Environmental Research 246 (2024) 118163

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

Environmental implications and levelized cost analysis of E-fuel production under photovoltaic energy, direct air capture, and hydrogen

Idiano D'Adamo [a,*], Massimo Gastaldi [b], Marco Giannini [c], Abdul-Sattar Nizami [d]

[a] Department of Computer, Control and Management Engineering, Sapienza University of Rome, Via Ariosto 25, 00185, Rome, Italy
[b] Department of Industrial and Information Engineering and Economics, University of L'Aquila, Italy
[c] Sapienza University of Rome, Rome, Italy
[d] Sustainable Development Study Centre, Government College University, Lahore, 54000, Pakistan

ARTICLE INFO

Keywords:
Environment
Cost analysis
Hydrogen
e-fuel
Renewable energy
Sustainable development

ABSTRACT

The ecological transition in the transport sector is a major challenge to tackle environmental pollution, and European legislation will mandate zero-emission new cars from 2035. To reduce the impact of petrol and diesel vehicles, much emphasis is being placed on the potential use of synthetic fuels, including electrofuels (e-fuels). This research aims to examine a levelised cost (LCO) analysis of e-fuel production where the energy source is renewable. The energy used in the process is expected to come from a photovoltaic plant and the other steps required to produce e-fuel: direct air capture, electrolysis and Fischer-Tropsch process. The results showed that the LCOe-fuel in the baseline scenario is around 3.1 €/l, and this value is mainly influenced by the energy production component followed by the hydrogen one. Sensitivity, scenario and risk analyses are also conducted to evaluate alternative scenarios, and it emerges that in 84% of the cases, LCOe-fuel ranges between 2.8 €/l and 3.4 €/l. The findings show that the current cost is not competitive with fossil fuels, yet the development of e-fuels supports environmental protection. The concept of pragmatic sustainability, incentive policies, technology development, industrial symbiosis, economies of scale and learning economies can reduce this cost by supporting the decarbonization of the transport sector.

1. Introduction

For the past three decades, sustainability has been one of the most relevant issues in the economic, industrial, ethical, social, and political spheres (Sachs, 2015). Development goals do not always combine the three dimensions of sustainability (Foong et al., 2022), and a pragmatic view can counteract civil society issues (Ali et al., 2023). Technological innovation and sustainable policy decisions aim to avoid environmental decay and depletion (Awosusi et al., 2022). Decarbonization, i.e., reducing the use of coal (as well as oil) and all its derivatives to mitigate the input of carbon dioxide (CO_2) into the atmosphere, the main cause of global warming, plays a key role among these goals (Gota et al., 2019; Linton et al., 2021). The actions put in place are manifold as the objective is also to meet the needs of citizens and businesses by identifying a correct balance of resources. Strategies for reshoring (Fernández-Miguel et al., 2022), digitisation and circularity (Vacchi et al., 2021), a vision of ecosystems (Li et al., 2022), energy efficiency (Li et al., 2022), renewable energy (Wang et al., 2023), optimising the use of raw materials (Núñez-Delgado et al., 2023) and other aspects of sustainable development are highlighted (Mohaddes Khorassani et al., 2019). Achieving a sustainable low-carbon environment is the goal to contribute to climate change (Kokkinos et al., 2020; Moustakas et al., 2020).

Globally, it denotes that emissions have increased ruinously over the years despite the efforts to make certain sectors as sustainable as possible. According to data reported by the European Environment Agency (2022), if one identifies the most polluting sectors, the first by percentage turns out to be energy, with as much as 77.1% of greenhouse gas emissions, only a third of this percentage is attributable to transport (25.7%). It is interesting to note that road transport is the most impactful within the transport sector, with a 71.7% share, of which 61% is associated with automobiles alone. In Europe, transportation is the only sector with an almost continuous increase in CO_2 emissions since 1990. This surely originates mainly from the increase in the number of cars per capita and per household in addition to the fact that car fleet is

* Corresponding author.
E-mail addresses: idiano.dadamo@uniroma1.it (I. D'Adamo), massimo.gastaldi@univaq.it (M. Gastaldi), marcogiannini97@gmail.com (M. Giannini), asnizami@gcu.edu.pk (A.-S. Nizami).

https://doi.org/10.1016/j.envres.2024.118163
Received 9 November 2023; Received in revised form 2 January 2024; Accepted 8 January 2024
Available online 11 January 2024

Nomenclature

Acronym	*Description*
c_{LCODAC}	conversion factor of LCODAC
c_{LCOE}	conversion factor of LCOE
c_{LCOH}	conversion factor of LCOH
Capex	Capital expenditure
CO_2	Carbon dioxide
DAC	Direct air capture
debt	Debt capital
e-fuel	Electrofuel
equity	Equity capital
FT	Fischer-Tropsch
H_2	Hydrogen
LCODAC	Levelized costs of CO_2
LCOE	Levelized costs of energy
LCOe-fuel	Levelized costs of e-fuel
LCOH	Levelized costs of H_2
N	Lifetime
Opex	Operational expenditure
PV	Photovoltaic
r	Cost of opportunity of capital
t	Time period

particularly old (useful life greater than 5/10 years) and pollutes more.

Against this alarming backdrop, pollution and emissions are also an ethical issue, as issues of sustainability and "green" have moved closer to individual consumers and businesses and have seen the emergence of reforms and directives at the global, European and national levels (D'Adamo et al., 2023a). This aims to change the behaviour of the former and reconvert the latter to more innovative and less environmentally impactful production processes. It is clear how the transportation sector is involved in this transformational framework, in which it is also possible to combine green economy models with waste management (Qyyum et al., 2022; Shelare et al., 2023; Xu et al., 2022). The model toward a sustainable mobility transition thus requires the use of renewable sources, circular practices, consumer involvement, and a focus on jobs in the sectors involved in the transformation. Consequently, policy choices must move flexibly based on a pragmatic sustainability model (D'Adamo et al., 2023b).

According to EU choices, the thermal engine powered by fossil fuels, such as gasoline, diesel, LPG, methane and hybrid solutions, will see a replacement, in addition to electric, by an engine, also thermal, powered by electrofuels (e-fuels) capable of emitting no emissions in their entire cycle of manufacture and use (Betgeri et al., 2023; Navas-Anguita et al., 2020). The transportation sector in this transition requires policy support (Skov and Schneider, 2022); however, the prospects for applying renewable electricity-based fuels and chemicals are much broader (Galimova et al., 2023). The literature draws attention to the potential of carbon-neutral e-fuels (made from hydrogen and CO_2) as an economically competitive and scalable solution (Peacock et al., 2023). There is an increasing focus on stakeholder participation and public information to facilitate this transition (Linzenich et al., 2023; Yang et al., 2023). Although the literature has extensively discussed the potential of e-fuels to decarbonize the transportation industry, many unknowns exist regarding production costs, vehicle costs, and environmental performance (Brynolf et al., 2022). Although some research points to the positive environmental role played by the use of e-fuels and CO_2 capture (Samavati et al., 2018; Yoo et al., 2022).

