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Title: Use of waste vegetable oil for hydrotreated vegetable oil production with high-temperature electrolysis as hydrogen source

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Abstract: The research of renewable alternatives to decarbonize the transport sector and to reduce the consumption of fossil fuels pushes towards the development of more sustainable solutions for fuel production. Among the diesel substitutes, hydrotreated vegetable oil (HVO) is considered one of the most promising options, since it can be blended with fossil diesel without limitations. In this context, this paper assesses the technical and economic feasibility of producing HVO using waste vegetable oil (WVO) as feedstock, with the help of a simulation model that maximizes the integration of renewable energy sources. The process to synthesize HVO requires a large amount of hydrogen that, in this study, is supplied through an upstream high-temperature electrolysis process occurring in solid oxide electrolysis cells (SOECs), which are fed by low-carbon electricity. The use of waste oils as feedstock eliminates the competition with food crops (e.g. soybean or rapeseed) and promotes the recycling of substances that need to be disposed. The results of the study prove the technical feasibility of a plant with an annual capacity of 100 kton of HVO, having an energy efficiency of 80%. Also, the breakeven point of such investment would be reached before the fourth year of operation, considering a WVO price of 400 €/ton, which is assumed as target price. However, the uncertainty on the market prices of WVO, HVO and electricity, as well as on other fixed and variable production costs, can, significantly affect the projected results.

1 **Use of waste vegetable oil for hydrotreated vegetable oil**
2 **production with high-temperature electrolysis as hydrogen**
3 **source**

4
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21 Electrolysis

22

1. Introduction

The research of solutions to incorporate renewable fuels in the transport sector has become urgent in recent years due to the need to limit the environmental impacts of passengers and freight transfer [1]. Also, in the last decades the consumption of diesel has risen significantly – due to the increase in sales of passenger vehicles using this fuel – reaching 44% of sales share in the European market in 2017 [2]. Combining this contribution with heavy-duty vehicles and buses, diesel occupies a large share (71% in 2016 [3]) of the road transport final energy consumption in the European Union.

Crude oil is by far the main feedstock for diesel production worldwide, and this contributes significantly to the emissions of the transport sector. In 2016 the global share of greenhouse gas emissions attributable to the transport sector was 24% [4].

Biofuels represent a valuable option for the decarbonization of the transport sector and they offer important advantages compared to other alternatives. In particular, they can be mixed with fossil fuels without major modifications of the engine design and they do not require a radical change in the infrastructure for fuel distribution. This aspect makes them the most short-term option to introduce a renewable energy source in vehicles. In terms of chemical composition, biofuels do not contain aromatics and their sulfur content is usually low (below 10 mg/kg) [5,6]. Moreover, these options may be a viable way of improving security of supply by promoting the use of local resources [7] and contributing to the recycling of the carbon present in waste substances [8].

The most relevant biofuels in the European context are mainly: FAME (Fatty Acid Methyl Esters), obtained from the reaction of vegetable oils or animal fats with alcohols (i.e. a transesterification reaction); and HVO (Hydrotreated Vegetable Oil) resulting from the reaction of virgin or waste oils with hydrogen in a process commonly called hydrotreatment.

1 Regarding the compatibility with fossil diesel, FAME fuels require engine modification for high
2 blends [9], while HVO can be used with no blend level restriction [10]. On the other hand, the
3 chemical properties of HVO (also called “green-diesel”) are more similar to those of fossil
4 diesel, especially for the absence of double bonds in the carbon chains, and this allows such fuel
5 to reach higher blends in fossil fuels. Furthermore, several sources confirm that HVO and
6 paraffinic synthetic fuels typically result in lower exhaust emission levels (NO_x, PM, CO, and
7 HC) and good engine performance [11].

8 One of the feedstock for HVO is waste vegetable oil (WVO) – the current production of which
9 was estimated between 700 and 1,000 kton per year in Europe [12]. The main challenges for the
10 use of these resources are associated to their collection and treatment. Producing biofuels, and
11 particularly biodiesel, from WVO enables the implementation of the circular economy concept
12 and avoids the use of virgin oils. Then, since WVO is considered a residue, its adoption for the
13 production of biodiesel can give a substantial contribution in the fulfillment of the Renewable
14 Energy Directive (RED) target for incorporating renewable sources in the transport sector. In
15 fact, the energy content of biofuels derived from residues is double counted [13], as such
16 biofuels are considered neutral in terms of greenhouse gas emissions [14].

17 The production of HVO via hydrotreatment requires large amount of hydrogen and, so far, the
18 main source of hydrogen has been the steam reforming of hydrocarbons². This fact justifies the
19 study of alternative solutions that achieve satisfactory hydrogen production performance, making
20 use of renewable energy sources. Among them, the use of low-carbon electricity to enable the
21 production of synthetic hydrocarbons has been extensively studied in conjunction with both

² Hydrogen obtained from steam reforming of natural gas is also called *grey hydrogen* and it is opposed to *green hydrogen*, which is generated by renewable energy sources and avoids the production of carbon emissions in the first place [89].

1 gaseous and liquid fuels [15–18]. The pathways integrating electrolysis with fuel production that
2 are currently available in literature are mainly focused on hydrocarbon synthesis through
3 methanation [19], Fischer-Tropsch processes [20], and on methanol/dimethyl ether (DME)
4 synthesis [21,22]. However, the integration of electrolysis with hydrotreatment has been
5 investigated only in a preliminary study developed by the authors of this paper [23]. Since many
6 studies suggest that the production of HVO will substantially contribute to the decarbonization of
7 the transport sector [24,25], with future scenarios projecting the phase-out of conventional
8 biodiesel replaced with HVO [26], a deeper analysis of the techno-economic and environmental
9 performance of this process should be carried out.

10 In recent years a few studies have scrutinized the performance and the profitability of different
11 options for HVO production. Sonthalia et al. [27] and No et al. [28] present a review on
12 hydrotreatment processes involving various types of feedstock, both virgin and waste oils, and
13 describe the main effects of HVO use in diesel engines. Glisic et al. [29] and Pinto et al. [30]
14 investigate the operation of different plant configurations for HVO production using either waste
15 oils or rapeseed virgin oil. The previous studies were mostly focused on demonstrating the
16 technical and economic viability of HVO production, proving it to be a competitive alternative to
17 FAME [31]. However, none of these studies considered hydrogen coming from electrolysis
18 processes, that could potentially make use of low-carbon electricity coming from renewable
19 sources. The aim of this paper is to fill this gap through the integration of a high-temperature
20 electrolysis unit, i.e. composed of Solid Oxide Electrolysis Cells (SOECs), with the
21 hydrotreatment process of WVO. The assessment of the energy efficiency and economic
22 viability of the integration of these two processes constitutes the main original contribution of
23 this research. The structure of the paper is the following: Section 2 describes the process for

1 HVO production. Section 3 illustrates the plant layout. Section 4 outlines the methodology and
2 includes the cost assumptions. Section 5 presents the energy and economic results of the plant.
3 Section 6 discusses the baseline assumptions through a Monte Carlo and sensitivity analyses.
4 Section 7 reports the conclusions of the paper.

5 **2. Process design**

6 This section illustrates the three main parts of the HVO production process, namely: feedstock
7 pre-treatment, water electrolysis for hydrogen production and hydrotreatment.

8

9 *2.1. Feedstock origin and pre-treatment*

10 The synthesis of HVO can be performed using virgin vegetable oils, waste oils (WVO) or animal
11 fats as feedstock. The conversion of waste materials, in particular WVO, has been preferred
12 because it is a feedstock that does not entail any competition with food crops. Moreover,
13 recycling waste oils and animal fats reduces the quantity of residues that are landfilled and that
14 can create problems to the wastewater collection system [32]. The main sources of WVO are
15 food processing industry, restaurants and households [33].

16 The adoption of feedstocks with different quality levels requires a pre-treatment process – that
17 the raw materials usually undergo before hydrogenation – in order to remove phosphorous and
18 sulfur compounds, traces of metals and soaps that negatively affect the quality of the final
19 product and the life of the hydrogenation catalyst [34]. This is an essential step to guarantee
20 higher yields in conversion, since catalyst deactivation can occur when phosphor- and sulfur-
21 containing compounds reach the active sites and irreversibly adsorb onto them [35]. For the same

1 reason, hydrogen sulfide and carbon monoxide should not be present in the hydrogen stream
2 [35].

