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Off-grid vs. grid-based: Techno-economic assessment of a power-to-liquid plant combining solid-oxide electrolysis and Fischer-Tropsch synthesis

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ABSTRACT

The economic performance of Power-to-Liquid processes depends substantially on the power source's features, i.e., electricity costs and full load hours. Off-grid solutions can ensure cheap, green electricity without being exposed to fluctuating electricity markets. A techno-economic assessment of a Power-to-Liquid plant combining solid-oxide electrolysis and Fischer-Tropsch synthesis has been conducted. Off-grid and grid-based scenarios of three process configurations at plant scales from 1 to 1000 $MW_{el.}$ rated electrolyzer power were evaluated. Net production costs of Fischer-Tropsch products ranging from 2.42 to 4.56 $€_{2022}$/kg were obtained for the grid-based scenarios. In contrast, values of 1.28 to 2.40 $€_{2022}$/kg were determined for the evaluated off-grid scenarios. Scaling up the plant showed a weakened decrease in net production costs after surpassing a threshold of 100 $MW_{el.}$ due to substantial relative electricity costs of up to 88 %. Thus, future Power-to-Liquid projects should be designed at a scale of 100 $MW_{el.}$ rated electrolyzer power. In addition, an availability exceeding 4000 h/a is recommended for off-grid plants, e.g., by implementing hybrid renewable power plants as well as electricity and syngas storage technologies.

1. Introduction

Combining CO_2 utilization with a business case is increasingly vital for economic and political institutions. The Danish Government published a national Power-to-X (PtX) strategy plan in 2021, including companies such as Vestas, Haldor Topsoe and Vattenfall as well as aviation and maritime companies [70]. A national hydrogen and PtX strategy has been initiated by the German Federal Ministry for Economic Cooperation and Development in 2023 [71]. The year 2022 and its effect on the electricity market [72] have disclosed the main weakness of Power-to-Liquid (PtL) processes: their substantial dependency on electricity costs. Innovative plant concepts are required to guarantee a steady supply of green and cheap electricity. Hence, the underlying study focuses on the economic performance of PtL plants based on grid-connected and off-grid systems.

The European Council is currently elaborating on two proposals to gradually increase the share of sustainable fuels in the aviation and maritime industry, i.e., ReFuelEU aviation and FuelEU maritime. According to ReFuelEU aviation, EU airport suppliers must provide sustainable aviation fuel shares of 2 % (2025), 6 % (2030), 20 % (2035), 34 % (2040), 42 % (2045) and 70 % by 2050. FuelEU maritime demands a greenhouse gas intensity reduction of vessels of 2 % (2025), 6 % (2030), 14.5 % (2035), 31 % (2040), 60 % (2045) and 80 % (2050) compared with the average in 2020 [73].

Wulf et al. provided an extensive review of Power-to-X, combining Power-to-Liquid and Power-to-Gas, projects in Europe, analyzing the plants' locations, scales and applied technologies. About a third of the listed projects process hydrogen into methane, methanol or Fischer-Tropsch (FT) products. Solid-oxide electrolyzers (SOEL) have only been a niche application in the years before 2020 [1]. The Norwegian company norsk e-fuel plans to commission three FT-based plants with a combined production capacity of 80,000 t/a synthetic aviation fuel until 2029 [2]. PtL projects producing methanol exceeding a capacity of 100,000 t/a are planned to be commissioned within the next five years [3]. The locations and scales of global Fischer-Tropsch plants, including

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Nomenclature

Parameters:

ΔH_r	Reaction enthalpy, kJ/mol
C	Costs, €$_{2022}$
d	Scaling exponent, –
FCI	Fixed capital investment, €$_{2022}$
i	Discount rate, -, %
n	Plant lifetime, a
$\dot{n}$	Material flow rate, mol/s
NPC	Net production costs, €$_{2022}$/kg
P	Electrical power, W
Plant availability	–, h/a
X	Conversion, –, %

Abbreviations:

AEL	Alkaline electrolyzer
ASF	Anderson-Schulz-Flory
BtL	Biomass-to-Liquid
CAPEX	Capital expenditure
CEPCI	Chemical Engineering Plant Cost Index
eASF	Extended Anderson-Schulz-Flory
Equ.	Equipment
FT	Fischer-Tropsch
IRENA	International Renewable Energy Agency
LCOE	Levelized cost of electricity
MEA	Monoethanolamine
Mil.	Million
OPEX	Operational expenditure
PEMEL	Proton exchange membrane electrolyzer
PtL	Power-to-Liquid
rWGS	Reverse water-gas shift
SOEL	Solid-oxide electrolyzer
SR	Steam reforming
TRL	Technology readiness level
USGC	U.S. Gulf Coast

Biomass-to-Liquid (BtL) projects, were summarized by Advanced Energy Technologies [74].

Solid-oxide electrolyzers have the lowest Technology Readiness Level (TRL) compared with other water electrolysis technologies, i.e., alkaline (AEL) and proton exchange membrane (PEMEL) electrolysis [4,5]. Nonetheless, the technology has the potential to be a central building block of future energy systems due to its lower specific electricity consumption [75]. The largest high-temperature electrolyzer, with a rated power of 2.6 $MW_{el.}$, has recently been installed at the Rotterdam harbor [76]. The Danish company Topsoe has laid the foundation for the world's first industrial-scale SOEL factory with an annual production capacity of 500 $MW_{el.}$ at Herning, Denmark [77]. Current data concerning the required fixed capital investment of SOEL units is still uncertain due to low production capacities [6–9]. The technical background regarding cell design, operating conditions and materials has been elaborated in previous studies [4,5,9–11]. In addition, numerous studies have focused on experimental studies to validate and improve established kinetic models [12–16]. Water electrolysis is highly sensitive to impurities affecting its performance, H_2 quality and stack lifetime. The understanding of the impact of impurities and associated degradation mechanisms is currently limited. Becker at al. recommend using ultra-pure water with a total organic carbon content below 50 μg/L [17].

Fischer-Tropsch processes have been industrially well-established for several decades [18]. State-of-the-art reactor concepts include fixed-bed multitubular, slurry bubble column and microchannel reactors [19,20] applying cobalt or iron-based catalysts [20,21]. Complex product mixtures, i.e., alkanes, alkenes, alcohols, aldehydes and carboxylic acids with chain lengths ranging from one to more than 40 carbon atoms as well as water, are produced via the Fischer-Tropsch synthesis. Thus, intricate product separation and upgrading concepts, e.g., hydrocracking, hydrotreating oligomerization, alkylation and adding fuel additives, are required [18,22,23]. A detailed composition of Fischer-Tropsch product water, typically showing oxygenate contents between 1 and 2 wt%, was provided by Rahman et al. [24]. It is an acidic solution comprising various oxygenates, e.g., alcohols, carboxylic acids, aldehydes and ketones, treated as waste water by existing industrial facilities [25].

Several methods at different levels of detail have been established to determine the required fixed capital investment (FCI) of chemical plants. Towler and Sinnott provide an overview of the AACE international cost estimate classes ranging from order of magnitude estimates, with almost no design information, to check estimates based on a completed plant design [26]. Towler and Sinnott, as well as Seider et al., provide additional details concerning factorial methods, i.e., Lang factor, location factor and material factor, and suggest cost curves for general plant equipment [26,27]. A detailed potential allocation of the Lang factor is given by Peters and Timmerhaus [28].

Determining a chemical plant's fixed operational expenditure (OPEX) can be based on factors as a function of the required capital expenditure (CAPEX) [6,9,29]. In contrast, Towler and Sinnot provide a method founded on the production rate [26]. Acquiring appropriate cost and price data can become a challenging task. Possible data sources are internal company forecasts, trade journals, consultants, online suppliers or reference books [26].

