Uncertainty Analysis for Power-to-Methanol plant regarding Economic and Flexibility Parameters

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ABSTRACT
Power-to-Methanol systems, utilizing renewable energy sources, present a promising solution for achieving sustainable and low-carbon energy systems. This study focuses on investigating the operational flexibility and economic parameters of a PtM system, where hydrogen is produced through water electrolysis and subsequently combined with carbon dioxide to produce methanol. The system is primarily powered by wind and solar energy, with the option to supplement with grid electricity, provided the grid usage remains within the surplus of renewable power as mandated by the rules for renewable fuels of non-biological origin (RFNBO). The main objective of this research is to assess the effects of plant and economic parameters on the operation, cost breakdown, and optimal capacities of the system's key components, namely the electrolyzer, synthesis unit, and hydrogen storage. Specifically, the study aims to identify dominant parameters that have a significant impact on system capacities and overall operation. Plant flexibility is determined by the availability of part load, storage, and combination of electricity sources. By conducting a comprehensive analysis incorporating technical and economic factors, this study seeks to provide insights into the uncertainties associated with investment decisions. The performance of the optimized plant design is tested by varying inputs such as renewable power and operational costs, allowing for a robust assessment of the system's viability under different scenarios. Ultimately, this research aims to advance the understanding of the interplay between plant flexibility, economic considerations, and the optimal capacities of PtM systems.

Keywords: *Power-to-methanol, PtX, methanol, hydrogen, electrolysis, synthesis*

1. INTRODUCTION

Methanol production is responsible for 24% (222 MtCO_2) of direct CO_2 emissions from all the main chemicals, ammonia being the largest emission source [1]. As emission reductions are pursued heavily across the industry and academics, the focus has been switched from fossil-based syngas to pure hydrogen and CO_2 as raw materials for synthesis [2]. This and several other Power-to-X (PtX) routes have been described in the review by Palys et al. [3]. For methanol production, several reactor and process concepts are available, as described, for example, by Leonzio et al. [4] and Dieterich et al. [2].

The investment and operation environment is not very clear for power-to-methanol, which makes it more difficult to make final investment decisions. In previous studies, e-methanol was not cost-competitive, as pointed out, for example, by Perez-Fortes et al. [5] and Nýari et al. [6]. However, with decreasing electricity cost and the utilization of side streams, cost-competitiveness can be achieved [7].

Many publications report that the investment cost (capex) of electrolysis and the cost of electricity dominates the production cost of methanol [8], [9], [10]. Investment cost and the full load hours of the electrolyzer are tightly related to this [11].

Cost reductions are expected for the PtX components, for example, a learning rate of 18% for electrolysis [12], which could lead to significant cost reduction in rather near future. Already, costs below 35 €/MWh for wind power have been reached in Europe [13]. Plenty of new wind power capacity is planned [14], which could further decrease electricity prices. At the same time, the costs of CO_2 emissions should be rising [15], making fossil-based methanol more expensive. Regulation for green fuels has advanced well in Europe [16], but the final effect on costs seem to be still somehow unclear.

The flexibility of the synthesis plant can also affect the optimal unit capacities, storage demand, and the overall production cost of methanol, as pointed out by Chen et al. [17]. As hydrogen production is often supposed to be done mainly by wind or solar power, the

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whole power-to-methanol system should be capable of flexible operation. Another, compensating option would be the usage of large buffer storage for electricity, hydrogen, and CO_2 to level out the fluctuations. However, knowledge of methanol synthesis flexibility is still rather limited, and there are large ranges for the cost of storage [18].

With all these uncertainties, it is not straightforward to make concrete techno-economic analyses. This study aims to show how the selection of main parameter values may affect to the results of basic techno-economic analysis. The uncertainties are divided into three categories: (1) availability of electricity in different scenarios, (2) values of the main economic parameters, and (3) flexibility of the power-to-methanol process.

The objective is to use global sensitivity analysis to find numerical results that can differentiate the studied parameters and scenarios based on the impact on the key indicators: levelized cost of produced methanol, optimal capacities of the main components, and technical performance indicators. A literature review is provided for the main parameters: flexibility and cost of the main units.

Several Power-to-Methanol studies considering a detailed, steady-state process model have been published, for example by Chen et al. [9], Yousaf et al., [10], Battaglia et al. [7], Perez-Fortes et al. [5], Nieminen et al. [19], Lonis et al. [20], Crivellari et al. [21], and Meunier et al. [22]. This kind of bottom-up studies are very important, as they capture process design, performance, and economics in very detail. However, transient operation or integration to the rest of the energy system are not often considered.