3 The feedstock pre-treatment usually consists of three processes: neutralization, degumming and
4 bleaching [31,36]. The presence and the amount of impurities in the waste oil influence the pre-
5 treatment process [37]. Free fatty acids are possible contaminants which can be removed by
6 means of a neutralization step involving the use of alkaline solutions [37]. Other impurities, e.g.
7 the calcium and magnesium salts of the phosphatidic acid, are usually nonhydratable and,
8 therefore, difficult to remove. Degumming is the process that eliminates all types of
9 phosphatides, including the nonhydratable ones. If the phosphatide content is small (<20 ppm),
10 as in palm oils, these impurities can be treated via a dry degumming process, with concentrated
11 phosphoric acid [31]. Otherwise, different processes (e.g. acid or EDTA degumming) can be
12 applied [31,36]. Bleaching is the final step and it aims at diminishing the amount of non-
13 converted phosphatides, trace metals and other contaminants present in the oil [35,37].

14

15 2.2. *Water electrolysis*

16 The production of hydrogen for hydrotreatment has been considered to occur in solid oxide
17 electrolysis cells (SOECs), having an operating temperature in the range of 600-1000°C and,
18 hence, are considered a high temperature electrolysis technology. There are other technological
19 options for water electrolysis, mainly alkaline cells and proton exchange membrane (PEM) cells,
20 which are characterized by lower temperature intervals (*ca* 60-100°C). However, SOECs have
21 been chosen because of their higher efficiency, which can reach 100% in thermo-neutral
22 conditions [38]. The thermo-neutral operation occurs when the heat produced by the Joule effect
23 of the flowing current is equal to the heat demand necessary for the water splitting. The higher

1 efficiency is due to the fact that part of the energy can be provided in form of heat, and not
2 necessarily as electricity. In addition, SOECs have a lower internal resistance compared to other
3 cell technologies and this reduces energy losses [39]. The high operating temperature favors the
4 integration of this technology with other processes, that can benefit from high quality heat and,
5 in turn, reduce the recourse to external sources of thermal energy. A more extensive description
6 of the working principle, the materials and the advantages of SOECs can be found in Laguna-
7 Bercero [40].

8

9 *2.3. Hydrotreatment process*

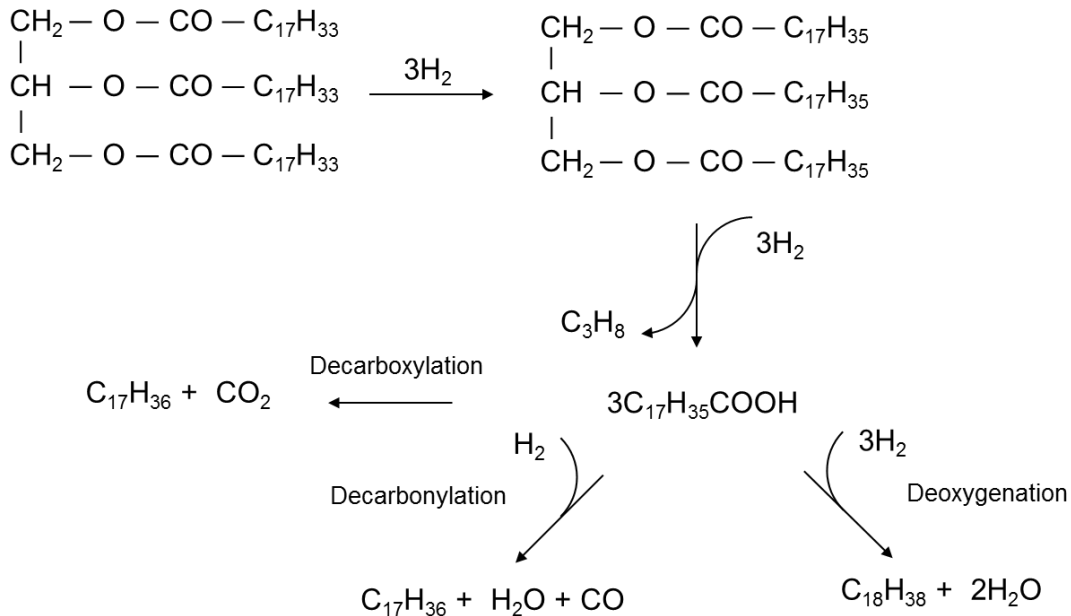
10 The catalytic hydrotreatment of vegetable oils is performed under a temperature which ranges
11 between 300 °C and 450 °C, while the hydrogen pressure applied is generally between 3 MPa
12 and 20 MPa [27,41]. Several noble or transition metal catalysts can be used for this reaction (Pd,
13 Pt, Co-Mo, Ni-Mo) and these, along with the temperature and pressure values, have an important
14 effect in controlling the product distribution [42].

15 In a continuous hydrotreatment process, the waste vegetable oils undergo three steps. First, the
16 substrate is mixed and pre-saturated with hydrogen under high temperature [43]. Then, the gas-
17 liquid mixture is fed to the reactor where it reacts over a fixed-bed of catalyst in a trickle-bed
18 configuration. The products are finally directed to a separator after being cooled down, in order
19 to degas the light by-products and the unreacted hydrogen dissolved in the liquid [27].

20 The first reaction occurring inside the hydrotreatment reactor is the hydrogenation of the double
21 bonds present in the fatty esters and the cracking of the molecules, to produce intermediate free
22 fatty acids and propane [44]. The oxygen is then removed via three routes. These include the
23 hydro-deoxygenation, hydro-decarboxylation and hydro-decarbonylation [45]. The former is

1 responsible for the formation of water and alkanes with an even number of carbon atoms, while
 2 the other two produce alkanes with an odd number of carbons, along with CO₂ and CO
 3 respectively [45]. Figure 1 shows these reaction pathways for the hydrotreatment of triolein.

4



5

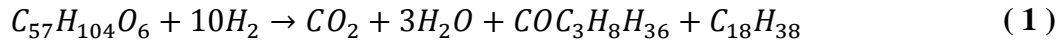
6 **Figure 1: Reaction pathways of triolein hydrotreating producing heptadecane, octadecane,**
 7 **propane, water, carbon monoxide and carbon dioxide (adapted from Sotelo-Boyas et al. [41]).**

8

9 Sulphided Co-Mo, Ni-Mo and Ni-W supported on $\gamma\text{-Al}_2\text{O}_3$ are generally more active than
 10 monometallic catalysts [42]. The Co-Mo and Ni-Mo catalysts normally favor the hydro-
 11 deoxygenation reaction pathway. In particular, in a hydrotreating reaction conducted on soybean
 12 oil, it was found that using Co-Mo/ $\gamma\text{-Al}_2\text{O}_3$ the C₁₇-to-C₁₈ product ratio was one of the lowest
 13 (i.e. 2.16) among the results from other mono- and bi-metallic catalysts [44].

14 In our work, the conversion of vegetable oils into green diesel occurs in a fixed bed reactor at
 15 300°C, using a commercial Co-Mo catalyst dispersed on an alumina support [29]. The waste oil

1 conversion process is modeled similarly to [46], while the inlet waste vegetable oil is assumed to
2 be completely composed of triolein [29]. The stoichiometry of the hydrotreatment reactions
3 represented in Figure 1 are summarized in equation (1). Only heptadecane and octadecane are
4 considered as products, which is in agreement with previous studies [41]. The flow of hydrogen
5 directed to the hydrotreatment reactor is in large excess³ compared to the stoichiometry of the
6 reaction.



7 The chemical behavior of HVO is more similar to the one of the fossil diesel also in terms of
8 water solubility and oxidative stability [47]. Therefore, no extra precautions are needed regarding
9 pipelines, tanks or service stations and the fuel does not experience any major degradation if
10 properly stored [48].

11 **Process layout**

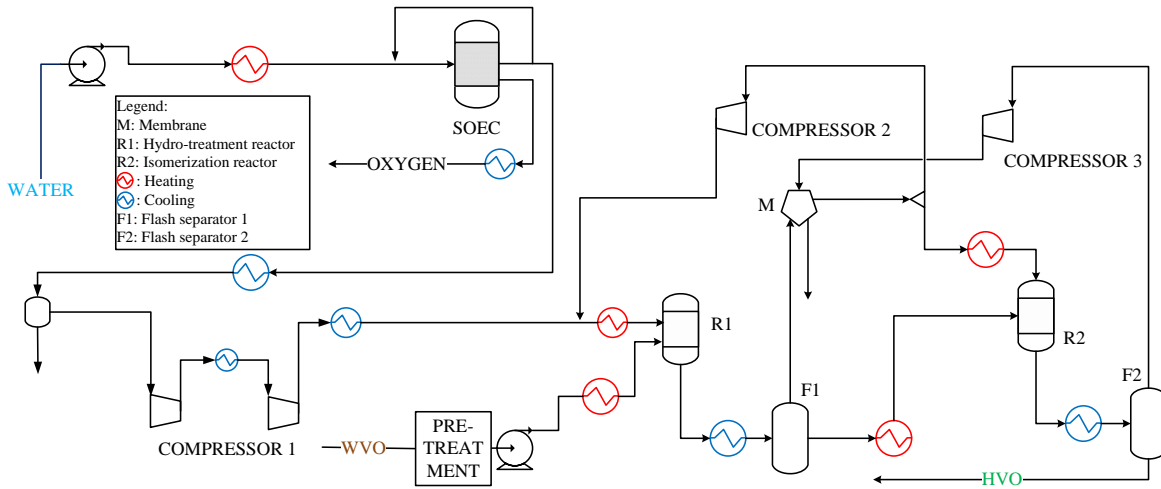
12 *2.4. Plant layout*

13 The schematic of the plant for HVO production is presented Figure 2. It is designed for an annual
14 production of 100,000 ton, working for 8,000 hours per year that correspond to a capacity factor
15 greater than 90% [29]. The engineering plant simulations were performed in the process
16 engineering software Aspen Plus using the RK-ASPEN thermodynamic model.