Other studies have focused on the economic performance of e-fuels (d'Amore et al., 2023; Ravi et al., 2023), but clearly there is still a gap in the literature evaluating multiple context of analysis. This work aims to evaluate the levelized cost of e-fuel (LCOe-fuel) obtained from the combination of four plants (photovoltaic (PV), direct air capture (DAC), electrolysis and Fischer-Tropsch (FT)) by providing the cost of e-fuel production under multiple scenarios. In addition to the baseline scenario, alternative scenarios will be evaluated based on variations in capex and opex of all plants and variations in some technical variables. In this way, the value range of the e-fuel cost will allow the policymaker to assess its applicability in a real-world context, and the cost components that most affect the result will be defined.

2. Methodology

The realization of e-fuel requires a chemical combination of hydrogen (H_2) and CO_2, respectively, obtained by electrolysis and direct capture from the atmosphere and processes requiring electricity. Thus, the production of e-fuel requires the combination of four plants - Fig. 1.

- PV system for green energy production;
- CO_2 capture plant from the atmosphere, that is Direct Air Capture (DAC);
- Electrolytic plant for H_2 production,
- FT plant for syngas processing and e-fuel production.

The synthetic fuel concept is based on the principle of sustainability, in that the electricity must come from renewable sources (Karbassi et al., 2023). Green hydrogen, i.e., hydrogen obtained from renewable sources, is distinguished from grey hydrogen (obtained from fossil sources) and will be combined with CO_2 extracted from the air in a high-pressure catalyst using FT synthesis, which has the task of transforming syngas (H_2 and CO_2) into a liquid energy carrier (e-fuel). This carrier is carbon-neutral (Nemmour et al., 2023) because CO_2 is taken from the atmosphere for its production, the same amount that will be emitted during its use in internal combustion engines.

2.1. The levelized cost economic model

This analysis aims to calculate the levelized cost of e-fuel (LCOe-fuel). In fact, calculating the cost of a fuel is a well-established method in the literature (Martin et al., 2023; Peacock et al., 2023; Ravi et al., 2023). To do this, since the entire plant is composed of multiple processes, it was also necessary to calculate the levelized costs of energy (LCOE), CO_2 (LCODAC) and hydrogen (LCOH). The following equations are considered, where t is the time period, N is the years of plant life, and r is the opportunity cost of capital:

$$LCOE = \frac{\sum_{t=0}^{N}\left[\left(capex_{Equity,t} + opex_t + debt_t\right)(1+r)^{-t}\right]}{Total\ kWh} \tag{1}$$

$$LCOH = \frac{\sum_{t=0}^{N}\left[\left(capex_{Equity,t} + opex_t + debt_t\right)(1+r)^{-t}\right]}{Total\ H_2} \tag{2}$$

$$LCODAC = \frac{\sum_{t=0}^{N}\left[\left(capex_{Equity,t} + opex_t + debt_t\right)(1+r)^{-t}\right]}{Total\ CO_2} \tag{3}$$

$$LCOe-fuel = \frac{\sum_{t=0}^{N}\left[\left(capex_{Equity,t} + opex_t + debt_t\right)(1+r)^{-t}\right]}{Total\ e-fuel} + c_{LCOH} * LCOH + c_{LCODAC} * LCODAC + c_{LCOE} * LCOE \tag{4}$$

The LCOe-fuel result is expressed in €/liter, and the total amount of energy that is reported in the formula for LCOe-fuel is for the entire process of producing 1 L of fuel, thus including the energy required for the electrolysis process and that for the DAC process, as well as that required for the FT chemical process. The value of LCOe-fuel is calculated using a conversion factor in €/l applied to the previous equations, equal to 0.5 kg/l for LCOH (c_{LCOH}), 3.6 kg/l for LCODAC (c_{LCODAC}) and 27.5 kW h/L for LCOE (c_{LCOE}).

2.2. The PV system

Among the renewable energy sources, the PV plant with advantageous conditions in Italy is chosen (D'Adamo et al., 2023c). The plant size chosen is 1 MW to meet the needs of other plants. This study considers that 1 kW produces, on average 1700 kWh of energy annually for electricity production. Thus, the annual production is set at 1,700,000 kWh annually (PVGIS, 2023).

2.3. The DAC plant

The size of the DAC system is chosen according to the required amount of synthetic fuel. For producing 1 L of e-fuel, 3.6 kg of CO_2 is required (Yugo and Soler, 2019). Such a plant, using a solvent, captures CO_2 from the air. A very large amount of energy is required, however, as it is necessary to "push" the air toward the solvent, then load the solvent, and later, additional energy is required to discharge the solvent for taking up the CO_2 captured in it.

2.4. The electrolysis plant

Along with CO_2, the other input for e-fuel production is hydrogen. The related facility is to extract hydrogen from water by electrolysis. The amount of water required to produce 1 kg of hydrogen is 9 L (Beswick et al., 2021). The cost of water is appropriately considered within operating costs. Again, the size of the plant is calculated according to the amount of e-fuel that is produced. The production of 1 L of e-fuel requires about 0.5 kg of hydrogen. Such a plant has a power requirement of 267 kW (Shell Global, 2022).

2.5. The e-fuel production plant

For the plant related to e-fuel production, annual production was estimated and set at 40,000 L. At this stage, syngas is transformed into liquid carriers. This process needs the use of a catalyst inside, usually cobalt. Operating cost assumptions at 6% of Capex remain, and data are assumed in accordance with the literature (Reuters, 2021).

2.6. Input data

The chosen plant is located in central Italy, which, compared to southern Italy, has less favorable irradiation conditions; however, presents better proximity to freshwater suitable for electrolysis. Table 1