A previous techno-economic assessment by Herz et al. determined net production costs (NPC) of Fischer-Tropsch products ranging from 3.56 to 8.08 €$_{2022}$/kg, in combination with SOEL, and 4.60 to 7.62 €$_{2022}$/kg, in combination with PEMEL. Cost reductions to 2.60 (SOEL) and 3.36 €/kg (SOEL) were figured out for a 2050 scenario [30]. Peters et al. obtained NPC of 1.45 to 2.85 €$_{2022}$/kg for a PtL plant based on SOEL and FT synthesis [31]. An assessment, including reverse water–gas shift (rWGS) and FT synthesis, conducted by Zang et al., resulted in NPC of 2.73 to 2.98 €$_{2022}$/kg [32]. NPC of 8.4 to 10.6 €$_{2022}$/kg were found by Markowitsch et al. by combining either rWGS or SOEL technology with Fischer-Tropsch synthesis [33]. Decker et al. assessed the economic performance of off-grid PtL plants, including a salt cavern as hydrogen intermediate storage, resulting in NPC of FT products of 3.20 to 5.01 €$_{2022}$/kg [6]. Neuling and Kaltschmitt evaluated a comparable process producing FT products via a Biomass-to-Liquid (BtL) route. NPC of 1.49 to 4.04 €$_{2022}$/kg were found within their evaluation of alternative aviation fuels [29]. An overview of comparable studies is given in

Table 1
Overview of comparable techno-economic assessments.

Technology	NPC [€$_{2022}$/kg]	FCI [mil. €$_{2022}$]	Scale MW_{FT}	Source
SOEL + FT [1)]	3.56–8.08	–	34.0	[30]
SOEL + FT [2)]	2.60–3.36	203.5	34.0	[30]
PEMEL + FT	4.60–7.62	429.6	29.9	[30]
SOEL + FT	1.45–2.85	949.9	392.7	[31]
PEMEL + FT	2.73–2.98	436.7 [3)]	349.4	[32]
PEMEL/SOEL + FT	8.40–10.6	46.4–60.4	4.6	[33]
PEMEL + FT	3.20–5.01	–	27.4	[6]
BtL	1.49–4.04	2798.6	1317.0	[29]

[1)] 2020 scenario.
[2)] 2050 scenario.
[3)] Excluding PEMEL. H_2 costs were accounted as variable OPEX.

Table 1. All values have been converted to 2022 levels based on the Chemical Engineering Plant Cost Index (CEPCI).

An essential factor of Fischer-Tropsch products is their CO_2 footprint compared with conventional fossil fuels, which mainly depends on the emission factor of the used electricity. Applying the EU's 2022 average grid electricity mix resulted in a greenhouse gas emission increase of 46 % compared with fossil fuels [34]. On the other hand, coupling PtL plants with renewable power sources led to a potential 95 % decrease in CO_2 emissions based on wind power and a 65 % decrease based on photovoltaic power [34]. Micheli et al. determined a CO_2 emission reduction potential between 52.6 % and 88.9 % for synthetic kerosene produced by a PtL plant combining direct air capture, high-temperature electrolysis and FT synthesis [35].

The majority of previously conducted techno-economic assessments of PtL processes are based on grid electricity [9,30,32,36] due to stable and cheap electricity prices in the European Union from 2008 to 2019 [72]. 2021 and 2022 caused a paradigm shift in the European electricity and energy markets, entailing soaring electricity prices for household and industrial consumers [72]. Thus, updated TEAs are essential to evaluate the performance of PtL processes for the 2022 European economic framework and to find alternative ways to avoid their substantial dependency on fluctuating grid electricity market prices. In addition, previous studies, e.g., by Spurgeon and Kumar [37], assume utilizing fossil power plants as a CO_2 source. Renewable power sources are vital to ensure the benign effect of PtL processes on the climate and to prevent the lock-in of fossil power generation.

The presented study adds value to preceding techno-economic assessments of Power-to-Liquid processes by simultaneously evaluating the effects of plant availability and electricity costs on the net production costs of Fischer-Tropsch products for grid-based and off-grid scenarios. Several renewable electricity sources, i.e., wind, solar, hydro and geothermal power, are applied and compared to the performance of grid-based process routes founded on 2022 economic parameters. In addition, the optimum scale of Power-to-Liquid plants from an economic vantage point is analyzed. Off-grid PtL plants profit from reduced electricity costs of renewable power sources, potentially balancing out their lower availability due to daily and seasonal fluctuations. Thus, off-grid PtL plants can potentially produce Fischer-Tropsch products at lower net production costs than grid-based options. This study's objective is to answer the following research question:

Should off-grid Power-to-Liquid plants powered with renewable electricity be prioritized over the supply with grid electricity?

2. Methodology

The presented techno-economic assessment is founded on a previously conducted study of a Power-to-Liquid plant by the authors [2]. The established plant concept comprises the following sub-processes:

- MEA-based CO_2 capture
- Solid-oxide electrolyzer operated in co-electrolysis mode
- Three-stage syngas compression
- Fischer-Tropsch synthesis
- Fischer-Tropsch product separation
- Tail gas recirculation and steam reforming of tail gas
- Purge gas combustion

2.1. Process modeling and process simulation

IPSEpro version 8.0, a stationary and equation-based process simulation tool, was applied to model the sub-processes and establish the designed plant configuration. The plant's main design parameter is the power input into the SOEL unit P_{SOEL}, ranging from 1 to 1000 $MW_{el.}$. Three process configurations were designed:

1. Short tail gas recirculation to the Fischer-Tropsch reactor's inlet without tail gas reforming
2. Short tail gas recirculation, including steam reforming of tail gas
3. Long tail gas recirculation to the SOEL unit's inlet

Figure 1 presents a simplified process flowchart including the mass balance of a grid electricity-based scenario at a scale of 100 $MW_{el.}$ rated electrolyzer power. The detailed IPSEpro process simulation flowchart can be found in a previous study conducted by the authors [2]. The CO_2 source's gas stream, e.g., raw biogas or off-gases emitted by the cement or steel industry, is transferred to the CO_2 capture unit's absorber column. Captured CO_2 is released in the desorber column, passes a catalyst guard bed based on activated carbon, ZnO and CuO and is further conveyed to the SOEL unit's inlet. The CO_2 stream is mixed with steam and converted to syngas consisting of CO, H_2 and unconverted components. As a next step, excess steam is condensed out of the syngas, which is subsequently pressurized by a three-stage compressor to the required synthesis pressure of 21 bar. The syngas and recirculated tail gas are converted into gaseous and liquid Fischer-Tropsch products, which are separated into naphtha, middle distillate, wax and FT water. A tail gas share of 85 % is recirculated to the syngas condenser's inlet, process configurations 1 and 2, or the SOEL's inlet, process configuration 3. The remaining share is purged from the system and combusted to supply the evaporators, the CO_2 capture unit and the tail gas reformer with the required heat.

2.1.1. Solid-oxide electrolyzer in co-electrolysis mode

The SOEL unit, operating at 850 °C and atmospheric pressure, is realized by a stoichiometric model based on the conversion of CO_2, $X_{CO2} = 85$ %, and water, $X_{H2O} = 90$ %, see equations (1) and (2). As stated by Wang et al., the rWGS reaction is the main contributor of CO_2 conversion, while the influence of direct CO_2 electrolysis is negligible [11]. Schmidt et al. propose a power consumption of SOEL units ranging from 3.2 to 3.7 $kWh_{el.}/Nm^3$ H_2 [5]. As in the previous study, a specific power consumption of 3.37 $kWh_{el.}/Nm^3$ H_2 was chosen [38]. According to Cinti et al., the produced syngas's H_2:CO ratio is primarily defined by the feed's H_2O:CO_2 ratio, which is adjusted to control the H_2:CO ratio at the FT reactor inlet [13]. A detailed elaboration of the presented model has been part of a previous study [2].

$$X_{H_2O} = \frac{\dot{n}_{H_2O,in} - \dot{n}_{H_2O,out}}{\dot{n}_{H_2O,in}} \tag{1}$$

$$X_{CO_2} = \frac{\dot{n}_{CO_2,in} - \dot{n}_{CO_2,out}}{\dot{n}_{CO_2,in}} \tag{2}$$

2.1.2. Fischer-Tropsch synthesis

A low-temperature Fischer-Tropsch synthesis, applying a cobalt-based catalyst system, was assumed for the underlying techno-economic assessment. The FT reactor operates at a temperature of 230 °C and a pressure of 21 bar. Only paraffinic products were considered, as stated in equation (3).

$$n\ CO + (2n+1)\ H_2 \rightarrow H(CH_2)_n H + n\ H_2O \qquad \Delta H_r = -166.4\ kJ/mol \tag{3}$$

The used model is based on the extended Anderson-Schulz-Flory (eASF) distribution, introduced by Förtsch et al., to consider the substantial deviation of real FT product distribution compared with the standard ASF model [39]. The assumed eASF parameters are based on gathered project experience summarized in a previous study [40]. Due to the application of a cobalt-based catalyst, CO_2 is considered to pass the FT reactor as an inert gas [21,41]. A per pass carbon monoxide conversion of $X_{CO,FT} = 55$ % was assumed. The FT reactor's per pass CO conversion combined with the rate of recirculated tail gas results in the overall system CO conversion. The separation concept of Fischer-Tropsch products is based on studies focusing on the elaboration of Fischer-Tropsch refineries, i.e., introduced by Petersen et al. [23] and de