17 The two main inflows to the process are demineralized water for hydrogen production and
18 WVO. The hydrogen production step is described in Section 2.5, then the gas is fed directly to
19 the hydrotreatment reactor (R1).

³ The molar ratio H₂: WVO is higher than 60:1.

1 The other input of the process is a flow of raw WVO. The first stage of the process consists in a
 2 pre-treatment (see Section 2.1), that yields a proper feedstock for the conversion into
 3 hydrocarbons. Then, the treated oil is pressurized to 70 bar and heated to 290°C and fed, together
 4 with the hydrogen coming from the electrolyzer, to the hydrotreatment reactor.



5
 6 **Figure 2: Scheme of the integrated high-temperature electrolysis and hydrotreatment plant.**

7
 8 The outlet stream of the reactor firstly goes through a flash tank, operating at 70°C, which is
 9 used to separate liquid hydrocarbons from water and syngas. The vapor stream from the first
 10 flash tank (F1) flows through a membrane (M) with a hydrogen selectivity of roughly 100%⁴
 11 [49] and the resulting stream is split: a part is recirculated to R1, while the remaining part is sent
 12 to the isomerization reactor (R2). The liquid stream reaches 355°C and 50 bar and it is directed
 13 towards R2 with the function of partially isomerizing the n-alkanes to improve the cold
 14 properties of the final fuel [27]. In the simulation 10% of both C₁₇H₃₆ and C₁₈H₃₈ was assumed to
 15 be isomerized into 6-pentyldecane and 8-propylpentadecane respectively. At the same time a

⁴ In the simulation the selectivity is assumed equal to 99.5%. The second stream exiting the membrane is a mixture of water, CO₂, CO, propane and hydrogen that is not furtherly utilized.

1 small fraction of heptadecane (4.7% wt) is cracked into gaseous compounds that have been
2 modeled uniquely as propane (equation (2) [46,50].



3 The products of the isomerization are cooled down to 50°C and a flash tank (F2) separates the
4 liquid hydrocarbons, constituting the HVO, from the gaseous components that are recirculated.

5 Hydrogen-rich streams are recirculated due to high H₂ flows required by both reactors.

6 In order to estimate the volume of the reactors the Liquid Hour Space Velocity (LHSV) was
7 established. In R1 the LHSV is 1.0 h⁻¹ [29], therefore, the hourly volume flow rate entering the
8 reactor is equivalent to the volume of the reactor itself and the vessel is considered to be vertical.

9 The isomerization reactor has a LHSV of 2.1 h⁻¹ [51]. The sizing of the flash tanks was done
10 according to the methods described in [52].

11 The efficiency of the plant is quantified through equation (3). The power inputs are represented
12 by the electric power (W_{el}) required by pumps, compressors and by the electrolyzer, as well as
13 the energy content of the feedstock expressed as lower heating value multiplied by the mass flow
14 rate ($LHV_{WVO} \cdot \dot{m}_{WVO}$). The power output is represented by the flow of HVO multiplied by its
15 mass flow rate ($LHV_{HVO} \cdot \dot{m}_{HVO}$).

$$\eta = \frac{LHV_{HVO} \cdot \dot{m}_{HVO}}{W_{el} + LHV_{WVO} \cdot \dot{m}_{WVO}} \quad (3)$$

16 The results of the simulations performed in the software Aspen Plus are summarized in Section
17 4.

18 2.5. SOEC model

19 Hydrogen is typically produced through steam-reforming of natural gas in oil refineries, which
20 does not promote a reduction of fossil-fuel dependency associated to the transport sector.

21 Alternatively, hydrogen could be produced through electrolysis in case there was a large

1 availability of cheap and low-carbon electricity. In this study, high-temperature Solid Oxide
2 Electrolysis Cells (SOECs) are used because of their high operating temperature and conversion
3 efficiency [40,53]. Part of the cathodic flow exiting the electrolyzer (Figure 2) is recirculated to
4 increase the hydrogen content at the inlet of the cathode (set to 10% in volume), to avoid an
5 excessively oxidizing environment, thus, limiting the risk of oxidation of the nickel catalyst of
6 the cells.

7 The electrolyser is operated at thermo-neutral conditions and it is fed with demineralized water
8 available at 20 °C and 1 atm, which must be pre-heated to reach the conditions suitable for the
9 electrolysis. The water electrolysis reaction is considered to take place at 850 °C. Part of the
10 oxygen produced at the anode is recirculated and it acts as sweep gas⁵, avoiding the use of air
11 that could compromise the quality of the outlet oxygen, which in this case could be collected and
12 used for other applications because of its very high purity. After the electrolyzer, the cathodic
13 flow is cooled down to 80 °C and it enters a flash separator in order to obtain a hydrogen stream
14 at 99% purity, that constitutes one of the reactants for the hydrotreatment process. The model of
15 the SOEC was adapted from [54] and the water conversion has been set to 70% to avoid losses
16 due to diffusion limitation [55]. The active area of the SOEC is calculated considering that the
17 operation occurs in thermo-neutral conditions and that the Area Specific Resistance (ASR) is
18 equal to 0.5 Ω cm². The flow of hydrogen goes through an intercooled compression in two stages
19 reaching 70 bar, which is the pressure at which the catalytic hydrotreatment takes place.

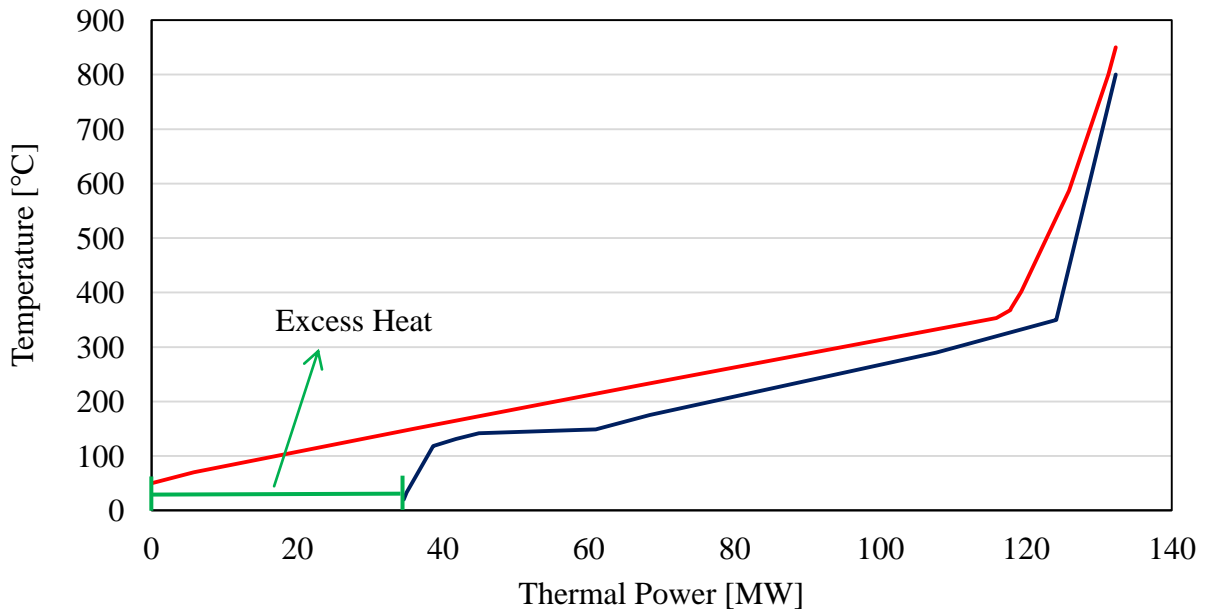
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⁵ The oxygen recirculation is not present in Figure 2, where only the outlet oxygen stream is represented.