If methanol production is considered part of a larger system, linear programming (LP), mixed-integer linear programming (MILP), or similar are typically used to optimize unit capacities and operation. Simplified models are used for components to capture efficiencies and transient behavior. This approach enables also the interaction of different units, such as heat integration. Some of the existing studies are reviewed here.

A multi-scale strategy for optimal design and operation of multi-product process systems that can generate power, chemicals, synthetic fuels, and energy carriers from fossil and renewable resources was presented by Demirhan et al. [23]. Using a MILP model, this approach integrates concepts from the supply chain, scheduling, and synthesis process to handle trade-offs in the integration of different fossil and renewable technologies.

Chen and Yang [17] studied a flexible Power-to-Methanol synthesis that operates with a variable load throughout the year, with an annual production rate of 400 000 tons. Wind and solar power data from real sites from the US and Germany were used as the main electricity source. Optimization with linear programming showed that the addition of flexibility lowers the levelized cost of methanol for 100% renewable production by about 21% and 34% for the two case study spots, respectively. The additional flexibility implementation costs brought on by the oversizing of the flexible process units and the storage units are outweighed by the economic benefits.

Svitnič and Sundmacher [24] investigated the design of a Power-to-Methanol production configuration, based on hourly renewable resource data from Port Arthur, Texas, USA. They took waste-heat utilization into account while simultaneously solving the design and scheduling problems by utilizing an extended optimization-based fluxmax technique, allowing them to identify energy-efficient process configurations. Due to the increased flexibility provided by the overall system, the flexibility of the methanol production was less important compared to the results by Chen and Yang [17].

2. FLEXIBILITY OF UNITS

2.1. Electrolysis

The first step of the Power-to-Methanol process is the production of hydrogen. The state-of-the-art solution for large scale is alkaline electrolysis, for which comprehensive reviews have been done by Mbatha et al. [25] and Buttler et al. [26].

The alkaline electrolyzer has so high ramping capabilities, over 5 %/s [25], that it should not be a limiting factor. The minimum part load is around 10 % or even above [25], which may seem as a problem. However, large electrolyzer facilities typically consist of several stacks running in parallel [26]. As the starting time from hot standby is very low, currently 1–5 min [25] and targeting below 1 s [26], some of the stacks may be shut down to achieve a very low total hydrogen production rate. Generally, hydrogen production can be considered very flexible. The effect of the dynamic operation on stack degradation is however unclear.

2.2. Methanol production

Methanol production from hydrogen and CO_2 consists of synthesis producing a mixture of methanol and water, followed by distillation, which is the main limitation of the methanol production flexibility [17]. The synthesis itself could be designed to be more flexible.

Seidel et al. [27] discussed the importance of considering the transient operation of methanol production, and developed a kinetic model suitable for transient operation in a continuously stirred tank reactor. Only a few detailed, dynamic process models have been published for direct CO_2-to-methanol plants. Chen et al. [17] and Zheng et al. [28] report that there are no published values for the maximum ramping rate of CO_2-to-methanol synthesis. To the author's knowledge, currently, there is a publication by Cui et al. [29], and some other assumptions available, which are gathered in table 2.2.

Cui et al. [29] used Aspen Plus Dynamic to simulate the whole methanol process (synthesis and distillation). They found that load ramp up to 200%/h could be

Table 1. Reported flexibility parameters for CO_2-methanol synthesis. Only Cui et al. [29] obtained the values as a result of a simulation, others are assumptions.

Min. part load	Max. ramp rate	Source
50 %*	200 %/h	Cui et al. [29]
50 %	1 %/h	Huesman [30]
35 %*	20 %/h	Zheng et al. [28]
10 %	-**	Chen et al. [17]
-**	30 %/h	Svitnič et al. [24]
50 %	5 %/h	Demirhan et al. [23]

*not reported explicitly
**various values used in a sensitivity analysis

used between loads of 50% and 100%. Zheng et al. [28] reported a lack of available literature and assumed a ramp rate similar to ammonia synthesis (20 %/h). Huesmann [30] assumed a ramp rate of 1 %/h. Varela et al. [31] developed a one-dimensional model for the synthesis part of the methanol process (distillation not modelled). Input step changes up to 20% were found applicable for hydrogen. Chen et al. [17] varied only the load of the synthesis, not the distillation. They did not limit the ramp rate in the main analysis but conducted a sensitivity analysis for it. Values of 0.01-20 %/h and infinite were studied. Only values of 1.0 %/h and below had a major effect on methanol cost and H2 storage size. Compared to results by Cui et al. [29], the ramp rate should not be a limiting factor. Therefore, ramp rate limitation is omitted from this study.