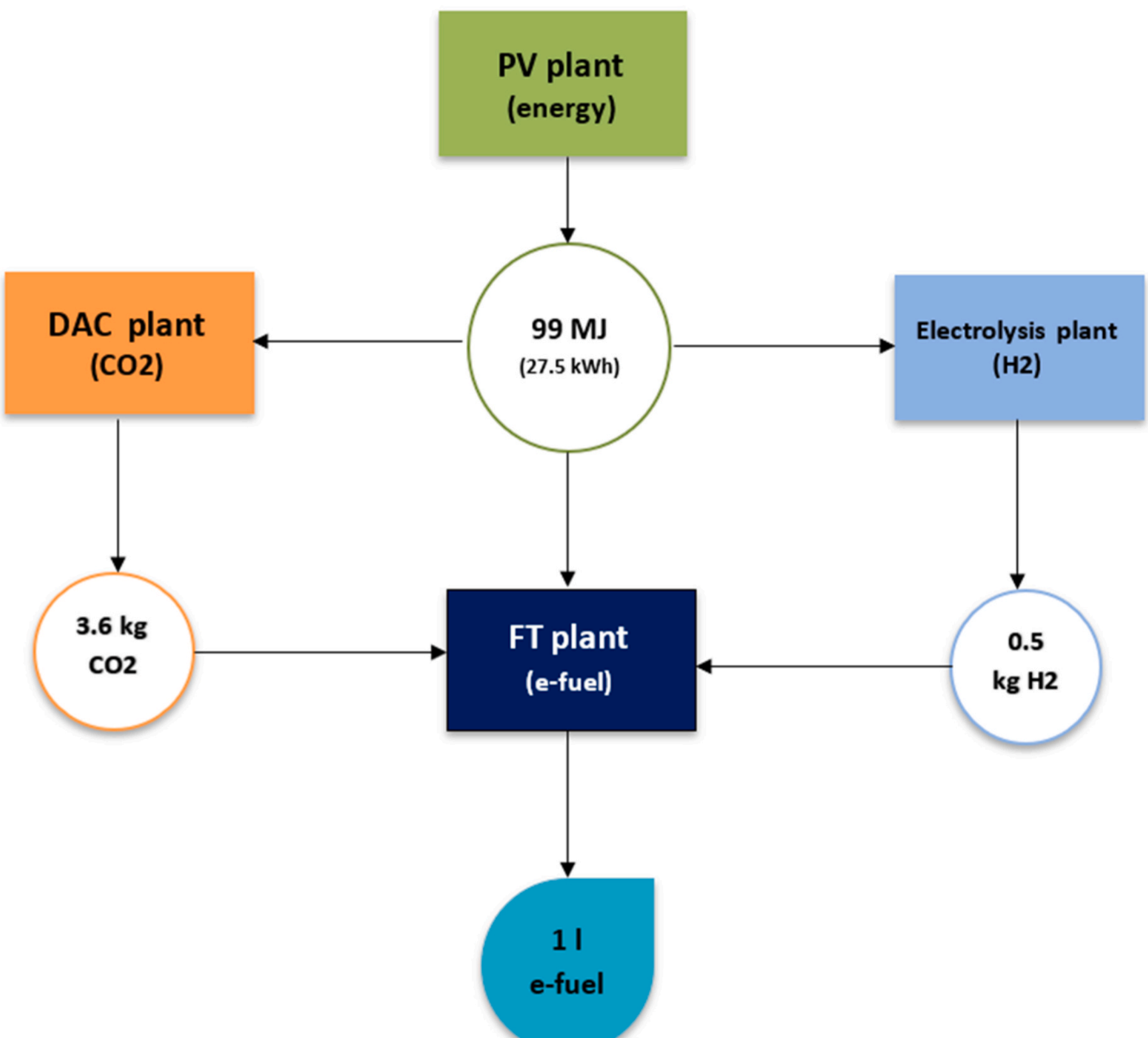

Fig. 1. Process diagram for the production of 1 L of e-fuel. Adapted from (Yugo and Soler, 2019).

Table 1
Input data (Beswick et al., 2021; D'Adamo et al., 2023c; d'Amore et al., 2023; Fasihi et al., 2019; Joshi et al., 2021; Libra et al., 2023; PVGIS, 2023; Reuters, 2021; Shell Global, 2022; Yugo and Soler, 2019).

General Data	
Number of operating days	280
Useful life	25 years
Realization time	1 year
Opportunity cost of capital	6%
Equity Capital-Debt Capital	40%–60%
Debt period	10 years
Debt interest rate	4%
Annual plant yield loss	0.8%
correction coefficient (LCOH)	0.5 kg/l
correction coefficient (LCODAC)	3.6 kg/l
correction coefficient (LCOE)	27.5 kW h/l
Photovoltaic system	
Plant power	1 MW
kWh produced per year 1	1,700,000 kW h/y
kWh produced in 25 years	38,659,590 kWh
Capex	1,500,000 €
Opex	90,000 €/y
Direct Air Capture Plant	
kg produced per year 1	144,000 kg/y
kg produced in 25 years	3,274,695 kg
Capex	105,120 €
Opex	6307 €/y
Electrolysis Plant	
Plant power	267 kW
H2 produced per year 1	20,000 kg/y
H2 produced over 25 years	454.819 kg
Capex	467,250 €
Opex	28,035 €/y
E-fuel production plant	
e-fuel products per year 1	40,000 l/y
e-fuel produced over 25 years	916,650 l
Capex	70,000 €
Opex	4200 €/y

presents the data used for this work. In addition to the literature, two experts with decades of experience, an engineering profile and a sustainability background were consulted in online meetings to validate the data assumed.

2.7. Alternative scenarios

In order to give robustness to the results of the baseline case scenario, alternative scenarios will be evaluated in which both sensitivity analysis (change in a single variable) and scenario analysis (simultaneous change in several variables) are proposed (Abdelhady et al., 2018; D'Adamo et al., 2023c; Martin et al., 2023). For most case studies, optimistic scenarios are considered in addition to pessimistic ones. Relative to the sensitivity analysis, the following variables can vary.

- capex of each individual plant (variation ± 10%);
- opex of each individual plant (variation ± 10%);
- yield loss of each individual plant (1% change).

Thus, the total number of alternative scenarios related to the sensitivity analysis is twenty. Relative to the scenario analysis, the analysis narrows in on the economic components and the technical component related to system performance loss in accordance with the literature (Libra et al., 2023; Poluzzi et al., 2022) as follows.

- capex of all plants (variation ± 10%);
- opex of all plants (variation ± 10%);
- yield loss of all plants (1% change).

Therefore, the total number of alternatives in the scenario analysis is five. Finally, to give a probability of occurrence of the events a risk analysis is proposed using Monte Carlo analysis, which is proposed through a thousand iterations. The variables involved in the risk analysis are all those chosen for the previous alternative analysis. The mean value is that of the baseline scenario, and the standard deviation is assumed to be equal to the range used in sensitivity analysis.

3. Results

This section is divided into the baseline scenario results (section 3.1) and the alternative scenarios (section 3.2). In addition, some implications and discussions on the results obtained are proposed in section 3.3.

3.1. Cost analysis in the baseline scenario

According to equations (1)–(4) and input data presented in Table 1, the e-fuel production cost can be calculated. More specifically, in addition to the costs related to the FT process, the cost of e-fuel is also composed of LCOE, LCOH, and LCODAC, which are multiplied by the conversion factors of 27.5 kWh, 0.5 kg, and 3.6 kg, respectively - Fig. 2.