1 2.6. Heat exchangers network

2 The plant is able to supply all the thermal energy that is needed for the chemical processes
3 without using external sources of heat. As a result, the Pinch Analysis methodology [56] has
4 been applied in order to calculate the minimum number of heat exchangers and the
5 corresponding heat exchange area that enables a complete thermal integration. The considered
6 heat-exchange coefficients are $200 \text{ W}/(\text{m}^2\text{K})$ for liquid-liquid heat exchange and $100 \text{ W}/(\text{m}^2\text{K})$
7 for gas-gas [57], while the minimum temperature difference between cold and hot flows is
8 imposed at $10 \text{ }^\circ\text{C}$. The composite curves for the hot and cold streams are shown in Figure 3,
9 where the heat excess is highlighted. The layout of the plant with the indication of the heat
10 exchangers is reported in Figure 4.

11



12

13 **Figure 3: Composite curves for hot (red) and cold (blue) streams for the integration of electrolysis**
14 **and hydrotreatment. The green segment represents the excess heat of the process. (For a clear**
15 **distinction of the colors refer to the online version).**

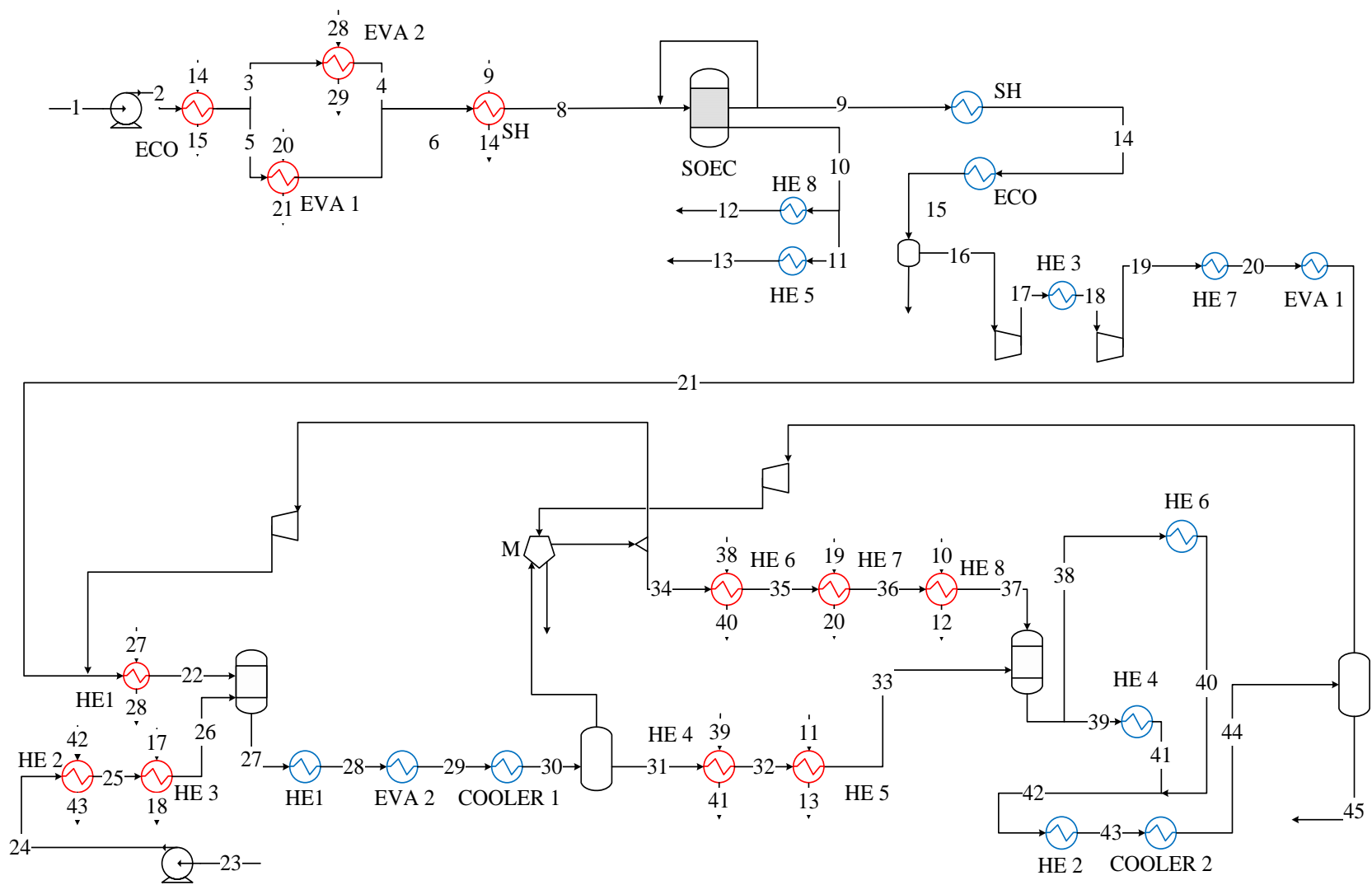


Figure 4: Scheme of the network of heat exchangers for the considered plant layout. Only the relevant streams are numbered. (For a clear distinction of the colors refer to the online version).

3. Economic considerations

3.1. Economic assessment methods

The approaches adopted to evaluate the economic performance of the plant are the levelized cost of fuel (LCOF) and the net present value (NPV) analysis. The first method gives an estimation of the unit production cost of HVO, while the second method allows the balance between future positive and negative cash flows to be estimated over the lifetime of the HVO plant. For both the approaches the costs of the equipment, of the feedstock, and of the disposable materials, as well as all the other fixed costs required for the HVO plant operation need to be calculated. A plant lifetime of 20 years was considered for all the components of the plant, except for the SOEC which was considered to have a lifetime (l_t) of 10 years [57]. A discount rate (d) of 5% was assumed. The levelized cost of fuel (LCOF) is computed as in equation (4).

$$LCOF = \frac{CRF \cdot INV^* + O\&M + INPUT}{Prod_y} \quad (4)$$

Where CRF is the capital recovery factor, INV^* is the initial investment that accounts for the replacement of the SOEC after 10 years⁶, $O\&M$ is the annual operation and maintenance cost, $INPUT$ is the sum of all the costs related to the input mass and energy streams and $Prod_y$ is the annual production of HVO. The numerator is expressed in €/year, while the denominator in $ton_{HVO}/year$.

The NPV is instead calculated according to equation (5).

⁶ $INV^* = \sum_{y=0}^{N=lifetime} \frac{INV_y}{(1+d)^y}$

$$NPV = \sum_{y=1}^{l_t} \left(\frac{Prod_y \cdot P_{HVO} - O\&M - INPUT - IT}{(1 + d)^y} \right) - \sum_{y=1}^{l_t} (INV_y) \quad (5)$$

1
2 Where P_{HVO} is the price of HVO in €/ton, IT stands for income tax and INV_y is the investment in
3 the y^{th} year.

4 The tax component is excluded from the calculation of the LCOF because this metric aims at
5 quantifying the cost related to the resources needed to produce the HVO. Income taxes should be
6 excluded when evaluating the pure production cost of the fuel since they are based on the annual
7 profit. On the other hand, they should be included in the calculation of the NPV since they
8 influence the profitability of the investment. Income taxes are charged on the taxable income of a
9 company that is the gross profit, defined as revenues minus operating cost (variable O&M costs
10 and utilities), minus the asset depreciation[58]. The considered tax rate is 22.5%, which is the
11 average European Union statutory income tax according to the OECD statistics [59].

12 13 *3.2. Component cost and material cost estimation*

14 The costs associated to the presented design are based on an estimation of each of the plant's
15 component. For all the pieces of equipment, with the exclusion of the electrolyser, the bare
16 erected costs were determined according to the formulations in [60] and expressed in $\$_{2001}$.
17 Conversely, the SOEC cost for unit of active area is 550 $\$_{2007}/\text{kW}$ which is accordance with the
18 estimation in [57]. All the costs have been harmonized in $\$_{2017}$ using the CEPCI index
19 ($C_{I,2017}=567.5$, $C_{I,2007}=525.4$, $C_{I,2001}=397$)⁷ [61], and, then, converted into Euros with the
20 application of an exchange rate of 1.1 €/\$. The cost for the hydrogen separation membrane has

⁷ The CEPCI index is applied as follows: $\frac{\$_{year,1}}{\$_{year,0}} = \frac{CEPCI_{year,1}}{CEPCI_{year,0}}$.

1 been set equal to 1500 \$/ft² which is equivalent to 16150 \$/m². This value has been derived from
2 a technical report that conducts a feasibility analysis on separation membranes to obtain >99%
3 pure hydrogen streams [62]. It is assumed that the membrane is replaced every 5 years.