The second main parameter describing the flexibility of methanol production is the minimum part load. With low part load, it could be possible to maintain the plant in operation during periods with low hydrogen production. In addition to buffer storage, another option could be shutdown of the synthesis. The ability for shutdown and idle are rarely reported for methanol synthesis, as it usually aims for continuous operation. Literature values for the minimum part load are shown in table 2.2. In the study by Cui et al. [29], the lowest utilized load was 50 %, but the absolute minimum was not reported or studied. Huesmann [30] and Chen et al. [17] assumed 50% and 10% as the minimum load, respectively. Zheng et al. [28] did not report the utilized constraint, but the lowest methanol production during the presented example daily profile is about 35% (690 kg/h) of the maximum of 2000 kg/h.

3. COST OF UNITS

Similarly to flexibility parameters, there are large variations in investment costs for the main components. Some values are derived as predictions or assumptions, others are results from bottom-up analysis. Various reported investment costs for alkaline electrolyzers, methanol production unit, CO_2 capture, and hydrogen storage are gathered in tables 2 and 3.

Table 2. Reported investment costs of alkaline electrolysis

capex €/kW$_e$	Year	Source
864	2019	IEA [32]
1564-1840	2023	IEA [12]
750	2030	Schmidt et al. [33]
550	2019	Proost [11]
135	2030	BloombergNEF [34]
98	2050	BloombergNEF [34]
516	2014	Saba et al. [35]
200-250	2030	McKinsey & Company [36]
803	2020	Aghahosseini et al. [37]
291	2050	Aghahosseini et al. [37]
1000	2022	Zheng et al. [28]

For currency conversion, 1 USD = 0.92 EUR

For hydrogen production, only alkaline electrolysis is considered, as it is the most mature technology for large scale [11], and PEM electrolysis suffers from the required iridium demand [38].

There are several reasons for the variation in electrolysis investment cost. The first is related to the different assumptions and years regarding learning rate by technology development and scale-up, and the second is about the difference between the cost of the actual stack and other components, and indirect costs such as buildings and planning. For example, Battaglia et al. [7] obtained 599 €/kW for the whole equipment cost, which increased to 1380 €/kW for the total overnight cost when indirect costs were included.

The latest electrolyzer capex from IEA (data from project developers and industry) is 1564-1840 €/kW in Europe [12].

Table 3. Utilized investment costs in techno-economic analysis.

Synthesis €/kW	H_2 storage €/kg	Source
350	9.3	Decker et al. [39]
826	897	Svitnič et al. [24]
838	692	Chen et al. [40]
5167	1156	Sánchez et al. [41]
839	500	Zheng et al. [28]
390–3512*	-	Battaglia et al. [7]

For currency conversion, 1 USD = 0.92 EUR
*Without and with heat integration

Similarly to electrolysis, the cost of the methanol production unit differs a lot (Table 3). One reason seems to be heat integration, which may bring clear benefits to operational costs but increases the investment cost [7]. The cost of CO_2 capture system might be also included [40].

For the investment cost of hydrogen storage, the utilized technology has a large impact, as presented by Papadias et al. [18]. Salt caverns are the cheapest options (19–95 €/kg). Also, lined rock caverns (44–160 €/kg) are orders of magnitude cheaper than pipe storage (516–817 €/kg).

The cost of CO_2 can be considered as per utilized mass of CO_2, instead of investment and operational cost. This represents a situation where a third party is selling the CO_2 for the PtX plant. Compared to carbon capture and storage (CCS), only the capture cost (15-120 $/t) is considered, as there is only limited demand for transportation and storage [42].

As all the resources, mainly CO_2 and electricity generation, might not be located at the same site, something should be transported [43]. Some of the transmission costs might be addressed by society or other companies, thus it is difficult to define the actual cost for a single plant. Therefore, transmission costs are omitted from this study.