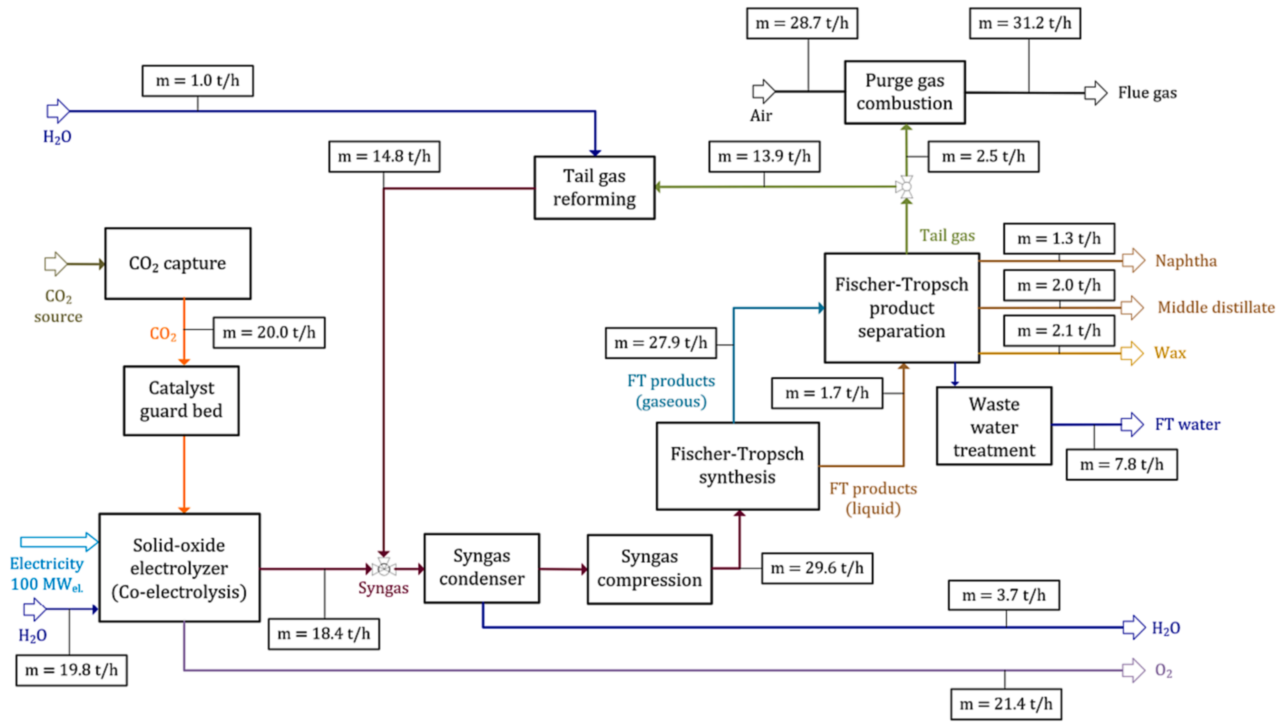

Fig. 1. Simplified process flowchart of the assessed Power-to-Liquid plant (Adapted from [2]) including the mass balance of the reference scenario.

Klerk [18].

Detailed information regarding the assumed Fischer-Tropsch process parameters was provided in a previous study [40].

2.1.3. Additional sub-processes

Besides the SOEL unit and the FT reactor, various sub-processes, e.g., CO_2 capture, multi-stage syngas compression and steam reforming of tail gas, are required to ensure a holistic evaluation of the presented PtL plant concept.

CO_2 capture by MEA absorption is a well-established industrial process. A CO_2 capture efficiency of 90 % [42,43] and a specific heat demand of 3.5 $MJ_{th.}$/kg CO_2 [44–46] was assumed for the presented techno-economic assessment. Additional information is given in a previous study by the authors [2].

A three-stage compression of syngas with intermediate water cooling was designed to realize a pressure in the FT reactor of 21 bar. Table 2 displays the assumed parameters concerning the pressurization of syngas.

The steam reforming of tail gas is based on a stoichiometric model converting CH_4, C_2H_4, C_2H_6, C_3H_8 and CO_2 as introduced by Pratschner et al. [2]. Table 3 summarizes the applied parameters of the steam reformer model.

2.2. Economic modeling and assessment

The presented study aims to provide a preliminary estimate, i.e., a class 4 study adhering to the Association for the Advancement of Cost Engineering International (AACE) classification, of a PtL plant combining SOEL and FT synthesis. AACE class 4 studies are typically based on basic process design and show an expected accuracy range of −15 % to −30 % (lower limit) and +20 % to +50 % (upper limit) [26].

Calculating the net production costs of Fischer-Tropsch products, see equation (4), includes the following steps:

1. Literature research to find the costs of applied equipment
2. Conversion of literature data to the design scale via the cost scaling method
3. Conversion to 2022 levels based on the cost escalation method
4. Conversion to German market levels based on location factors
5. Determination of the required fixed capital investment based on the factorial method
6. Discounting and allocating the total fixed capital investment via the annuity method
7. Determination of fixed OPEX, variable OPEX and by-product revenue
8. Determination of the net production costs based on the annuity, OPEX, revenue and the total mass flow rate of Fischer-Tropsch products

Table 2
Assumed efficiencies of compressors and electric motors.

Parameter	Value
Compressor: Isentropic efficiency	90 %
Compressor: Mechanical efficiency	90 %
Motor: Electric efficiency	96 %
Motor: Mechanical efficiency	90 %
Pressure ratio per stage	2.7–3.0

Table 3
Assumed parameters of the steam tail gas reformer.

Parameter	[47]	[48]	This study
Temperature	850 °C	830 °C	850 °C
Pressure	1.05 bar	10 bar	10 bar
Steam/Carbon ratio	2.2–4	3	2.5
CH_4 conversion	90 %	92 %	90 %
C_2H_4 conversion	90 % [1)]	–	90 % [1)]
C_2H_6 conversion	95 %	–	95 % [2)]
C_3H_8 conversion	99 %	–	99 % [2)]
CO_2 conversion	–	–	Chem. eq.

1) Assumption based on ΔH_r.
2) Assumption: The conversion of C_2H_6 and C_3H_8 behaves simultaneously at elevated pressure as for CH_4.

$$NPC = \frac{Annuity + OPEX_{Fixed} + OPEX_{Variable} - O_2\ revenue}{Annual\ production\ of\ FT\ products} \quad (4)$$

Corporate overhead charges, i.e., product distribution, R&D as well as selling and marketing, are assumed to be 5 % of the NPC in accordance with Towler and Sinnott [26].

The required FT product selling prices for varying amortization periods were determined by applying the net present value method, see equation (5) [26].

$$NPV = FCI + \sum_{m=1}^{n} \frac{Cash\ flow_m}{(1+i)^m} \quad (5)$$

A detailed explanation of the described steps, including formulas, is given in the following chapters. Table 4 summarizes the assumed economic parameters for the underlying techno-economic assessment of a Power-to-Liquid plant located in central Europe. The average electricity price for non-household consumers in Germany was around 0.2 €/kWh_{el} in 2022 [72] and slightly above 0.1 €/kWh_{el} in the European Union from 2008 to 2019 [78].