4 The cost of waste vegetable oil and the price for HVO have been assumed based on the data
5 provided by the biodiesel broker Greenea [63]. The margin between the price of the final product
6 and the cost of the raw material has been reported to be the interval 150 – 400 €/ton, in the
7 period January 2017 to January 2020. Considering that the price of WVO has ranged between
8 800 and 600 €/ton, it is evident that the margin of the biodiesel producers is not very high, with
9 clear implications on the viability of such business. The price of WVO is similar to that of virgin
10 oil⁸ and this is mainly due to the double-counting of the biodiesel produced from waste material
11 as part of the renewable energy directive [13]. A good example of the consequences of the RED
12 is the Portuguese case, which shows that in recent years the country has radically changed its raw
13 material import mix for biodiesel production, switching to massive importation and use of WVO
14 [64]. In this study the baseline value for WVO cost has been assumed to be 400 €/ton, which
15 belongs to the upper part of the price range available in similar studies. Glisic et al. [29] assumes
16 a price of 260 \$/ton⁹, Farid et al. [65] uses a price of 200 \$/ton¹⁰ and Mandolesi de Araújo et al.
17 [66] reports a price ranging between 224 and 415 \$/ton. Other researches [67,68] consider WVO
18 to be available at no or very low cost.

19 An estimate of WVO pre-treatment costs can be derived from the work of Zhang et al. [69],
20 where an economic feasibility study is made on alternative processes that produce biodiesel via
21 transesterification. The pre-treatment cost is considered to be 0.76 M\$, referred to a biodiesel

⁸ As an example, the price of the Malaysian palm oil ranged between 480 and 780 €/ton in the period (2015-2019) [90].

⁹ A WVO price of 260 \$/ton is equivalent to 235 €/ton with the exchange rate considered in this study.

¹⁰ A WVO price of 200 \$/ton is equivalent to 182 €/ton with the exchange rate considered in this study.

1 production of 8000 ton/year and assuming a product yield equal to $0.9 \text{ ton}_{\text{biodiesel}}/\text{ton}_{\text{feedstock}}$. This
2 results in a cost of $85.5 \text{ } \$/(\text{ton}_{\text{in,WVO}}/\text{year})$. This unit capacity cost has been employed to scale up
3 the total capacity cost, using an exponent equal to 0.6 [60]. Therefore, it is assumed that the pre-
4 treatment cost for a HVO plant is comparable with that of a biodiesel production plant adopting a
5 transesterification process.

6 The HVO price has been assumed in line with the average price of FAME registered in the
7 period January 2017 – January 2020, namely 1000 €/ton [70]. This assumption is conservative
8 because, as described in the introduction, HVO quality is superior to FAME. The electricity cost
9 has been fixed at 40 €/MWh. This value represents a target value for electricity cost when
10 electrolysis for hydrogen and fuel synthesis is considered [71]. In Europe, similar prices are
11 charged to large energy consumers (>150 GWh/year) in Sweden and Norway¹¹. these are the
12 European countries where these types of consumers have access to the lowest tariff [72]. These
13 two countries have also a very high renewable content of the electricity (65 % in Sweden and
14 over 100% in Norway [73]) and, therefore, represent an ideal setting for the integration of high-
15 temperature electrolysis and hydrotreatment. In this study the produced oxygen is assumed to
16 positively contribute to the profitability of the plant. Its large production rate (3 ton/y) and its
17 high purity (>99% [74]) are two factors that contribute to its economic exploitation. The oxygen
18 price for industrial customers is considered equal to 50 \$/ton [75].

19 The operation and maintenance (O&M) cost has a fixed and a variable component. The fixed
20 components include labor, maintenance and insurance costs. Labor is accounted with 21 workers
21 (7 workers per shift / 3 shifts per day) with an income of 40,000 \$/year [29], while insurance and
22 ordinary maintenance costs correspond to 1% and 2% of the total plant cost, respectively [76].

¹¹ The price excludes VAT and other recoverable taxes and levies.

1 The variable component includes the cost for the replacement of the catalysts in the
2 hydrotreatment and isomerization processes. The cost for the hydrotreatment catalyst is assumed
3 equal to 56.96 $\$/\text{ton}_{\text{HVO}}$ [29]; while the isomerization catalyst is considered equal to 258
4 $\$/\text{ton}_{\text{HVO}}$, which is an average of the values reported in Ngo et al. [77]. All the parameters and
5 assumptions concerning the economic analysis are summarized in Table 1.

6

1 **Table 1: Summary of the parameters used in the economic assessment of the plant.**

	Unit	Value
SOEC Cost	\$/kW	500
Hydrogen Separation Membrane Cost	\$/ft ²	1,500
Pre-treatment Cost	\$/ton _{WVO} /year	85.5
Hydrotreatment Catalyst Cost	\$/ton _{HVO}	57
Isomerization Catalyst Cost	\$/ton _{HVO}	258
Labor Cost	\$/year	840,000
Insurance (fraction of plant cost)	%	1
Fixed O&M (fraction of plant cost)	%	2
Electricity Price	€/MWh	40
WVO Price	€/ton	400
Demineralized Water Price	€/ton	2.1
HVO Price	€/ton	1,000
Oxygen Price	€/ton	45
SOEC Lifetime	years	10
Plant Lifetime (excl. SOEC)	years	20
SOEC Depreciation Period	years	10
Plant Depreciation Period (excl. SOEC)	years	20
Discount Rate	%	5
Income Tax	%	22.5
Exchange Rate	\$/€	1.1

2

3

1 **4. Results**

2 The next section reports the energy and economic performance of the plant.

3

4 *4.1. Energy efficiency*

5 Following the assumptions presented in Section 3, the input and output energy and mass flows

6 obtained for the considered plant are summarized in Table 2.

7 **Table 2: Input and output flows with the indication of the corresponding unit costs**

Input	Quantity	Unit	Total Cost	Unit	Specific Cost	Unit	Ref.
Water	5	ton/h	11	€/h	2.1	€/ton	[57]
	43	kton/y	0.1	M€/y			
WVO	16	ton/h	6286	€/h	400	€/ton	[70]
	126	kton/y	50	M€/y			
Power	111	MW	4438	€/h	-	-	[72]
Electrical Energy Consumption	888	GWh/y	35.5	M€/y	40	€/MWh	
Output	Quantity	Unit	Total Price	Unit	Specific Price	Unit	Ref.
HVO	13	ton/h	12514	€/h	1000	€/ton	[63]
	100	kton/y	100	M€/y			
Oxygen	3	ton/h	881	€/h	45	€/ton	[75]
	27	kton/y	7	M€/y			

8

1 The energy efficiency of the plant¹² (see equation (3)) is equal to 80%, which is in accordance
2 with similar studies [27]. This value is influenced by the thermal integration of the plant, which
3 eliminates the needs of external heat, with savings equivalent to 98 MW. Furthermore, 18 MW
4 of extra heat are available above 100 °C, meaning that there is additional room for heat
5 integration, especially with the buildings connected to the plant.

6

7 *4.2. Economic assessment*

8 The economic performance of the plant was estimated through the calculation of the net present
9 value and of the levelized cost of fuel (see Section 3), including fixed and variable costs
10 associated to the construction of the HVO plant. The capital cost has been obtained by applying
11 the methodology defined by the National Energy Technology Laboratory [78] for energy
12 conversion facilities. Table 3 reports the total plant cost (TPC), indicating the share for each
13 category of components, the variable costs associated to the replacement of the disposables,
14 mainly catalysts, and the fixed operation and maintenance costs (e.g. insurance and labor).
15 Following the procedure in [76], the TPC is increased by 20% to obtain the Total Overnight Cost
16 (TOC) which includes the purchase of land, legal fees and permission costs, preliminary
17 feasibility analyses, capital inventory and cost of securing financing. Finally, in order to obtain
18 the Total as Spent Cost (TASC)¹³, the TOC is multiplied by a 1.075 as suggested in [78].

19

¹² The lower heating value for vegetable oil is 39.5 MJ/kg [91] while for HVO is 44 MJ/kg [81].

¹³ Total as-spent cost (TASC) accounts for capital cost escalation during capital expenditure period and interest on debt during construction (assumed equal to 3 years in this case).