The following results are obtained:

$$LCOE = 0.068 \text{ €/kWh}$$

$$LCODAC = 0.056 \text{ €/kg}$$

$$LCOH = 1.795 \text{ €/kg}$$

$$LCOe - fuel = 3.097 \text{ €/l}$$

Thus, the cost of e-fuel is about 3.1 €/l, and its cost comes mainly from the cost of energy, which accounts for 60% of the total cost. The other components are the cost of hydrogen (29%), that of CO_2 (7%) and

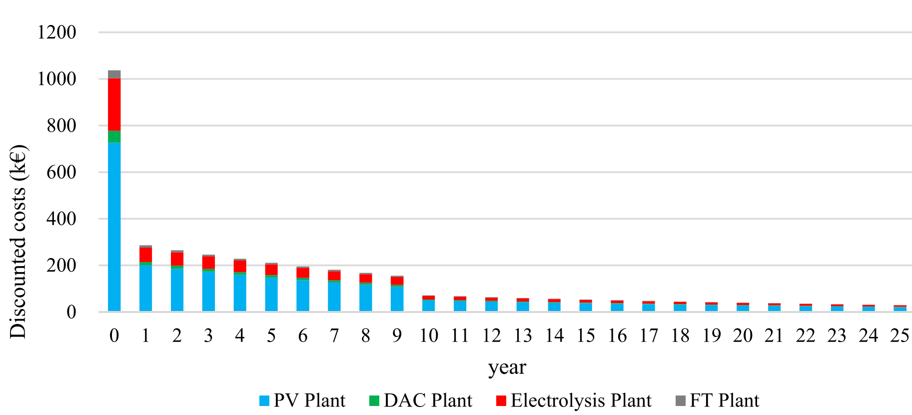

Fig. 2. Distribution of discounted costs.

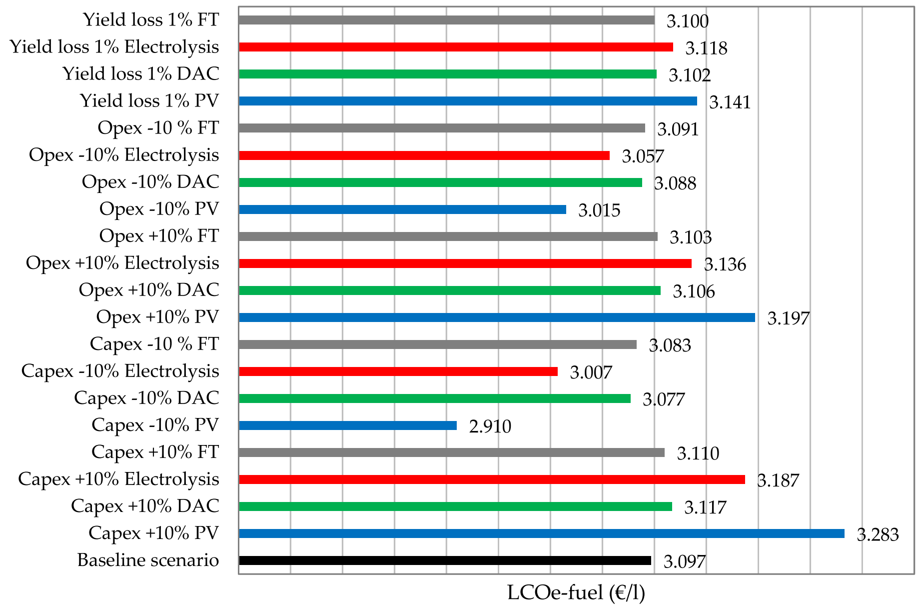

Fig. 3. LCOe-fuel (€/l) – Sensitivity analysis. The following legend is used: FT (grey), Electrolysis (red), DAC (green), PV (blue) and baseline scenario (black).

finally, that of the FT process (4%). In these results, it should be mentioned that within the opex costs of individual plants, the energy required to carry out specific processing was not counted, which was only considered in the levelized cost of an e-fuel unit. More specifically, the total energy for each process, which thus includes CO_2 capture via the DAC process, hydrogen production via the electrolysis process and e-fuel production via the FT process, is only considered in the final LCOe-fuel formula.

However, it is also useful to propose the decomposition of the LCOe-fuel cost at the component level: equity-related capex accounts for 23% of the total cost, while debt-related capex accounts for 33%. Finally, the opex component influences less than half the total cost (44%).

The introduction showed that this topic is not yet well investigated in the literature; however, it is possible to show how the obtained results align with what has been proposed in other studies (Table S1). In particular, the final cost is dependent on the hours of plant operation and the cost of electricity needed in the processes. It reaches a value ranging between 50 and 260 €/GJ (d'Amore et al., 2023), which it is estimated to be 1.8–9.3 €/l. A similar range (1.3–7.7 €/l) emerges from the analysis of Brynolf et al. (2018), which proposes a value ranging between 130 and 770 €/MWh where impacts from different contributions are highlighted. A case study with a less positive economic performance identifies a cost of 3.12 € ct/MJ (Hombach et al., 2019), while analyses indicate the potential to also produce methanol for a value of 379–564 USD/MWh (Ravi et al., 2023), which through conversion corresponds to 3.6–5.3 €/l. There is also work quantifying a lower value of $93.7/MWh (Hansen et al., 2019) in which the key role of electricity in the entire synthetic fuel production process is inferred, as confirmed in other studies (Ababneh and Hameed, 2022; d'Amore et al., 2023).

3.2. Cost analysis in the alternative scenarios

A comparison of the results in the baseline scenario with those proposed in the literature showed how relevant it is to analyze alternative scenarios. In accordance with section 2.7, various economic and technical variables are varied. The sensitivity analysis measures how the LCOe-fuel varies as a function of the change in a single variable.

For example, at capex level, a variation of 10% on the PV plant increases/decrease of 0.007 €/kWh in terms of LCOE. Thus, it must be emphasised how changes in inputs (energy, CO_2 and H_2) affect first the relative levelised cost and then the LCOe-fuel cost. Similarly, a 10% change in opex on the DAC plant increases/decreases 0.002 €/kg in LCODAC. In contrast, no such intermediate step exists in the variation of the FT process costs (Table S2).

The optimistic scenarios are those characterized by decreasing costs. In addition to the economic variables, the technical parameters used to calculate LCOe-fuel are also varied. Specifically, for the yield loss, it was decided only to observe a worse situation than the reference scenario (Table S3). Fig. 3 proposes the variation of LCOe-fuel as a function of individual parameters.

This analysis made it possible to assess how output changes as a function of multiple scenarios. LCOe-fuel tends to vary between 2.910 €/l and 3.283 €/l. This confirms the robustness of the baseline scenario, as a percentage difference of about±six points emerges, variation that

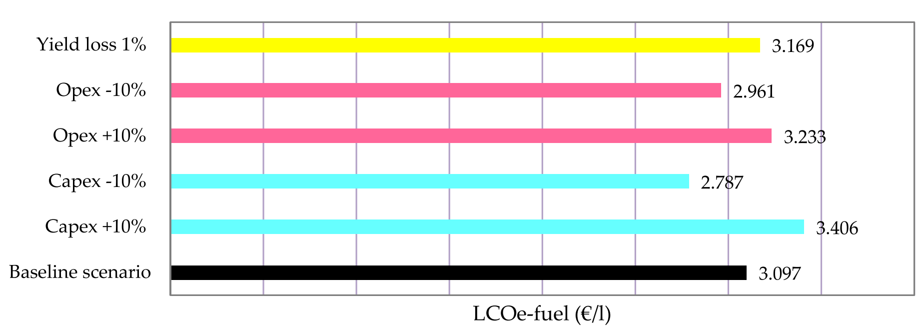

Fig. 4. LCOe-fuel (€/l) – Scenario analysis.

cannot be considered mathematically significant. The comparison of the variables shows that the PV system components have a greater impact on the result. This is expected as it was the variable with the greatest influence among the four plants used to produce e-fuel.