2.2.1. Capital expenditure and annuity

Initially, the obtained equipment literature cost data must be converted to the design plant scale and the reference year 2022. Scaling up or down cost data of a unit or process, see equation (6), requires a capacity value, e.g., mass flow rate, volume flow rate or electric performance, and the scaling exponent d. Determining the scaling exponent d of single units or whole chemical processes has been extensively discussed in several studies [26,27,49–51].

$$Costs_{Design} = Costs_{Base} \left(\frac{Scale_{Design}}{Scale_{Base}}\right)^d \quad (6)$$

The effect of cost escalation due to inflation is considered via the Chemical Engineering Plant Cost Index introduced by the Chemical Engineering Magazine. The CEPCI comprises the weighted average of 41 industry and commodity indices as well as twelve labor cost indices and is divided into sub-categories with different weighting factors, e.g., construction labor, heat exchangers, engineering and buildings [52]. Converting cost data to the chosen reference year 2022 is done with equation (7).

$$Costs_{2022} = Costs_{Base\ year} \cdot \left(\frac{CEPCI_{2022}}{CEPCI_{Base\ year}}\right) \quad (7)$$

Regional differences in equipment and plant costs were considered by implementing location factors, as stated in Equation (8) [26].

$$Costs_{Location\ i} = Costs_{USGC} \cdot Location\ factor_{Location\ i} \quad (8)$$

A factorial method was applied to convert equipment costs to the actual fixed capital investment by counting in additional expenditures, e.g., installation, engineering, piping, instrumentations and services, as stated by equation (9). The updated Lang factor of 5.04 for modern industry standards, as proposed by Seider et al. [27], was assumed for the underlying assessment.

$$FCI = 5.04 \cdot \sum Costs_{Equipment} \quad (9)$$

As a next step, the annuity was determined based on the plant's total fixed capital investment FCI, the discount rate i and the plant lifetime n, see equation (10).

$$Annuity = FCI \cdot \frac{(1+i)^n \cdot i}{(1+i)^n - 1} \quad (10)$$

2.2.2. Fixed OPEX, variable OPEX and O_2 revenue

Determining the fixed OPEX, i.e., maintenance, insurance, administration, unforeseen expenses and additional costs, and variable OPEX, e.g., electricity, catalysts and waste water treatment, is critical to ascertaining the net production costs of Fischer-Tropsch products. Electricity is a major cost driver within the presented plant concept and is thus listed as a separate cost center. Various approaches were proposed in previous studies to determine the fixed and variable OPEX of industrial plants, e.g., by Neuling and Kaltschmitt [29], Decker et al. [6] and Herz et al. [9]. Table 5 lists the chosen factors to determine the fixed OPEX as a function of the total CAPEX.

The plant's labor costs were determined by applying a method proposed by Green and Southard [53] by determining the required shift operators based on equipment coefficients and detailed process flowcharts for the CO_2 capture unit [54], SOEL and FT unit [2]. It was assumed that 4.2 operators are necessary for a continuous plant operation. An annual salary of 60,500 €/a per plant operator was considered, adhering to the salaries of industrial operators in Germany in 2022 [79]. In addition, supervision was counted in at 20 % of the operating labor expenses. The payroll charges amount to 30 % of operating labor and supervision expenses [53]. Table 6 provides an overview of the plant's necessary labor costs.

Table 7 displays the specific variable expenses for electricity (grid-based scenarios), operating materials and services. The required catalysts, nickel-based for the steam reformer and cobalt-based for the FT synthesis, are assumed to be replaced every three years, adhering to Neuling and Kaltschmitt [29]. The costs for an entire FT catalyst loading, as proposed by Zang et al., have been converted to the presented study's scale [32]. The specific costs of a Ni-based steam reforming catalyst are based on a report on biofuels conducted by Müller-Langer [55]. A stack replacement period of ten years is assumed for the SOEL unit in accordance with Decker et al. [6].

3. Results

The obtained net production costs of Fischer-Tropsch products produced by grid-based and off-grid Power-to-Liquid plants are presented in the following chapter. Various scenarios for 2022 and 2050 based on different power sources were evaluated. In addition, a sensitivity analysis is presented to highlight the influence of the electricity costs, plant availability, discount rate, plant lifetime and FCI.

3.1. Effect of plant configuration and scale-up

The influence of the different plant configurations and scale-up, i.e.,

Table 4
Assumed economic parameters.

Parameter	Value
Reference year	2022
Plant availability (grid-based)	8000 h/a
Discount rate	6 %
Plant lifetime	20 a
Electricity costs (grid-based)	0.1–0.2 €/$kWh_{el.}$
Lang factor	5.04
Exchange rate	0.95 €/$

Table 5
Factors to determine the fixed OPEX as proposed by Neuling and Kaltschmitt [29].

Cost center	Factor of CAPEX [%]
Maintenance	1.50
Insurance	1.00
Administration	0.50
Unforeseen expenses	1.00
Additional costs	0.75
SUM	4.75

Table 6
Labor costs for a continuous plant operation based on Green and Southard [53].

Sub-process	Required operators per shift
CO_2 capture	1.7
SOEL	1.5
FT synthesis	3.4
Whole PtL plant	6.6
Required operators	28
	Costs [mil. €/a]
Labor	1.69
Incl. supervision	2.03
Incl. payroll charges	2.64

Table 7
Specific factors for variable OPEX and oxygen revenue.

Position	Costs (2022)	Unit	Comment	Source
Electricity	0.1–0.2	€/$kWh_{el.}$	–	[72,78]
Waste water	1.87	€/m^3	–	[29]
Co catalyst (FT)	99.45	€/kg	Changed every 3 years	[32]
Ni catalyst (SR)	70.91	€/kg	Changed every 3 years	[55]
Process water	0.95	€/t	–	[32]
O_2 revenue	81.30	€/t	–	[56]
Stack overhaul	12 % of FCI_{SOEL}		Every 10 years	[6]

the SOEL's rated power, on the net production costs of Fischer-Tropsch products is displayed in Figure 2. A grid-based scenario realizing 8000 operating hours per year based on electricity costs of 0.2 €/$kWh_{el.}$ was assumed. The NPC range from 5.2 to 5.9 €/kg for a 1 $MW_{el.}$ pilot-scale plant. Scaling up the plant to 10 $MW_{el.}$ results in a cost reduction of 16 % to values of around 4.6 €/kg. A decrease in NPC of 20 %, compared with a rated power of 1 $MW_{el.}$, can be expected for a PtL plant based on a 100 $MW_{el.}$ electrolyzer. Scaling up by another factor to 1 $GW_{el.}$ does only result in a minor decrease in NPC by another 2 percentage points to values around 4.3 €/kg. Thus, the NPC of Fischer-Tropsch products can be significantly lowered by scaling up the PtL plant. However, the economy of scales' effect diminishes after surpassing a rated power of 100 $MW_{el.}$. A significant difference in NPC for the different plant configurations can be obtained for small-scale pilot plants. Nonetheless, this effect weakens for increased plant scales. Hence, process configuration 2, based on tail gas reforming by a steam reformer, is chosen as a reference scenario for this study due to its realistic technical feasibility.

3.2. CAPEX and OPEX

The costs of required equipment, e.g., compressors, pumps, reactors, solid-oxide electrolyzer and heat exchangers, in combination with fixed OPEX, variable OPEX and revenue for O_2, serve as a groundwork for the presented study.

3.2.1. CAPEX

The fixed capital investment, including base capacity and scaling exponent d, for the reference scenario of the evaluated PtL, process configuration 2, including a short tail gas recirculation and a tail gas reformer at a plant scale of 100 $MW_{el.}$ electrolyzer power input are listed in Table 8. The given data can be converted to different design scales by applying equation (6) in chapter 2.2.1. The solid-oxide electrolyzer unit is the major cost center with a required fixed capital investment of almost 80 mil. € in 2022. However, a significant cost reduction to 30 mil. € can be expected until 2050. Other central cost centers are the CO_2 capture unit, the FT process, steam reforming and the combustion of purge gas. The plant's input and output streams for the base scenario powered with grid electricity are displayed in Table 9.

3.2.2. Fixed OPEX, variable OPEX and oxygen revenue

The annual total fixed OPEX, variable OPEX and O_2 revenue of the reference scenario, process configuration 2, including a tail gas reformer based on a rated electrolyzer power of 100 $MW_{el.}$, is summarized in Table 10.

3.3. Cost allocation of Fischer-Tropsch products

As seen in chapter 3.1, scaling up PtL plants significantly affects the reduction of NPC until a certain threshold is reached. Analyzing the net production costs' respective cost centers and their allocation, displayed in Figure 3, is crucial in understanding Power-to-Liquid plants' ideal economic design parameters.

Figure 3 shows the respective cost centers' share, e.g., electricity, OPEX excluding electricity and CAPEX, as a function of the SOEL unit's rated power. The presented data is based on process configuration 2, including tail gas reforming with a steam reformer, with grid electricity costs of 0.1 and 0.2 €/$kWh_{el.}$.