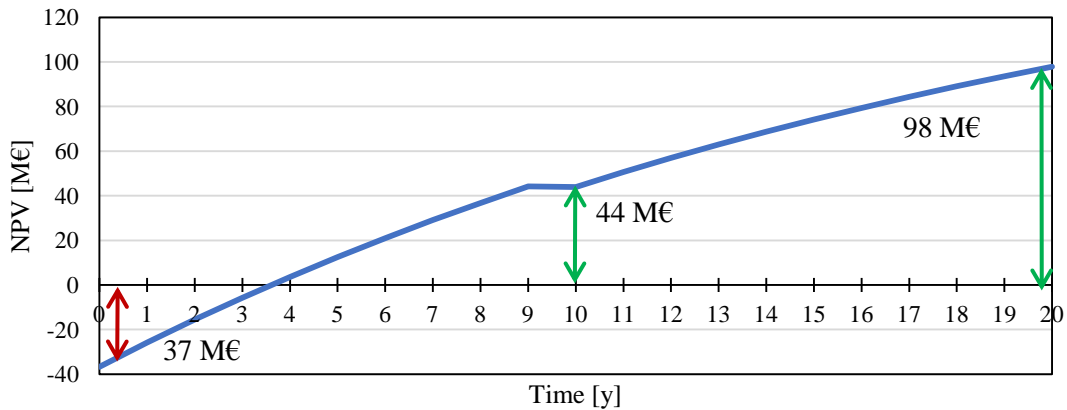
1 **Table 3: Total plant cost, fixed and variable operation and maintenance costs.**

Investment Cost (TPC)			O&M Cost	
			[M€/year]	
Components	Value [M€]	% of total	Fixed	Value [M€/year]
Pre-treatment	1.9	6%	Labor	0.76
R1 (Hydrotreatment)	1.1	4%	Ordinary maintenance	0.54
R2 (Isomerization)	0.7	2%	Insurance	0.27
COMPR 1	7.2	23%	Variable	
COMPR 2	0.8	3%	Hydrotreatment catalyst	5.2
COMPR 3	2.1	7%	Isomerization catalyst	23
Pumps	0.1	0.3%		
Membrane	3.3	11%		
Heat exchangers	3.6	12%		
Coolers	1.1	4%		
SOEC	9.2	29%		
Total	31.1	100%		

2

3 The levelized cost of fuel is 901 €/ton, which corresponds to 0.73 €/l (density 0.8 kg/l). This
 4 value is aligned with the results obtained by [29] for a WVO hydrogenation unit which is not

1 incorporated in a refinery¹⁴. The NPV analysis shows that the baseline case produces positive
2 results with a discounted value of 44 M€ after 10 years and 98 M€ after 20 years, corresponding
3 to 119% and 265% of the initial investment, respectively (Figure 5). The flat behavior of the
4 NPV around the 10th year is due to the replacement of the SOEC stack, that has a shorter life
5 compared to the rest of the components.



6
7 **Figure 5: NPV results for the HVO production plant.**

8
9 The comparison of the LCOF with the price of HVO, assumed equal to 1000 €/ton, reveals that
10 the margin is around 10%. This implies that substantial fluctuations of the HVO price could
11 compromise the financial viability of the investment (see Section 5.1). However, the NPV results
12 suggest that the investment has the potential to be profitable, with a final value of the investment
13 that is more than double the capital initially invested.

14

¹⁴ Glisic et al. [29] calculated that the cost of HVO is 1 \$/kg (ca 0.91 €/kg with the considered exchange rate), considering a WVO price of 260 \$/ton, which is lower than the price considered in the current analysis (i.e. 400 €/ton).

1 5. Discussion

2 5.1. Monte Carlo analysis

3 The results highlighted the strong dependence of the economic performance on the assumptions
4 for some of the parameters reported in Table 1. In order to assess the variables that have higher
5 impact the profitability of the plant, a Monte Carlo analysis has been conducted on the value of
6 the NPV at the end of the project considered lifetime (i.e. 20 years). Several parameters were
7 varied separately as shown in Table 4, assuming a uniform random distribution between the
8 considered lower and upper boundary. For each of the parameters, 10,000 simulations were run
9 to guarantee the convergence of the model.

10 **Table 4: Baseline, lower and upper boundaries for the parameters varied in the Monte Carlo analysis.**

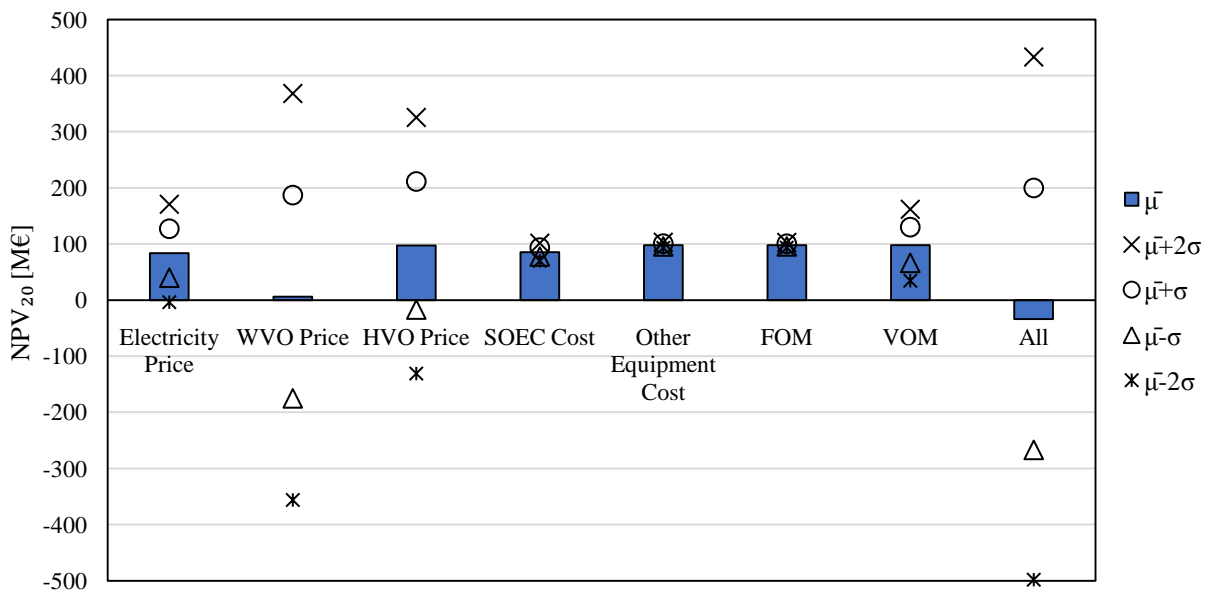
Variable	Baseline	Lower boundary	Upper Boundary
Electricity Price [€/MWh]	40	0	100
WVO Price [€/ton]	400	235	700
HVO Price [€/ton]	1000	800	1200
SOEC Cost [€/kW]	500	300	1500
Other Equipment Cost (EC_0)*	EC_0	$0.8*EC_0$	$1.2*EC_0$
Fixed OM Cost (FOM_0)*	FOM_0	$0.8*FOM_0$	$1.2*FOM_0$
Variable OM Cost (VOM_0)*	VOM_0	$0.8*VOM_0$	$1.2*VOM_0$
All	All parameters at the same time		

11 *The subscript 0 indicates the baseline conditions

12

13 The outcomes of the assessment, consisting in the average values and the confidence intervals,
14 are illustrated in Figure 6. A variable that has a large impact on the economic viability of the

1 project is the price of WVO. Considering a price interval that spans between 235 €/ton (which is
 2 aligned with the assumption made by Glisic et al. [29]) and 700 €/ton (which is representative of
 3 the price of virgin oils [66]) implies that in more than half of the scenarios, the NPV at the end of
 4 the project is negative. The threshold price to obtain a positive NPV is equal to 480 €/ton, which
 5 is higher than what the WVO price that is usually considered in these sorts of analysis (see
 6 Section 3.2). Imposing such a high upper boundary has been done to investigate profitability of
 7 the process with virgin oils, in case WVO was difficult to retrieve. However, this option turns
 8 out not to be viable. The cost for the plant equipment (SOEC and others), and the maintenance
 9 costs are not so influential in the final NPV outcome of the project, compared to the price of
 10 external variables.

