, the economy of the plants is the most challenging aspect. In this sense, incentives from the government for the installation of the plants, by terms of subsidies or tax reductions for the biorefinery and its associated activities are measures that would possibly promote the viability of the plants.

6. Conclusions

Biorefineries are identified as part of the path for a more sustainable future. Nevertheless, their implementation still faces some challenges, mostly regarding their economic viability. The techno-economic assessment carried out in this study shows that from the three evaluated biorefinery plants for the Azores archipelago, only the hydrogen one would be economically viable. Nonetheless, since currently no hydrogen is consumed as transportation fuel in the archipelago, its implementation is aimed for a near future when the energy transition takes place. Although technologically achievable, the production of methanol and FT-fuels in the Azores context are economically unviable. In the case of the methanol synthesis, besides its prohibitive production costs, no current utilization is known in the region. In regard of the FT-fuels, although their production costs are prohibitive, there is currently a market for these fuel products in Azores.

In regard to future research, there are several important issues to analyse, namely:

- Assessment and optimization of the biomass distribution systems in the islands;
- Life-cycle assessment of the biorefinery activities;
- Assessment of the possibility of using different feedstocks, mixed or not (agricultural residues, municipal solid waste, other endogenous species);
- Assessment of the use of *Pittosporum undulatum* for the synthesis of other products through bio or thermochemical routes;
- Assessment of the ammonia synthesis from the produced hydrogen for the Azores market.

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