Furthermore, the capex component tends to prevail over opex. On the other hand, the cost of capex related to electrolysis has the greatest impact on the PV plant's performance loss. Therefore, the following results follow what was obtained from the decomposition of the levelised costs but do not evaluate the probability of occurrence of events. The same is true for the scenario analysis, where several variables vary simultaneously. The analysis is repeated for the economic components (Table S4) and for the technical components (Table S5) to evaluate alternative values of LCOe-fuel (Fig. 4).

The variation of all variables simultaneously implies a greater variation in output, which varies from 2.787 €/l to 3.406 €/l for the capex scenarios. It is possible to note that plant loss's impact is less significant than those related to opex. To overcome the limitation of the two previous analyses, the study proceeds to a risk analysis in which all critical variables are varied to assess the probability of occurrence relative to LCOe-fuel. The mean value and standard deviation of the twelve variables involved in this analysis are proposed in Table S6. The results of the Monte Carlo method show the probability distribution associated with the LCOe-fuel output – Fig. 5.

The risk analysis results make it possible to narrow the range of the potential value of LCOe-fuel. In particular, analyzing its tails shows that about 84% of the values fluctuate between 2.8 €/l and 3.4 €/l (range emerged from the scenario analysis) and about 65% between 2.9 €/l and 3.3 €/l (range emerged from the sensitivity analysis). This result therefore, supports the previous analyses and narrows the wide uncertainty that had emerged in some works. It should be emphasised that in the assumptions of this study, the use of a PV system was considered, which not only provides green energy and thus protects the environment but also produces economic benefits. Without it, it is necessary to purchase energy from the grid at a presumably higher cost, which would impact the final cost of LCOe-fuel.

3.3. Discussion and practical implications of this study

The transport sector is one of the largest contributors to environmental pollution, and in recent years technological development has enabled a significant reduction in emissions from fossil-fuelled vehicles. However, this effort requires a further contribution as the goal of climate neutrality by 2050 would risk not being achieved (D'Adamo et al., 2023b; Wu et al., 2023). In this direction, electric vehicles from renewable sources (Barman et al., 2023), biofuel (Li et al., 2023) and e-fuel (d'Amore et al., 2023) can be viable solutions. All fields of application - urban as well as rural and mountainous (Colasante et al., 2024; Ingersoll, 2022; Nemmour et al., 2023) - require transport to be more sustainable.

Thus, the first political consideration is not to exclude one of these sources, but to favour their development in the market in order to reward the most competitive solution while also respecting the balance of ecosystems.

Sustainable technological development is able to combine competitiveness with blue ocean strategies and reduce the uncertainties that currently burden the e-fuel sector. The results of this work, consistent with what has been proposed in the literature (Table S1), have shown that the quantified production cost of 3.1 €/l is higher than the price at the distributor of fossil fuels on the market, which is approximately 1.7–2.1 €/l in Italy. It should be pointed out that the production cost must be incorporated into the value chain, which will inevitably lead to an increase in the final value compared to the production cost alone. This aspect will have a negative consequence on the consumer who will be forced to pay a higher price to be able to drive his/her vehicle.

So here the second policy consideration emerges, based on the concept of pragmatic sustainability. This approach optimises environmental needs with social and economic aspects by favouring solutions applicable in real-life contexts. Therefore, it is crucial to foster research and development of this resource in order to utilise possible learning economies. Similarly, sustainable community models can bring about collaboration among the various firms present in the territories, translating into models of industrial symbiosis that can not only foster a social model of industrial inclusion but also exploit economies of scale.

This study supports the ecological transition as the combination of planting allows for environmental benefits. The literature highlights their environmental footprint, which protects the balance of ecosystems at the level of CO_2 capture (Swennenhuis et al., 2022) and renewable energy production (Qin et al., 2022). In addition, the role of green hydrogen on a global level is emphasised (AbouSeada and Hatem, 2022; Ji and Wang, 2021; Zhou et al., 2022). In particular, this study has quantified the LCOH by proposing a value in the base case of €3.65/kg. It should be specified that this value differs from the one proposed in section 3.1 as it also includes the cost of energy production. In addition, a range of 3.25–4.00 €/kg can be identified by analysing the alternative scenarios. This study is related to the Italian context, and green hydrogen could play an important role in a forward-looking political strategy represented by the Mattei Plan. It prefigures a new energy and social plan concerning Italy (but more generally Europe) and Africa. In this way, the Mattei Plan based on an approach of sharing resources and skills can support the achievement of global sustainability goals.

Public incentives can be given to technologies that can support the development of green and circular models in order to enable their diffusion and technological advancement leading to their cost reduction. Likewise, taxes/excise duties on green resources should be minimised in

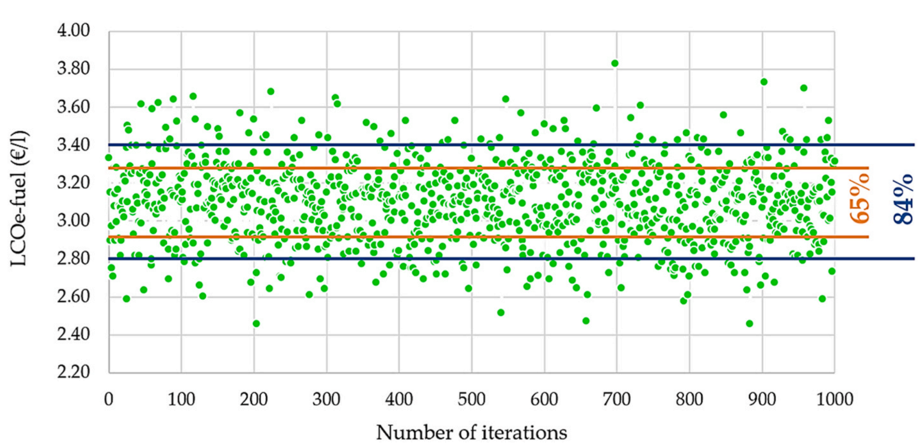

Fig. 5. LCOe-fuel (€/l) – Risk analysis.

contrast to fossil fuels, and in particular, the aim should be to minimise environmentally harmful subsidies. In this policy framework, it should be considered that the sustainable model must also be inclusive, and therefore the higher upfront costs of sustainable solutions must not burden the already weak populations.

This study provides an assessment of the cost of e-fuel, however in its real application the technical characteristics required for use in road transport, aviation and the maritime sector are different and therefore require further analysis. Furthermore, it is crucial to understand whether some of these sectors have sustainable alternatives and where this is not the case to favour the use of e-fuel in these contexts. A further consideration is to assess how e-fuel can be used in endothermic engines. Indeed, this would not trigger a surge in end-of-life vehicles, which should be accompanied by their monitoring towards reuse and recycling practices. Moreover, such synthetic fuel can be blended with fossil fuels, providing a more environmentally friendly solution than in the current context. This would guarantee a gradual increase in their production and no change in the current distribution networks for conventional fuels.