4. SCENARIOS

Three scenarios are studied to illustrate the main differences regarding the availability of electricity. Renewable electricity is available from wind power and solar photovoltaics in the form of a power purchase agreement (PPA). The PPA is defined so that the PtX plant owner buys all the electricity produced by specific wind and solar farms. It is assumed that no profit is obtained from the surplus which the PtX plant cannot utilize. In addition to wind and solar power, regular grid electricity is also an option with the following restrictions:

- Scenario 1: Only wind and solar power are available
- Scenario 2: In addition to wind and solar power, also grid electricity may be used with RFNBO rules (grid electricity cannot exceed monthly PPA surplus [44])
- Scenario 3: Any combination of wind, solar, and grid power is permitted.

The global sensitivity analysis is conducted by using low, medium, and high values for the most important parameters, as presented in table 4. The values are selected so that they represent the full range observed in the literature. These create 243 cases. For each case, capacities of wind power, solar power, electrolyzer, synthesis, and hydrogen storage are optimized simultaneously with the operation of the plant.

Table 4. Varied parameter values for the global sensitivity analysis.

	Low	Medium	High	
electrolyzer capex	200	800	1400	€/kW$_e$
H2 storage capex	10	50	500	€/kg
PPA price	20	40	60	€/MWh
Synthesis min. load	0.2	0.5	0.8	-
CO_2 price	10	50	150	€/ton

5. METHODS

The main simulated system (Fig. 1) consists of alkaline electrolysis, methanol production, and renewable electricity sources (solar and wind) in the form of PPA. The considered flexibility options are part load, buffer storage for hydrogen, and grid connection for electrolysis. Additional methanol storage is used to provide constant methanol output of 100 MW (18 t/h). The utilized CO_2 is considered to be bought from a pulp mill, which makes CO_2 abundant for MW-scale power-to-methanol plant [43].

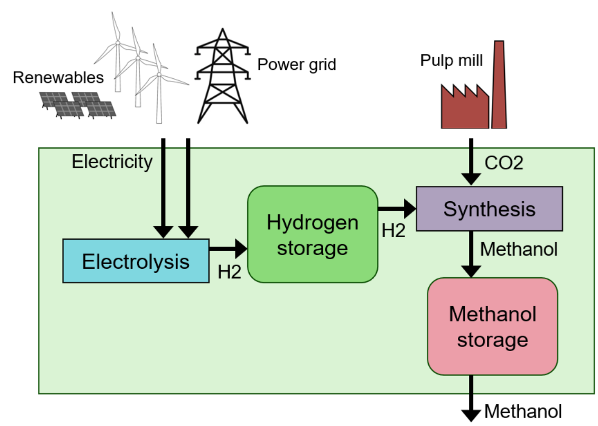

Figure 1 Illustration of the studied system.

Hourly mass and energy balance model is developed with Calliope framework [45]. It enables node-based energy system modelling, with linear and mixed integer-linear programming methods for the optimization of operation and unit capacities. Several solvers can be used, such as GLPK, CBC, Gurobi, or CPLEX. In this study, CBC (Coin-or branch and cut) is used.

5.1. *Electricity source*

Wind and solar power profiles were derived from ERA5 data [46] for a location in South-East Finland. For wind power, a 3 MW turbine with a hub height of 125 m and a rotor diameter of 100 m was considered. Fixed panels were assumed for solar PV. For both, hourly power output was computed for 2021, leading to full-load hours of 2435 h and 887 h. A detailed description of the method is provided by Hyypiä et al. [47]. Grid electricity may be also used to produce hydrogen, depending on the scenario. The hourly cost of grid power is obtained for Finland from the ENSTO-E transparency platform [48], and no transmission cost or taxes are considered.

If the RFNBO rule is followed, the grid electricity consumption should not exceed the surplus of the PPA-based renewable power on a monthly basis [44]. In this case, the power grid is modelled as a battery with 100% roundtrip efficiency. Surplus wind and solar power are charged into the battery, and the discharge cost equals the hourly electricity spot market cost. However, this method did not guarantee the monthly match of the surplus and grid usage. For some months, too much grid electricity is used, and less for some other months. The balance is guaranteed at the annual level, so the results in scenario 2 must be considered as optimistic. The capacity of the virtual battery was limited for a monthly nominal electricity demand. Smaller capacity could be used for more conservative results.

5.2. *Power-to-Methanol plant*

Constant techno-economic assumptions are gathered in table 5. Alkaline electrolysis is assumed, and several stacks will be used at this scale. As each stack would have a minimum part load of about 10-15% [26], the overall minimum part load can be assumed as 0%.

Methanol synthesis and the distillation of the raw methanol are considered as a single operational unit. Part load is allowed for the synthesis, but shutdown is not permitted.