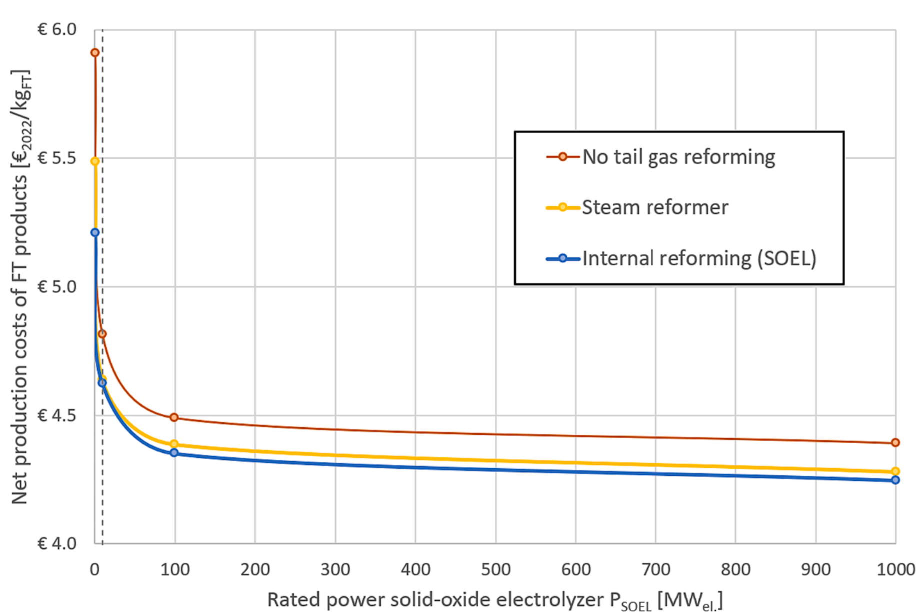

Fig. 2. Effect of plant configuration and scale-up on the net production costs of Fischer-Tropsch products.

Table 8
Fixed capital investment for process configuration 2 at a scale of 100 $MW_{el.}$ rated electrolyzer power.

Equipment	Capacity	Unit	d	FCI [mil. €$_{2022}$] 1)	Source
MEA CO_2 capture	20	t_{CO2}/h	0.65	23.03 2)	[54]
$SOEL_{2022}$	100	$MW_{el.}$	1.00	79.75	[6,7,57]
$SOEL_{2050}$	100	$MW_{el.}$	1.00	30.00	[8]
FT reactor	66.5	MW_{FT}	0.70	19.68	[10,30,32,58,59]
FT product separation 3)	5,430	kg_{FT}/h	0.65	5.51	[32]
Syngas compressor	6.6	$MW_{el.}$	0.60	7.02 2)	[26]
Steam reformer	980	kmol/h	0.65	12.02	[29,32]
Purge gas combustion	11	$MW_{th.}$	0.80	1.28 2)	[26]
Add. heat exchangers	–	m^2	–	5.90 4)	[26]
Product storage	5,430	kg_{FT}/h	0.65	1.94	[32]
Pumps and blowers	–	kg/h;Nm^3/h	0.65	0.05	[26,30]
Waste water plant	2.2	kg/s	1.00	0.40	[29]
Auxiliaries	–	–	–	1.07	–
SUM_{2022}	–	–	–	157.62	–
SUM_{2050}	–	–	–	107.87	–

1) Lang factor included.
2) Location factors: China = 0.61, U.S. Gulf Coast = 1, Germany = 1.11 [26].
3) Includes gas/liquid separation, wax separation and product drying.
4) Installation factor of 3.5 [26].

Table 9
Input and output streams of process configuration 2 at a scale of 100 $MW_{el.}$.

Input streams		Output streams	
Flue gas	150.0 t/h	Naphtha	1.3 t/h
(of which CO_2	20.0 t/h)	Middle distillate	2.0 t/h
Water	20.8 t/h	Wax	2.1 t/h
Air	28.7 t/h	FT water	7.8 t/h
		Flue gas	31.2 t/h
		(of which CO_2	3.2 t/h)
		Oxygen	21.4 t/h
		Water	3.7 t/h
		MEA off-gas	130.0 t/h
		(of which CO_2	2.2 t/h)
SUM	199.5 t/h	SUM	199.5 t/h

The electricity expenses are the plant's most substantial cost center, with shares of 78 % for a grid electricity price of 0.1 €/$kWh_{el.}$ and 88 % for a grid electricity price of 0.2 €/$kWh_{el.}$. The total NPC can be reduced by 26 % (0.2 €/$kWh_{el.}$) or 40 % (0.1 €/$kWh_{el.}$) when scaling up from 1 to 100 $MW_{el.}$. Responsible for that is the reduction in CAPEX and OPEX due to the benign effect of the economies of scale. The electricity's financial expenditure is directly proportional to the amount of synthesized Fischer-Tropsch products, thus explaining the substantial increase in electricity costs from 50 % to 78 % of the total NPC based on electricity costs of 0.1 €/$kWh_{el.}$. This phenomenon substantially limits the positive effect of plant scale-up on the net production costs of Fischer-Tropsch products after exceeding a SOEL rated power of 100 $MW_{el.}$.

3.4. 2022 and 2050 off-grid scenarios based on renewable electricity

This study aims to determine the economic differences between off-grid and grid-based PtL plants. The net production costs of Fischer-Tropsch products based on five different renewable sources for 2022 and 2050 are displayed in Figure 4. The presented outcomes are all founded on a discount rate of 6 % and a plant lifetime of 20 years. The respective levelized cost of electricity (LCOE) is based on a study by the International Renewable Energy Agency (IRENA) [60]. Expected values for the 2050 scenarios were taken from studies conducted by Sens et al. [61], Tran and Smith [62] and IRENA [60]. The evaluated power sources' expected full load hours were chosen adhering to studies published by Fraunhofer ISE [63], Tramme and Trieb [64], Fuchs [65] and Frick et al. [66]. Data concerning the SOEL unit's fixed capital investment is provided in chapter 3.2.1.

The results depicted in Figure 4 stress the plant availability's significant influence on the economic performance of Power-to-Liquid plants. Fischer-Tropsch products derived from a plant powered with geothermal electricity obtain the lowest NPC of 1.52 €/kg (2022) and 0.55 €/kg (2050) due to a plant availability of 7700 h per year. Supplying the presented plant concept with hydropower entails NPC of 1.55 €/kg in 2022 due to a satisfactory availability of 4400 annual operating hours. However, the LCOE of hydropower plants is not expected to decrease until 2050, thus showing limited potential for cost reductions until 2050. Off-grid PtL plants powered with onshore wind parks show promising potential for the 2050 scenario due to a significant decrease in LCOE, obtaining NPC of 1.10 €/kg. Offshore wind park and PV-powered PtL plants obtain the highest NPC of around 2.40 €/kg for the 2022 scenario. However, PV-based systems show the potential to significantly lower their NPC due to a projected significant decrease in LCOE until 2050.

A comparison between the economic performance of grid-based and off-grid Power-to-Liquid plants is given in Figure 5. Applying a grid electricity price of 0.1 €/$kWh_{el.}$ results in potential NPC of 2.42 €/kg. Grid-based PtL plants show a broad distribution in NPC due to their significant dependency on the electricity market. Applying electricity costs of 0.2 €/$kWh_{el.}$ results in NPC of 4.56 €/kg. Off-grid PtL plants powered with an onshore wind park (3500 operating hours and LCOE of 0.038 €/$kWh_{el.}$) can achieve lower NPC than the grid-based scenario of 1.85 €/kg. Implementing hybrid power plants, e.g., combining wind and solar power, has the potential to increase the plant availability, resulting in an enhanced economic performance of PtL plants. Applying additional electricity and syngas storage technologies can potentially result in plant availabilities exceeding 6000 annual operating hours. Based on these assumptions, NPC ranging from 1.08 to 1.28 €/kg can be realized based on the LCOE of onshore wind parks and photovoltaic farms in 2022.

Table 11 shows the differences in obtained NPC of FT products based

Table 10
Total annual OPEX and O_2 revenue for process configuration 2 at a scale of 100 $MW_{el.}$.