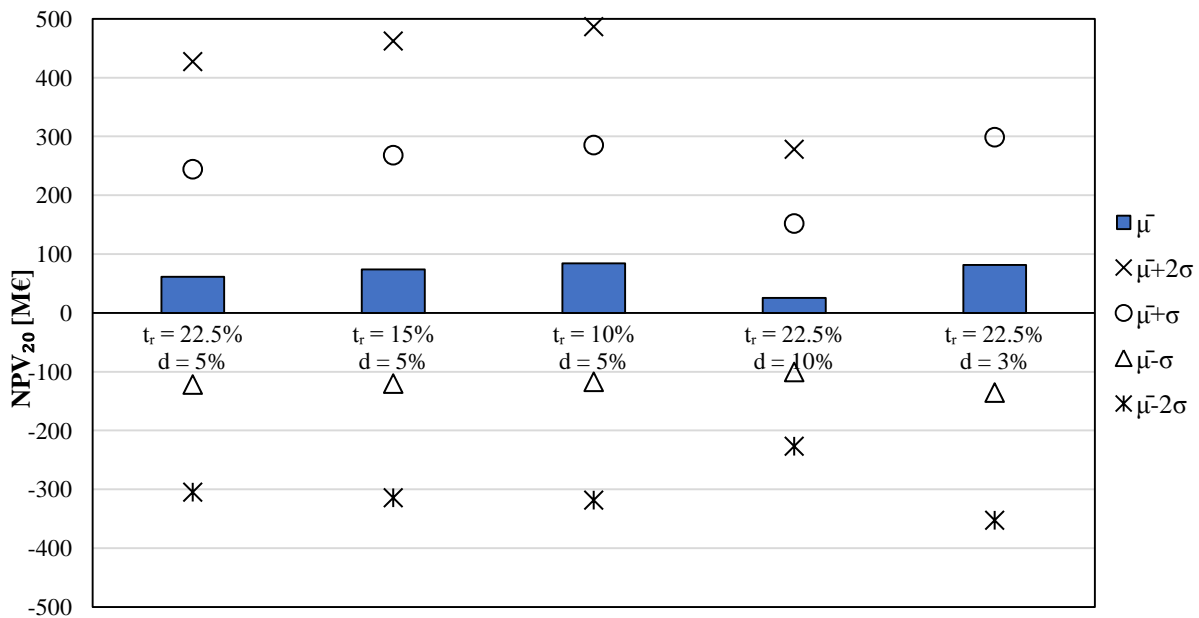


11
 12 **Figure 6: Result of Monte Carlo analysis for the net present value after 20 years (NPV₂₀). Solid columns are**
 13 **the average values, while markers represent the confidence intervals ($\mu \pm \sigma \approx 68\%$, $\mu \pm 2\sigma \approx 95\%$).**

14 Extending the sensitivity interval for WVO up to a price that is characteristic of virgin oil
 15 appears excessively penalizing for the profitability of the plant. Instead, imposing the upper
 16 boundary so that it is symmetrical with respect to the base case (565 €/ton) is more representative

1 of the fluctuations that the price can experience. In addition, considering a possible subsidy in
 2 terms of lower fiscal load (by varying the income tax level from 22.5% to 15% and 10%), the
 3 profitability of the plant further improves, as shown in Figure 7. Income tax reduction to
 4 10% improves the average NPV results by 37%, portraying that this could be a useful policy
 5 instrument to promote the production of more sustainable hydrotreated vegetable oil. On the
 6 other hand, lowering the discount rate to 3%, hence, simulating a situation with lower financial
 7 risk, increases the NPV by 33%.

8



9

10 **Figure 7: Result of Monte Carlo analysis for net present value after 20 years (NPV₂₀) for different tax (t_r) and**
 11 **discount rates (d). The results are referred to the scenario “All” where the sensitivity interval of WVO has**
 12 **been limited to 235-565 €/ton.**

13 The solid oxide electrolyzer is the most expensive component of the whole plant and also the one
 14 with the shortest lifetime. In spite of this, a three-fold increase in the price does not seem to
 15 cause the NPV₂₀ to be negative. This means that the main focus of the plant operator should be to
 16 secure long-term contracts for raw material and electricity with commodity prices that are

1 compatible with the profitability of the investment. On the other hand, a strategy to protect the
2 revenue stream from excessive HVO price fluctuations should be implemented. A possible way
3 of mitigating this issue is to sell large part of the HVO on the future market with a secured price.

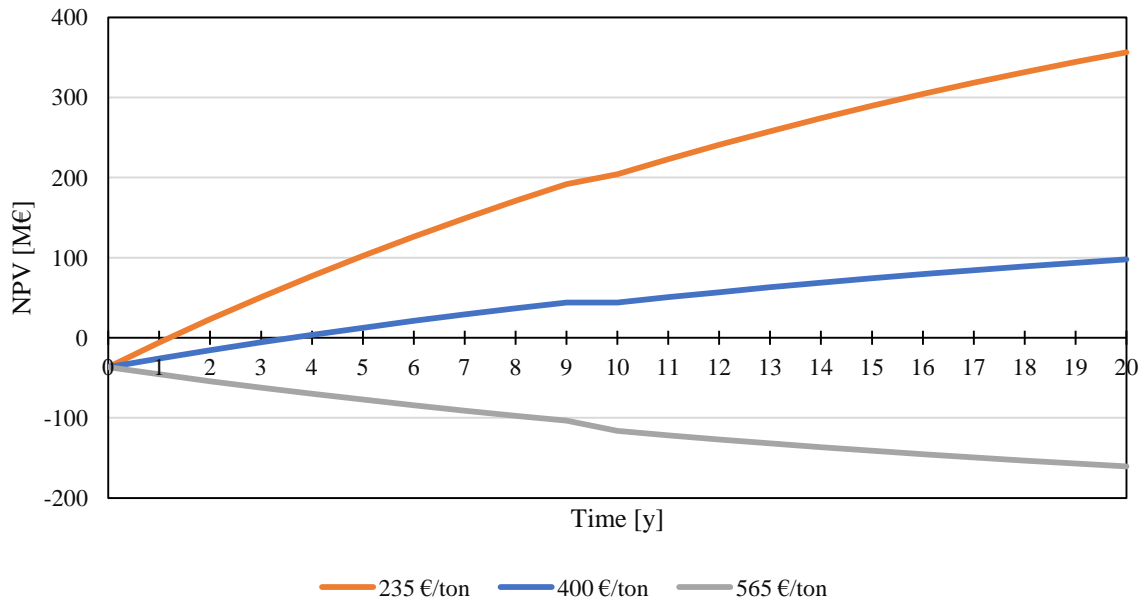
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5 *5.2. Sensitivity analysis*

6 The Monte Carlo analysis has highlighted that WVO, electricity and HVO market price are the
7 most relevant variables that determine the profitability of the investment. According to Figure 6,
8 in most than 50% of the cases the project has a positive NPV after 20 years. However, NPV is
9 not the only variable that should be used to evaluate the investment, but the payback time is also
10 important to determine when the project has recovered all the initial costs. This aspect is
11 analyzed by assessing the behavior of the NPV along the project lifetime, varying one variable at
12 a time.

13 Evaluating the WVO price (see Figure 8), The 400 €/ton scenario for WVO price is characterized
14 by a payback period of less than 4 years, meaning that the project has positive returns for more
15 than 75% of its lifetime. A price reduction of 38% to 235 €/ton would lead to lower payback
16 period, between 1 and 2 years. Since WVO is a residue and its use in this context is aligned both
17 with the circular economy concept and with the decarbonization goals, this low-price scenario
18 could be favored by specific policies aiming at a complete reutilization of the waste oils. A
19 scenario of increasing WVO price, or of partial feed of virgin oil, represented by a price equal to
20 565 €/ton, would not encourage the investment result, since the NPV would be largely negative
21 at the end of the project lifetime.

22



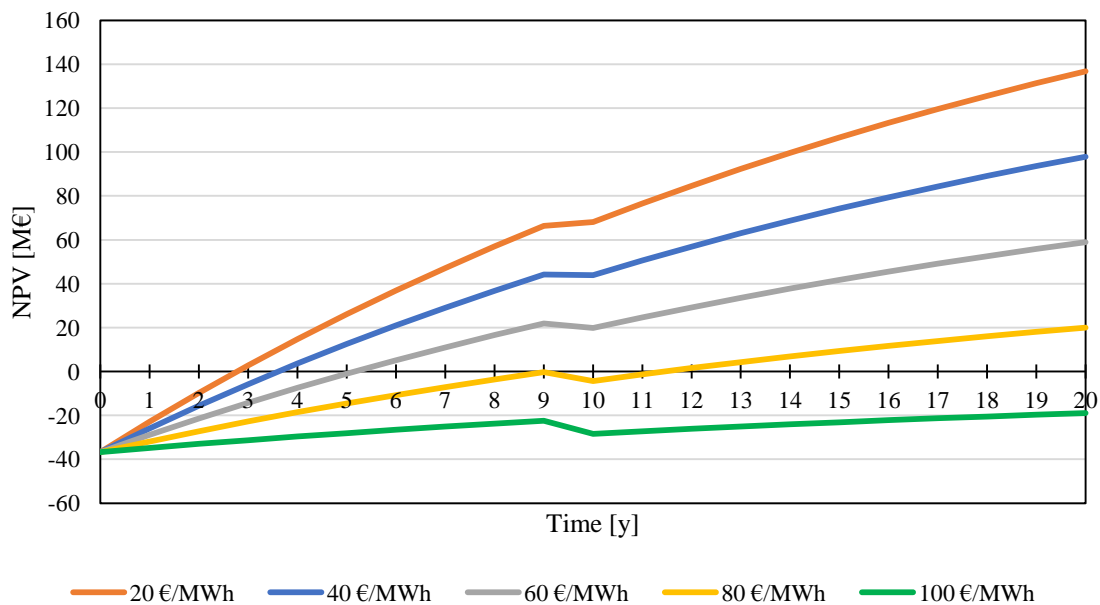
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2 **Figure 8: Sensitivity analysis on the price of WVO. Electricity price 40 €/MWh and HVO price**