4. Conclusions and way forward

The transport system requires a profound transformation to support the decarbonization process. The European regulation to 2035 rightly moves towards solutions with a lower environmental impact; however, the pragmatic notion of sustainability advises us that alternative solutions are truly sustainable. Therefore, this concept requires green energy and circular solutions and does not create a dependence on raw materials from other countries, exposing Europe to a high vulnerability rate. Added to these aspects is that of maintaining jobs. Within this framework, both electric and e-fuel can offer viable solutions. This study focused on e-fuel and analyzed a specific dimension of sustainability. The literature showed a gap in economic analyses, and this work provided methodological and operational insights.

From a methodological point of view, a consolidated approach based on levelized-cost is used, but different analyses are proposed to support the result obtained. From an operational point of view, the LCOe-fuel is calculated to be approximately 3.1 €/l. Among the cost components, capex has a significant impact and energy production costs are the most relevant. However, special attention must also be paid to the costs associated with hydrogen production. To give solidity to the economic performance of e-fuel, sensitivity and scenario analysis are conducted obtaining values that are confirmed also by risk analysis. In fact, LCOe-fuel ranges between 2.9 and 3.3 €/l and 2.8–3.4 €/l, respectively 65% and 84% of the simulations performed in the Monte Carlo analysis.

It is worth pointing out that the cost contained in this work is obtained from a green source. This can lead to economic improvements, as such plants are profitable and therefore cost less than purchasing from other energy sources. The capex component can be reduced through economies of scale, so evaluating sustainable community models that pursue this objective is useful. This work has two limitations. The first relates to the absence of analysis concerning the environmental and social dimensions of sustainability. The second relates to the fact that it does not evaluate the difference between the different sectors where it could be applied, such as aviation, maritime and road transport. However, it should be emphasised that e-fuel is currently characterised by a lower yield than current fossil fuels, and therefore innovation and research are key to overcoming this limitation and ensuring greater compatibility of use with current infrastructure and vehicles.

These results show that the cost is not competitive with competing fuels but indicates which components must be addressed. Within this framework, the crucial element remains the strategic nature of developing renewable sources capable of supporting a real ecological transition in the transport sector. Furthermore, with CO_2 recovery, e-fuel is a resource that combines the concepts of green economy and circular economy.

CRediT authorship contribution statement

Idiano D'Adamo: Conceptualization, Data curation, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Massimo Gastaldi:** Conceptualization, Data curation, Methodology, Writing – original draft, Writing – review & editing. **Marco Giannini:** Conceptualization, Data curation, Methodology, Writing – original draft, Writing – review & editing. **Abdul-Sattar Nizami:** Conceptualization, Data curation, Methodology, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgements

This study was carried out within the PEACE (Protecting the Environment: Advances in Circular Economy) which received funding from the "Fondo per il Programma Nazionale di Ricerca e Progetti di Rilevante Interesse Nazionale (PRIN)" Investimento 1.1-D.D. 104.02-02-2022, 2022ZFBMA4 funded by the European Union - Next Generation EU. This manuscript reflects only the authors' views and opinions, and can be considered responsible for them.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2024.118163.

References

Ababneh, H., Hameed, B.H., 2022. Electrofuels as emerging new green alternative fuel: a review of recent literature. Energy Convers. Manag. 254, 115213 https://doi.org/10.1016/j.enconman.2022.115213.

Abdelhady, S., Borello, D., Shaban, A., 2018. Techno-economic assessment of biomass power plant fed with rice straw: sensitivity and parametric analysis of the performance and the LCOE. Renew. Energy 115, 1026–1034. https://doi.org/10.1016/j.renene.2017.09.040.

AbouSeada, N., Hatem, T.M., 2022. Climate action: prospects of green hydrogen in Africa. Energy Rep. 8, 3873–3890. https://doi.org/10.1016/j.egyr.2022.02.225.

Ali, S.M., Appolloni, A., Cavallaro, F., D'Adamo, I., Di Vaio, A., Ferella, F., Gastaldi, M., Ikram, M., Kumar, N.M., Martin, M.A., Nizami, A.-S., Ozturk, I., Riccardi, M.P., Rosa, P., Santibanez Gonzalez, E., Sassanelli, C., Settembre-Blundo, D., Singh, R.K., Smol, M., Tsalidis, G.A., Voukkali, I., Yang, N., Zorpas, A.A., 2023. Development goals towards sustainability. Sustainability 15, 9443. https://doi.org/10.3390/su15129443.

Awosusi, A.A., Adebayo, T.S., Kirikkaleli, D., Altuntaş, M., 2022. Role of technological innovation and globalization in BRICS economies: policy towards environmental sustainability. Int. J. Sustain. Dev. World Ecol. 29, 593–610. https://doi.org/10.1080/13504509.2022.2059032.

Barman, P., Dutta, L., Bordoloi, S., Kalita, A., Buragohain, P., Bharali, S., Azzopardi, B., 2023. Renewable energy integration with electric vehicle technology: a review of the existing smart charging approaches. Renew. Sustain. Energy Rev. 183, 113518 https://doi.org/10.1016/j.rser.2023.113518.

Beswick, R.R., Oliveira, A.M., Yan, Y., 2021. Does the green hydrogen economy have a water problem? ACS Energy Lett. 6, 3167–3169. https://doi.org/10.1021/acsenergylett.1c01375.

Betgeri, V., Bhardwaj, O.P., Pischinger, S., 2023. Investigation of the drop-in capabilities of a renewable 1-Octanol based E-fuel for heavy-duty engine applications. Energy 282, 128811. https://doi.org/10.1016/j.energy.2023.128811.

Brynolf, S., Taljegard, M., Grahn, M., Hansson, J., 2018. Electrofuels for the transport sector: a review of production costs. Renew. Sustain. Energy Rev. 81, 1887–1905. https://doi.org/10.1016/j.rser.2017.05.288.

Brynolf, S., Hansson, J., Anderson, J.E., Skov, I.R., Wallington, T.J., Grahn, M., Korberg, A.D., Malmgren, E., Taljegård, M., 2022. Review of electrofuel feasibility—prospects for road, ocean, and air transport. Prog. Energy 4, 42007. https://doi.org/10.1088/2516-1083/ac8097.

Colasante, A., D'Adamo, I., De Massis, A., Italiano, S., 2024. An exploratory study of stakeholder views on the sustainable development of mountain tourism. Sustain. Dev. https://doi.org/10.1002/sd.2878 n/a.

D'Adamo, I., Gastaldi, M., Hachem-Vermette, C., Olivieri, R., 2023a. Sustainability, Emission Trading System and Carbon Leakage: an approach based on neural networks and multicriteria analysis. Sustain. Oper. Comput. 4, 147–157. https://doi.org/10.1016/j.susoc.2023.08.002.