Cost center	Costs/revenue [mil. €$_{2022}$/a]
$OPEX_{Fixed}$	10.85
Electricity	177.68
Waste water	0.21
Process water	0.17
Co catalyst	0.56
Ni catalyst	0.23
Stack overhaul	0.48
O_2 revenue	−13.89
SUM	176.29

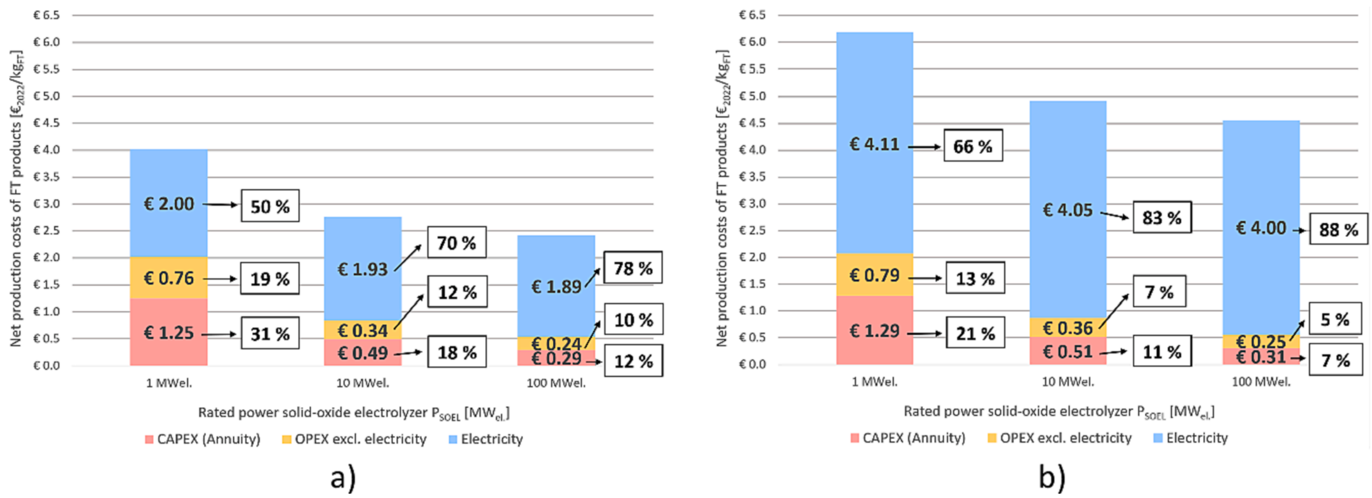

Fig. 3. Cost centers and cost allocation of Fischer-Tropsch products. a) Electricity costs = 0.1 €/kWh$_{el.}$. b) Electricity costs = 0.2 €/kWh$_{el.}$.

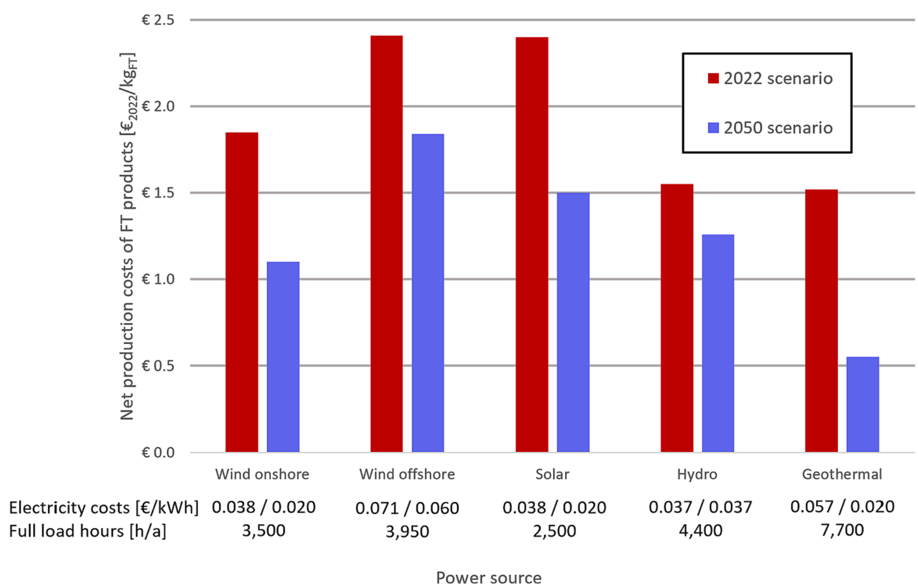

Fig. 4. Net production costs of Fischer-Tropsch products based on off-grid renewable power sources.

on SOEL and PEMEL technology for grid electricity scenarios. An increased electrolyzer scale of 152.8 MW$_{el.}$ is required to process the same mass flow rate of CO_2 based on an assumed specific electricity demand of 5 kWh$_{el.}$/Nm^3 H_2 [67] and a required fixed capital investment of 380 €/kW$_{el.}$ [68]. In addition, an rWGS reactor is necessary to convert CO_2 and H_2 into Syngas. Table 12 summarizes the different assumptions and specifications of the PEMEL process route. Assuming electricity costs of 0.2 €/kWh$_{el.}$ results in NPC of 4.46 €/kg (SOEL) and 6.53 €/kg (PEMEL), an increase of 46 %.

3.5. Required Fischer-Tropsch product selling price to break even

Table 13 summarizes the required FT product prices for amortization periods of 5, 10 and 20 years for scenarios based on grid electricity, an off-grid onshore wind park and a hybrid power plant. The grid electricity scenario requires prices ranging from 4.35 to 4.90 €/kg to break even between 5 and 20 years. A PtL plant based solely on onshore wind power must sell its FT products at prices between 1.77 and 3.02 €/kg. The most promising results of 1.22 to 1.95 €/kg are obtained by an off-grid power plant based on an assumed plant availability of 6000 h/a.

3.6. Sensitivity analysis

A sensitivity analysis, as displayed in Figure 6, has been conducted to evaluate the economic parameters', i.e., discount rate, plant lifetime, plant availability, electricity costs and fixed capital investment, influence on the net production costs of Fischer-Tropsch products. The assumed base values are listed in a separate textbox in Figure 6. An increase in electricity costs of 0.05 €/kWh$_{el.}$ leads to a rise in the NPC of Fischer-Tropsch products of 1.07 €/kg. The NPC decline exponentially for increasing plant availabilities. Power-to-Liquid plants operating below 3000 h per year entail a significant increase in net production costs. Enhancing the plant availability from 3000 to 6000 h/a results in a 15 % reduction in NPC. An additional increase to 8000 h/a reduces the NPC by 18 % compared with a plant availability of 3000 h/a. Compared to the electricity costs and the plant availability, the discount rate and plant lifetime have a negligible influence on the NPC of Fischer-Tropsch products. The impact of the plant's fixed capital investment on its economic performance is not as significant as the electricity costs and plant availability due to the substantial share of annual electricity expenses. Doubling the fixed capital investment from 160 to 320 mil. € results in an increase in NPC of 20 %.

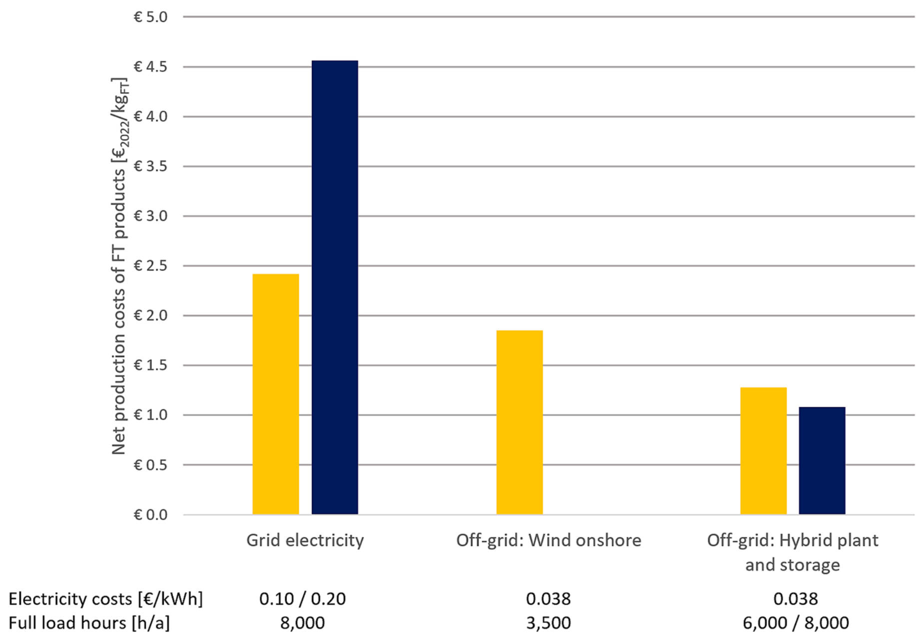

Fig. 5. Comparison of grid-based and off-grid scenarios of a Power-to-Liquid plant.