3 **1000 €/ton. (For a clear distinction of the colors refer to the online version).**

4

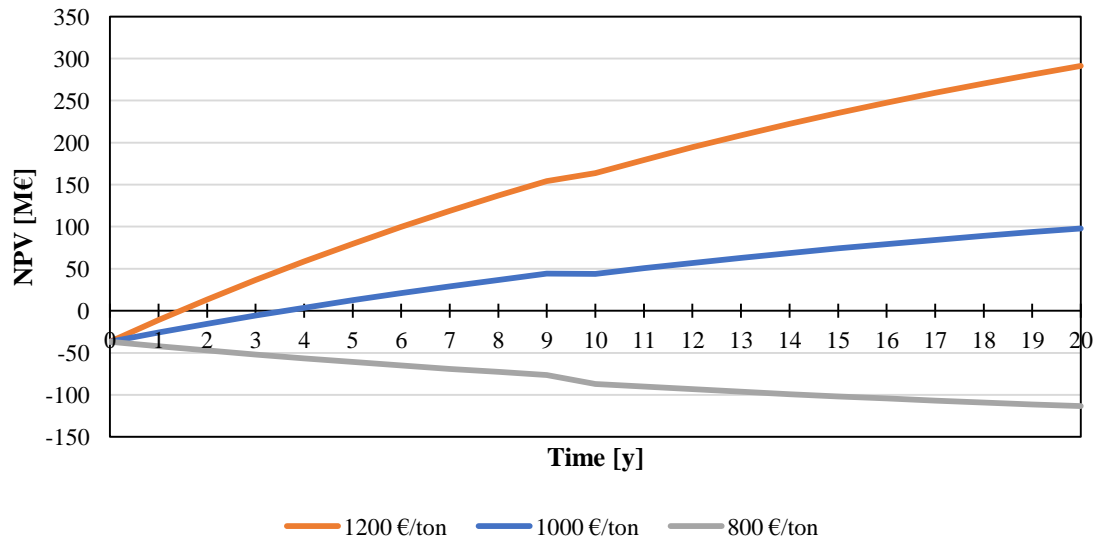
1 Regarding the price of electricity, a 50% reduction of the baseline price (20 €/MWh) would
 2 mean that the payback is reached before the third year. On the other hand, higher electricity
 3 prices (60 and 80 €/MWh) delay the payback time of the investment. A price higher than 80
 4 €/MWh would compromise the profitability of the investment since the NPV after 20 years
 5 would likely be negative. The range of electricity prices reflects the different production costs for
 6 different countries and power generation mixes. High shares of hydro and nuclear energy in the
 7 generation mix push the cost down, while gas and fuel oil plants entail higher costs. Generation
 8 costs for variable renewables, such as solar and wind, are experiencing a sharp decrease [79],
 9 which, coupled with increasing market penetrations, are likely to push the wholesale electricity
 10 price down.



11
 12 **Figure 9: Sensitivity analysis on the electricity price. WVO price 400 €/ton and HVO price 1000**
 13 **€/ton. (For a clear distinction of the colors refer to the online version).**

14

1 Finally, the HVO market price variations have been taken into account to model the fluctuations
2 of the quotations on global markets (
3 Figure 10).
4 An increase from 1000 to 1200 €/ton would result in a decrease of the payback period from 3.5
5 to less than 2 years. The variability on the selling price is the variable that has the highest
6 influence on the profitability, since a 20% variation in the unit price entails a percentage
7 variation on the NPV₂₀ around 200%.



8
9 **Figure 10: Sensitivity analysis on the SOEC cost, WVO price 400 €/ton, electricity price 40 €/MWh.**
10 **(For a clear distinction of the colors refer to the online version).**

11
12 *5.3. Environmental benefits and comparison with other studies*

13 The large benefits deriving from the decarbonization of the transport sector justify the efforts to
14 explore synergies between complementary processes to increase the conversion efficiency. The
15 promotion of liquid biofuels is considered one of the main pathways to pursue in the short-
16 medium term [80]. These energy carriers can contribute to a rapid decrease in greenhouse gas

1 emissions since they can be adopted with conventional diesel vehicles and distributed using
2 existing infrastructures. HVO produced from WVO is one of these options, since it enables
3 higher incorporation ratios in fossil diesel than FAME. It also allows large quantities of waste
4 oils to be recycled, without being landfilled or, inputted in the sewage system. The lifecycle
5 emissions for the production of biodiesel that can be found in Arvidsson et al. [81] are estimated
6 around 375 gCO₂/kWh of HVO, which are two thirds of those for diesel (i.e. 563 gCO₂/kWh).
7 This means that the annual production of HVO from a plant like the one described in this study
8 would save 230 kton of CO₂ for replacing fossil diesel. Moreover, the use of electricity with a
9 low or zero carbon content bears a considerable environmental benefit. The production of
10 hydrogen through steam reforming entails a CO₂ emission of 0.45 mol_{CO₂}/mol_{H₂} [82,83], while
11 the emission factor for electricity production can be very close to zero. For instance, 1 MWh of
12 electricity generated in Sweden and Norway produces respectively 0.023 and 0 ton_{CO₂} [84].
13 Considering that the plant is located in one of these two countries, the emissions deriving from
14 electricity would be 2.8 kton for the Swedish case and zero for the Norwegian one. On the other
15 hand, the annual CO₂ emitted by the steam reforming would amount to 33.8 kton (*ca* 0.34
16 ton_{CO₂}/ton_{HVO}). This entails that the environmental performance of SOEC-hydrotreatment
17 integrated process can add a further environmental benefit to the production of HVO, which is
18 already less polluting than fossil diesel. The total of the avoided emissions, deriving from fossil
19 diesel substitution and from the use of low carbon electricity, translates into a reduction equal to
20 the emissions of roughly 100,000 cars in one year¹⁵.
21 The Monte Carlo analysis has highlighted that WVO prices below 500 €/ton are necessary to
22 make this process profitable and that the relation between NPV and WVO price is quite steep.

¹⁵ Considering an average car travelling 15,000 km/y with an average emission of 0.176 kgCO₂/km [92].

1 Therefore, securing a stable supply with a long-term contract appears as a fundamental step to
2 ensure the profitability of this kind of plant.

3 The cost for the HVO production of 901 €/ton that has been obtained in this study is comparable
4 with the results of other techno-economic analyses as reported in Table 5. This value is in line
5 with the results obtained by other authors that analyzed both FAME and HVO production
6 processes [29,85,86]. The main difference in the estimations lies in the different assumptions on
7 the cost of the raw material.

8

1 **Table 5: Comparison with other studies focusing on the techno-economic analysis of biofuel**
 2 **production.**

Feedstock	Feedstock cost (\$/t)	Type of process	Plant capacity	Production cost (\$/kg)	Ref.
Palm Oil	805	Hydrotreatment	202	1.36	[86]
Palm fatty acid distillate	608	Transesterification	120	0.91 – 1.11	[85]
Waste vegetable oil	260	Hydro-treatment	100	0.81 - 1	[29]
Waste vegetable oil	260	Transesterification	100	0.67 – 0.73	[29]
Waste vegetable oil	440	Hydrotreatment	100	0.99	This study

3

4 **6. Conclusion**

5 The proposed HVO plant proves to be viable for the production of 100,000 tons per year of HVO
 6 with an energy efficiency of 80% and with no need of external sources of heat, since the plant is
 7 self-sufficient in supplying all the thermal energy required for the chemical processes. This type
 8 of facility has the potential of having a surplus of heat that can be used for other uses, mainly
 9 residential space heating, due to its low temperature level (100 - 150 °C).

1 The economic analysis associated to the HVO plant indicates that an overall plant investment
2 would reach a break-even point after less than 4 years in the base case situation. Furthermore, the
3 variable that has the highest influence in the production cost of HVO is the price of the WVO,
4 since it constitutes almost half of the LCOF in the base case. The presented concept is a way of
5 promoting the decarbonization in the transport sector in a short-to-medium-term perspective,
6 since the penetration of RES in this sector, especially electricity, may be slower because a
7 vehicle technology turnover is required [87]. Average vehicle age in Europe is on average of 11
8 years old for a passenger cars, 10.9 years for vans and 12 years for heavy commercial vehicles
9 [88], indicating that the total fleet turnover will take more than a decade. This fact justifies the
10 need for other alternatives which do not require a technology shift. In addition to that, the
11 presented process constitutes a valid alternative to other process for biofuel production using
12 hydrogen (e.g. Fischer-Tropsch synthesis) and it has the advantage of using a waste material,
13 promoting the circular economy framework, avoiding the need for a gasification process.

14

15 **Acknowledgments**

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Declaration of interests

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.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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