D'Adamo, I., Gastaldi, M., Piccioni, J., Rosa, P., 2023b. The role of automotive flexibility in supporting the diffusion of sustainable mobility initiatives: a stakeholder attitudes assessment. Global J. Flex. Syst. Manag. 24, 459–481.

D'Adamo, I., Mammetti, M., Ottaviani, D., Ozturk, I., 2023c. Photovoltaic systems and sustainable communities: new social models for ecological transition. The impact of incentive policies in profitability analyses. Renew. Energy 202, 1291–1304. https://doi.org/10.1016/j.renene.2022.11.127.

d'Amore, F., Nava, A., Colbertaldo, P., Visconti, C.G., Romano, M.C., 2023. Turning CO2 from fuel combustion into e-Fuel? Consider alternative pathways. Energy Convers. Manag. 289, 117170 https://doi.org/10.1016/j.enconman.2023.117170.

European Environment Agency, 2022. Greenhouse gas emissions from transport in Europe [WWW Document]. URL. https://www.eea.europa.eu/ims/greenhouse-gas-emissions-from-transport. accessed 4.9.23.

Fasihi, M., Efimova, O., Breyer, C., 2019. Techno-economic assessment of CO2 direct air capture plants. J. Clean. Prod. 224, 957–980. https://doi.org/10.1016/j.jclepro.2019.03.086.

Fernández-Miguel, A., Riccardi, M.P., Veglio, V., García-Muiña, F.E., del Hoyo, Fernández, Alfonso, P., Settembre-Blundo, D., 2022. Disruption in resource-intensive supply chains: reshoring and nearshoring as strategies to enable them to become more resilient and sustainable. Sustainability 14, 10909. https://doi.org/10.3390/su141710909.

Foong, S.Y., Chan, Y.H., Loy, A.C.M., How, B.S., Tamothran, A.M., Yip, A.J.K., Liew, R.K., Peng, W., Alstrup, A.K.O., Lam, S.S., Sonne, C., 2022. The nexus between biofuels and pesticides in agroforestry: pathways toward United Nations sustainable development goals. Environ. Res. 214, 113751 https://doi.org/10.1016/j.envres.2022.113751.

Galimova, T., Ram, M., Bogdanov, D., Fasihi, M., Gulagi, A., Khalili, S., Breyer, C., 2023. Global trading of renewable electricity-based fuels and chemicals to enhance the energy transition across all sectors towards sustainability. Renew. Sustain. Energy Rev. 183, 113420 https://doi.org/10.1016/j.rser.2023.113420.

Shell Global, 2022. Shell to start building Europe's largest renewable hydrogen plant [WWW Document]. URL. https://www.shell.com/media/news-and-media-releases/2022/shell-to-start-building-europes-largest-renewable-hydrogen-plant.html. accessed 8.8.23.

Gota, S., Huizenga, C., Peet, K., Medimorec, N., Bakker, S., 2019. Decarbonising transport to achieve Paris Agreement targets. Energy Effic 12, 363–386. https://doi.org/10.1007/s12053-018-9671-3.

Hansen, N.H., Pedersen, T.H., Rosendahl, L.A., 2019. Techno-economic analysis of a novel hydrothermal liquefaction implementation with electrofuels for high carbon efficiency. Biofuels, Bioprod. Biorefining 13, 660–672. https://doi.org/10.1002/bbb.1977.

Hombach, L.E., Doré, L., Heidgen, K., Maas, H., Wallington, T.J., Walther, G., 2019. Economic and environmental assessment of current (2015) and future (2030) use of E-fuels in light-duty vehicles in Germany. J. Clean. Prod. 207, 153–162. https://doi.org/10.1016/j.jclepro.2018.09.261.

Ingersoll, J.G., 2022. The renewable hydrogen–methane (RHYME) transportation fuel: a practical first step in the realization of the hydrogen economy. Hydro 3, 84–111. https://doi.org/10.3390/hydrogen3010008.

Ji, M., Wang, J., 2021. Review and comparison of various hydrogen production methods based on costs and life cycle impact assessment indicators. Int. J. Hydrogen Energy 46, 38612–38635. https://doi.org/10.1016/j.ijhydene.2021.09.142.

Joshi, S., Mittal, S., Holloway, P., Shukla, P.R., Ó Gallachóir, B., Glynn, J., 2021. High resolution global spatiotemporal assessment of rooftop solar photovoltaics potential for renewable electricity generation. Nat. Commun. 12, 5738. https://doi.org/10.1038/s41467-021-25720-2.

Karbassi, V., Trotter, P.A., Walther, G., 2023. Diversifying the African energy system: economic versus equitable allocation of renewable electricity and e-fuel production. Appl. Energy 350, 121751. https://doi.org/10.1016/j.apenergy.2023.121751.

Kokkinos, K., Karayannis, V., Moustakas, K., 2020. Circular bio-economy via energy transition supported by Fuzzy Cognitive Map modeling towards sustainable low-carbon environment. Sci. Total Environ. 721, 137754 https://doi.org/10.1016/j.scitotenv.2020.137754.

Li, H., Appolloni, A., Dou, Y., Basile, V., Kopsakangas-Savolainen, M., 2022. A parametric method to estimate environmental energy efficiency with non-radial adjustment: an application to China. Ann. Oper. Res. https://doi.org/10.1007/s10479-022-05053-z.

Li, S., Chang, H., Zhang, S., Ho, S.-H., 2023. Production of sustainable biofuels from microalgae with CO2 bio-sequestration and life cycle assessment. Environ. Res. 227, 115730 https://doi.org/10.1016/j.envres.2023.115730.

Libra, M., Mrázek, D., Tyukhov, I., Severová, L., Poulek, V., Mach, J., Šubrt, T., Beránek, V., Svoboda, R., Sedláček, J., 2023. Reduced real lifetime of PV panels – economic consequences. Sol. Energy 259, 229–234. https://doi.org/10.1016/j.solener.2023.04.063.

Linton, S., Clarke, A., Tozer, L., 2021. Strategies and governance for implementing deep decarbonization plans at the local level. Sustainability 13, 154. https://doi.org/10.3390/su13010154.

Linzenich, A., Bongartz, D., Arning, K., Ziefle, M., 2023. What's in my fuel tank? Insights into beliefs and preferences for e-fuels and biofuels. Energy. Sustain. Soc. 13, 35. https://doi.org/10.1186/s13705-023-00412-5.

Martin, J., Neumann, A., Ødegård, A., 2023. Renewable hydrogen and synthetic fuels versus fossil fuels for trucking, shipping and aviation: a holistic cost model. Renew. Sustain. Energy Rev. 186, 113637 https://doi.org/10.1016/j.rser.2023.113637.

Mohaddes Khorassani, S., Ferrari, A.M., Pini, M., Settembre Blundo, D., García Muiña, F.E., García, J.F., 2019. Environmental and social impact assessment of cultural heritage restoration and its application to the Uncastillo Fortress. Int. J. Life Cycle Assess. 24, 1297–1318. https://doi.org/10.1007/s11367-018-1493-1.