Table 11
NPC comparison between SOEL and PEMEL for process configuration 2.

Electrolyzer	0.1 €/kWh$_{el.}$	0.2 €/kWh$_{el.}$
SOEL	2.42 €/kg	4.56 €/kg
PEMEL	3.36 €/kg	6.53 €/kg

Table 12
Fixed capital investment of PEMEL and rWGS reactor.

Equipment	Capacity	Unit	d	FCI [mil. €$_{2022}$]	Source
rWGS reactor	22.8	t/h	0.60	8.83	[32]
PEMEL	152.8	MW$_{el.}$	1.00	58.05	[67,68]

Table 13
Required FT product prices for amortization periods of 5,10 and 20 years.

Scenario	5 years	10 years	20 years
Grid electricity 1)	4.90 €/kg	4.53 €/kg	4.35 €/kg
Wind onshore 2)	3.02 €/kg	2.17 €/kg	1.77 €/kg
Hybrid plant 3)	1.95 €/kg	1.46 €/kg	1.22 €/kg

1) 0.2 €/kWh$_{el.}$; 8000 h/a.
2) 0.038 €/kWh$_{el.}$; 3500 h/a.
3) 0.038 €/kWh$_{el.}$; 6000 h/a.

4. Discussion

The economic performance of three different plant configurations, i. e., short tail gas recirculation with and without a tail gas reformer and a long tail gas recirculation cycle to the SOEL unit's inlet, were analyzed within the underlying study. A significant difference in NPC of 12 % was obtained at small-scale plants at a rated electrolyzer power of 1 MW$_{el.}$. However, only a 3 % difference was found at a rated power of 100 MW$_{el.}$. Scaling up PtL plants is necessary to make the technology cost-competitive with conventional fossil-based processes. A scale-up from 1 to 100 MW$_{el.}$ results in a 20 % reduction in NPC of Fischer-Tropsch products. Nonetheless, scaling up the plant by another factor of 10 has only a minor influence due to the increasing relative share of electricity costs per unit of FT product. Thus, the process route based on a short tail gas recirculation, including tail gas reforming at a scale of 100 MW$_{el.}$, was chosen as this study's reference scenario.

Total fixed capital investments of 157.6 and 107.9 mil. € were determined for the 2022 and 2050 scenarios, respectively. Annual fixed OPEX of 10.9 mil. € and annual variable OPEX of 179.3 mil. € are required to operate a grid-based PtL plant at the chosen reference scenario. Electricity costs accounted for the major share of OPEX with 177.7 mil. € per year. Sales for the by-product O_2 amount to 13.9 mil. € per year.

Furthermore, the cost allocation of Fischer-Tropsch products was analyzed for a grid-based scenario assuming electricity costs of 0.1 and 0.2 €/kWh$_{el.}$. CAPEX and fixed OPEX combined obtain significant shares of 34 % and 50 % for small-scale plants at 1 MW$_{el.}$ rated electrolyzer power but have only a minor influence on the NPC of FT products for industrial-scale PtL plants. The relative share of electricity costs increases substantially to shares of 78 % to 88 % at a scale of 100 MW$_{el.}$, thus explaining the limited effect of scale-up when surpassing a rated electrolyzer power of 100 MW$_{el.}$.

Various off-grid scenarios of PtL plants were evaluated in the presented study. Lower electricity costs can be realized by off-grid renewable power sources. However, this comes at the expense of decreased plant availability due to limited full load hours. The NPC of Fischer-Tropsch products based on off-grid scenarios ranged from 1.52 €/kg for a geothermal power plant to 2.40 €/kg for a photovoltaic farm for the 2022 scenario. NPC ranging from 0.55 to 1.84 €/kg were obtained for the 2050 scenario. The inferior economic results based on photovoltaic plants can be explained by its limited full load hours of only 2500 h/a and below. In contrast, geothermal plants provide relatively low electricity costs in combination with beneficial full load hours of up to 7700 h/a. Hybrid power plants, based on solar and wind power, in combination with electricity or syngas storage technologies could be applied to increase the plant availability to industrial levels of around 8000 h/a, potentially realizing NPC based on non-grid scenarios of 1.08 to 1.28 €/kg. Analyzed grid-based scenarios lead to NPC ranging between 2.42 and 4.56 €/kg for assumed electricity costs of 0.1 and 0.2 €/kWh$_{el.}$. A comparison with a grid-based process configuration including a PEMEL unit and an rWGS reactor resulted in NPC ranging from 3.36 to 6.53 €/kg.

In addition, the required FT product selling prices for amortization periods of 5,10 and 20 years were determined for scenarios based on grid electricity, an onshore wind park and a hybrid power plant. The most promising selling prices of 1.22 to 1.95 €/kg were obtained based

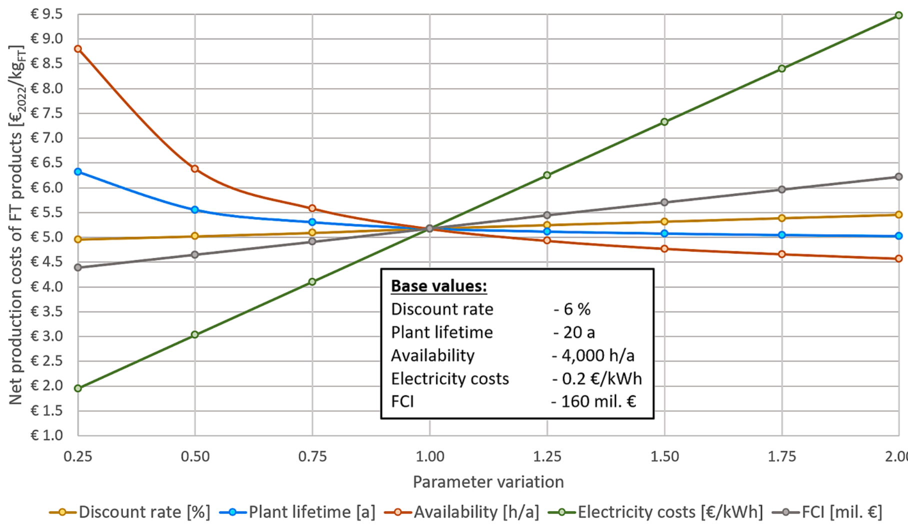

Fig. 6. Sensitivity analysis – influence of economic parameters on the net production costs of Fischer-Tropsch products.

on a hybrid power plant. Significantly higher selling prices between 1.77 and 3.02 €/kg are required to amortize an off-grid PtL plant solely based on onshore wind power compared with the grid electricity-based scenario, obtaining prices ranging from 4.35 to 4.90 €/kg.

The plant availability and electricity costs are the main levers for the economic performance of PtL plants. Off-grid-based plants are unaffected by the electricity market's uncertainty, making them less susceptible to potential future crises, but entail disadvantageous plant availability. As indicated by a sensitivity analysis, the availability of PtL plants should not drop below 3000 h/a. The long-term goal should be the realization of 6000 h/a by implementing hybrid off-grid power plants in combination with electricity and syngas storage technologies.

Table 14 displays a comparison of this study's results, grid-based as well as off-grid scenarios for 2022 and 2050, with previously conducted economic assessments of PtL processes. All values have been converted to 2022 levels based on the CEPCI. The presented study's results lie within the obtained values of previous studies. Compared with BtL plants, PtL plant concepts underlie larger uncertainties due to their high dependency on electricity costs and alternating plant availabilities.

Power-to-liquid plants based on photovoltaic farms and offshore wind parks obtained the highest NPC of 2.40 €/kg regarding the evaluated off-grid scenarios. PtL plants based on onshore wind parks obtained better results than those powered with offshore wind parks by balancing their lower availability with decreased LCOE. Geothermal power plants are tailor-made for PtL plants due to their availability of up to 7700 h/a in combination with LCOE or around 0.05 €/kWh$_{el.}$. The 2050 scenarios based on onshore wind parks and geothermal plants showed the most promising reductions in NPC, which were 41 % and 64 %, respectively. It has to be stated that the assessed 2050 scenarios did not consider technology learning curves for already established industrial processes, i.e., MEA-based CO_2 capture and Fischer-Tropsch technology.

Finding the optimum location for PtL plants is a highly challenging task. Choosing locations with low electricity costs and high availability of renewable power sources seems reasonable but entails additional risk factors due to long supply chains and political and economic dependency. Compelling arguments for implementing PtL plants in Europe are shortened supply chains, regional added-value and jobs as well as an independent supply with sustainable fuels and platform chemicals. The North Sea and Baltic coast, i.e., Denmark, Sweden, The Netherlands and northern Germany, are promising PtL plant locations in Europe due to their high availability of water and wind power as well as their vicinity to CO_2 emitting industries. Viable locations of off-grid PtL plants could be offshore PtX hubs in the North Sea, based on offshore wind power, Iceland, based on geothermal power plants and the North Sea and Baltic coastline, based on onshore wind power.

Recirculating the FT water to the electrolyzer or steam reformer can potentially increase the plant's performance but entails too much risk under current circumstances. Water electrolysis is highly sensitive to impurities. Thus, utilizing the FT water as a feedstock can significantly reduce stack lifetime and, hence, the process's economic performance. A possible alternative is using FT water for tail gas reforming, thus providing the reformer with steam while reforming the FT water's oxygenate content. However, technology providers have strict water purity specifications and might not guarantee liability if those are not met.

The presented study is based on static process simulation; thus, the fluctuating behavior of renewable power sources was not considered. Only limited economic and technical data is available due to the SOEL technology's comparably low TRL. Nonetheless, the TRL is expected to increase significantly within this decade because of the spiking interest in this technology. As a result, the required fixed capital investment is anticipated to drop substantially due to increased production capacities. Another factor of uncertainty is the assumed revenue realized by selling produced O_2. Future industrial sites must be founded on smart sector coupling concepts, bringing together the supply and demand of by-products like oxygen.

Supplying PtL plants with grid electricity ensures an industrial availability of up to 8000 h/a but also entails exposure to possible electricity market disruptions. In addition, the plant's location substantially influences the CO_2 footprint of Fischer-Tropsch products concerning the local electricity mix's emission factor. In contrast, off-grid-based solutions ensure the supply of cheap and clean electricity but have to deal with low full load hours. The presented study adds value to previous techno-economic assessments by providing detailed economic information concerning the most beneficial electricity sources for PtL plants based on 2022 parameters. In addition, this study facilitates the design of future PtL plants by discussing the effects of plant configuration and scale-up from an economic vantage point. An analysis of the FT products' cost allocation underpinned the substantial impact of electricity costs with increasing plant scales. A scale of 100 MW$_{el.}$ rated electrolyzer power emerged as the optimum and is thus recommended for future PtL projects.

5. Conclusions

The presented study's objective was to evaluate the economic performance of a Power-to-Liquid plant combining a solid-oxide electrolyzer and Fischer-Tropsch synthesis. In detail, grid-based and off-grid scenarios for various renewable electricity sources, i.e., wind,

Table 14
Comparison of obtained results with previous PtL and BtL techno-economic assessments.

NPC [1)]	This study: grid-based	This study: off-grid (2022)	This study: off-grid (2050)	[31]	[30]	[36]	[9]	[33]	[30]	[32]	[69]	[29]
Tech.	SOEL + FT	SOEL + FT	SOEL + FT	SOEL + FT	SOEL + FT	SOEL + FT	SOEL + FT	Elec + FT	PEM + FT	rWGS + FT	BtL	BtL
NPC_{Min}	2.42	1.28	0.55	1.38	3.40	1.26	2.24	8.40	4.39	2.59	3.09	1.42
NPC_{Max}	4.56	2.40	1.84	2.72	7.70	1.61	5.38	10.60	7.26	2.84	4.65	3.85

1) All values in €/kg and converted to 2022 levels (CEPCI = 816.0).

photovoltaic, hydro and geothermal, were assessed to answer the following research question:

Should off-grid Power-to-Liquid plants powered with renewable electricity be prioritized over the supply with grid electricity?

Three process configurations were evaluated for plant scales ranging from 1 to 1000 $MW_{el.}$ rated electrolyzer power. Scaling up the plant from 1 $MW_{el.}$ to 100 $MW_{el.}$ results in a 20 % reduction in net production costs of Fischer-Tropsch products. However, further scaling up the plant to 1000 $MW_{el.}$ resulted only in an additional decrease of 2 percentage points. No significant differences in net production costs of Fischer-Tropsch products were obtained for the three analyzed process configurations at a plant scale exceeding 100 $MW_{el.}$. Thus, plant configuration 2, based on a short tail gas recycle, including steam reforming of tail gas, was chosen as a reference for further analyses.

Additionally, the Fischer-Tropsch products' cost allocation was assessed in detail for a grid-based scenario. The capital expenditure and the electricity costs are significant cost centers for pilot-scale Power-to-Liquid plants at a rated electrolyzer power of 1 $MW_{el.}$, obtaining shares of 31 % and 50 %. The electricity costs become the main cost driver for industrial-scale Power-to-Liquid plants at 100 $MW_{el.}$ with a share of up to 88 %. This observation explains the diminishing effect of economies of scale for Power-to-Liquid plants.

The most promising results of the analyzed off-grid 2022 scenarios of 1.52 €/kg were obtained based on geothermal electricity, whereas applying offshore wind power or photovoltaic power resulted in the worst outcome of 2.40 €/kg. Using onshore wind power resulted in net production costs of 1.85 €/kg. Net production costs of 1.55 €/kg were obtained for the 2022 off-grid scenario based on hydropower.

In addition, 2050 scenarios were established based on expected reductions in the solid-oxide electrolyzer's fixed capital investment and the renewable power sources' levelized cost of electricity. Reduced net production costs ranging from 0.55 €/kg (geothermal) and 1.84 €/kg (offshore wind) are expected for off-grid scenarios until 2050.

In comparison, the assessed grid-based scenarios for the reference plant configuration resulted in Fischer-Tropsch net production costs ranging from 2.42 to 4.56 €/kg, based on electricity costs of 0.1 and 0.2 €/$kWh_{el.}$, respectively.

Fischer-Tropsch products must be sold at 1.95 €/kg for an off-grid PtL plant powered by a hybrid power plant to realize an amortization period of five years. A substantially higher selling price of 4.90 €/kg is necessary for the grid-based scenario due to significantly higher electricity costs.

The sensitivity analysis underlined the crucial influence of electricity costs and plant availability on the economic feasibility of Power-to-Liquid plants. Increasing the electricity costs by 0.05 €/$kWh_{el.}$ entails an increase in net production costs of 1.07 €/kg. Furthermore, the economic performance of Power-to-Liquid plants sinks substantially when the plant availability falls below 3000 operating hours per year. In general, plant availabilities surpassing 4000 h/a are recommended for future Power-to-Liquid projects.

Uncertain economic parameters regarding the solid-oxide electrolyzer are a potential weakness of the underlying assessment. However, significant reductions in required fixed capital investment are expected within the following years due to a substantial expansion in solid-oxide electrolysis production capacities. Another uncertainty factor is the study's foundation on static process simulation software.

The presented techno-economic assessment of a Power-to-Liquid plant adds value to existing studies showing that off-grid solutions have the potential to be cost-competitive with grid-based plants. Off-grid configurations offer cheap electricity but underlie the significant downfall of inferior full load hours. Thus, hybrid power plants and storage technologies must be established to further increase off-grid Power-to-Liquid concepts' feasibility. In addition, future Power-to-Liquid projects are facilitated by this study's findings concerning the ideal plant configuration and scale of 100 $MW_{el.}$ rated electrolyzer power.

Future research based on this study's findings should implement dynamic simulation tools to analyze the power supply of renewable volatile electricity sources, e.g., wind and solar, for different seasons and plant locations. In addition, hybrid power plants, including electricity or syngas storage technologies, could be designed in combination with the presented plant concept, thus approximating industrial plant availabilities of 7500 annual operating hours or higher. Integrating Fischer-Tropsch waste water as a feedstock for the electrolyzer or reformer can potentially increase the process's performance and hence, should be evaluated in experimental studies. Furthermore, future studies focusing on life cycle assessments of the grid-based and off-grid scenarios established in this work are essential to ensure a holistic evaluation of Power-to-Liquid processes. Conducting economic studies assessing potential business cases of the presented Power-to-Liquid plant is recommended for different plant locations in Europe.

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CRediT authorship contribution statement

Simon Pratschner: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Martin Hammerschmid:** Methodology, Project administration, Software, Validation, Writing – review & editing. **Stefan Müller:** Funding acquisition, Project administration, Resources, Software, Supervision, Writing – review & editing. **Franz Winter:** Funding acquisition, Project administration, Resources, Supervision, 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.

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