Moustakas, K., Loizidou, M., Rehan, M., Nizami, A.S., 2020. A review of recent developments in renewable and sustainable energy systems: key challenges and future perspective. Renew. Sustain. Energy Rev. 119, 109418 https://doi.org/10.1016/j.rser.2019.109418.

Navas-Anguita, Z., García-Gusano, D., Iribarren, D., 2020. Long-term production technology mix of alternative fuels for road transport: a focus on Spain. Energy Convers. Manag. 226, 113498 https://doi.org/10.1016/j.enconman.2020.113498.

Nemmour, A., Inayat, A., Janajreh, I., Ghenai, C., 2023. Green hydrogen-based E-fuels (E-methane, E-methanol, E-ammonia) to support clean energy transition: a literature review. Int. J. Hydrogen Energy 48, 29011–29033. https://doi.org/10.1016/j.ijhydene.2023.03.240.

Núñez-Delgado, A., Álvarez-Rodríguez, E., Fernández-Sanjurjo, M.J., Arias-Estévez, M., Fernández-Calviño, D., López-Ramón, M.V., Sánchez-Polo, M., 2023. Low-cost materials to face soil and water pollution. Curr. Opin. Environ. Sci. Heal. 32, 100453 https://doi.org/10.1016/j.coesh.2023.100453.

Peacock, J., Cooper, R., Waller, N., Richardson, G., 2023. Decarbonising aviation at scale through synthesis of sustainable e-fuel: a techno-economic assessment. Int. J. Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2023.09.094 (in press).

Poluzzi, A., Guandalini, G., Guffanti, S., Elsido, C., Moioli, S., Huttenhuis, P., Rexwinkel, G., Martelli, E., Groppi, G., Romano, M.C., 2022. Flexible Power & Biomass-to-Methanol plants: design optimization and economic viability of the electrolysis integration. Fuel 310, 122113. https://doi.org/10.1016/j.fuel.2021.122113.

PVGIS, 2023. Photovoltaic Geographical Information System [WWW Document]. URL. https://joint-research-centre.ec.europa.eu/photovoltaic-geographical-information-system-pvgis_en. accessed 8.8.23.

Qin, Y., Xu, Z., Wang, X., Škare, M., 2022. Green energy adoption and its determinants: a bibliometric analysis. Renew. Sustain. Energy Rev. 153, 111780 https://doi.org/10.1016/j.rser.2021.111780.

Qyyum, M.A., Ali Shah, S.F., Qadeer, K., Naquash, A., Yasin, M., Rehan, M., Tabatabaei, M., Aghbashlo, M., Lee, M., Nizami, A.-S., 2022. Biowaste to bioenergy options for sustainable economic growth opportunities in developing countries: product space model analysis and policy map development. Renew. Sustain. Energy Rev. 169, 112832 https://doi.org/10.1016/j.rser.2022.112832.

Ravi, S.S., Mazumder, J., Sun, J., Brace, C., Turner, J.W.G., 2023. Techno-Economic assessment of synthetic E-Fuels derived from atmospheric CO2 and green hydrogen. Energy Convers. Manag. 291, 117271 https://doi.org/10.1016/j.enconman.2023.117271.

Reuters, 2021. Uzbekistan launches first gas-to-liquids plant [WWW Document]. URL. https://www.reuters.com/business/energy/uzbekistan-launches-first-gas-to-liquids-plant-2021-12-25/#:~:text=UZGTLPLANT%2CQashqadaryoProvince%2CUZBEKISTAN,onimportsofoilproducts. accessed 8.8.23.

Sachs, J.D., 2015. The Age of Sustainable Development. Columbia University Press.

Samavati, M., Martin, A., Santarelli, M., Nemanova, V., 2018. Synthetic diesel production as a form of renewable energy storage. Energies 11, 1223. https://doi.org/10.3390/en11051223.

Shelare, S.D., Belkhode, P.N., Nikam, K.C., Jathar, L.D., Shahapurkar, K., Soudagar, M.E.M., Veza, I., Khan, T.M.Y., Kalam, M.A., Nizami, A.-S., Rehan, M., 2023. Biofuels for a sustainable future: examining the role of nano-additives, economics, policy, internet of things, artificial intelligence and machine learning technology in biodiesel production. Energy 282, 128874. https://doi.org/10.1016/j.energy.2023.128874.

Skov, I.R., Schneider, N., 2022. Incentive structures for power-to-X and e-fuel pathways for transport in EU and member states. Energy Pol. 168, 113121 https://doi.org/10.1016/j.enpol.2022.113121.

Swennenhuis, F., de Gooyert, V., de Coninck, H., 2022. Towards a CO2-neutral steel industry: justice aspects of CO2 capture and storage, biomass- and green hydrogen-based emission reductions. Energy Res. Social Sci. 88, 102598 https://doi.org/10.1016/j.erss.2022.102598.

Vacchi, M., Siligardi, C., Cedillo-González, E.I., Ferrari, A.M., Settembre-Blundo, D., 2021. Industry 4.0 and smart data as enablers of the circular economy in manufacturing: product Re-engineering with circular eco-design. Sustainability 13, 10366. https://doi.org/10.3390/su131810366.

Wang, Q., Zhang, F., Li, R., 2023. Revisiting the environmental kuznets curve hypothesis in 208 counties: the roles of trade openness, human capital, renewable energy and natural resource rent. Environ. Res. 216, 114637 https://doi.org/10.1016/j.envres.2022.114637.

Wu, F., Muller, A., Pfenninger, S., 2023. Strategic uses for ancillary bioenergy in a carbon-neutral and fossil-free 2050 European energy system. Environ. Res. Lett. 18, 14019 https://doi.org/10.1088/1748-9326/aca9e1.

Xu, M., Yang, M., Sun, H., Gao, M., Wang, Q., Wu, C., 2022. Bioconversion of biowaste into renewable energy and resources: a sustainable strategy. Environ. Res. 214, 113929 https://doi.org/10.1016/j.envres.2022.113929.

Yang, Z., Ahmad, S., Bernardi, A., Shang, W., Xuan, J., Xu, B., 2023. Evaluating alternative low carbon fuel technologies using a stakeholder participation-based q-rung orthopair linguistic multi-criteria framework. Appl. Energy 332, 120492. https://doi.org/10.1016/j.apenergy.2022.120492.

Yoo, E., Lee, U., Zang, G., Sun, P., Elgowainy, A., Wang, M., 2022. Incremental approach for the life-cycle greenhouse gas analysis of carbon capture and utilization. J. CO2 Util. 65, 102212 https://doi.org/10.1016/j.jcou.2022.102212.

Yugo, M., Soler, A., 2019. A look into the role of e-fuels in the transport system in Europe (2030–2050). Concawe Rev. 28, 4–22.

Zhou, Y., Li, R., Lv, Z., Liu, J., Zhou, H., Xu, C., 2022. Green hydrogen: a promising way to the carbon-free society. Chin. J. Chem. Eng. 43, 2–13. https://doi.org/10.1016/j.cjche.2022.02.001.