CO_2 is captured from a pulp mill, which are well available in Finland and produce abundant amounts of CO_2 for GW-scale electrolysis [43]. It is assumed that the pulp mill is selling the CO_2.

Table 5. Fixed parameters.

Parameter	Value	Source
Plant lifetime	20 a	This study
Interest rate	10 %	This study
Year	2021	This study
Electrolysis efficiency	65 %	[26]
Synthesis ramp rate	20 %/h	[17]
H2 consumption	0.208 $kg/kg_{methanol}$	[49]
CO_2 consumption	1.45 $kg/kg_{methanol}$	[49]
Methanol storage capex	100 €/t	[50]
Synthesis capex	800 $€/kW_{out}$	[40]

6. RESULTS

The results are organized by studied parameters, and how each of them are affecting to key performance indicators (KPI). This is done by first labeling each individual optimization result by the corresponding value of the studied parameter, as illustrated in figure 2, where the studied parameter is electrolyzer capex, and the primary KPI is the cost of methanol. Here, the secondary KPI is the optimal H_2 storage capacity. After labeling the results, they can be sorted for histograms to see the distribution within all of the cases.

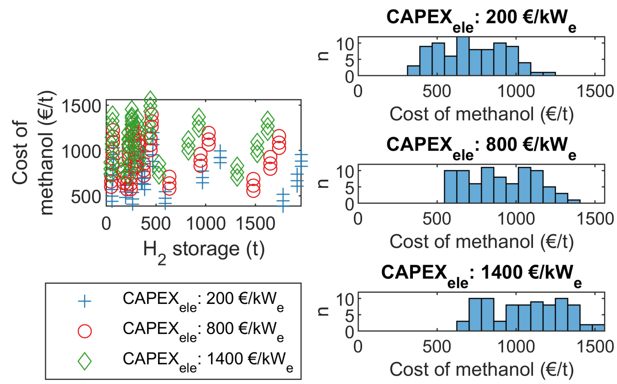

Figure 2 (a) Resulting KPI (cost of methanol) is labeled by the studied parameter (electrolyzer capex), (b) The distribution of KPI (cost of methanol), and the difference due to studied parameter (electrolyzer capex).

Finally, statistics can be derived from the histograms, such as median, min, and max, and half of the cases around the median (percentiles 25 and 75). These can be illustrated with boxplots (an example in Fig. 3), and be used to describe the differences between scenarios and the effects of studied parameters for KPIs.

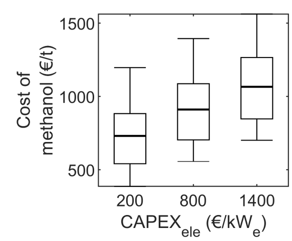

Figure 3 Effect of the studied parameter (electrolyzer capex) on median, min, and max, and percentiles 25 and 75 of the KPI (cost of methanol)

Increasing electrolyzer capex is increasing the median and the general level of methanol cost from 730 to 1065 €/t. The range of methanol cost between different electrolyzer capex values is maintained nearly the same. The range is also rather large, well above 500 €/t, which indicates that there are also some other important parameters affecting the cost.

To provide an overview of the results at a glance, the effect of each parameter is illustrated by the relative difference of the min and max values of the medians. For example, in figure 3, the difference of the medians is 31.5% (730–1065 €/t). The same procedure is repeated for all KPIs, parameters, and scenarios, and the values are then gathered in figure 4. This can be used to compare the general impact of each parameter and to put important parameters in the focus. The details must be discovered separately, from data and figures like 2–3.

There are some parameters and KPIs that lead to a 100% difference. In practice, it means that the median goes to zero with some parameter value. All these occur in scenario 3, in which unlimited grid electricity is available. This can replace all wind and solar electricity with certain parameter values (high PPA cost, low electrolyzer capex). Similarly, some parameters do not affect some of the medians of KPIs, such as CO_2 price, PPA cost, and synthesis minimum load. The CO_2 seems to affect only the cost of methanol, so it does not affect the capacities or operation of the plant. PPA cost has negligible effect only in scenario 2, where only wind share, solar share, and cost of methanol have a value greater than zero. These are further explained in becoming sections.

6.1. *Electrolysis capex*

The investment cost of the electrolyzer has a major impact on the optimal electrolysis capacity (Fig. 5a) and consequently the full-load hours (Fig. 5d). High capex leads to low electrolyzer capacity and high full-load hours. It can be stated also that the capex is rather decisive over the rest of the studied parameters for the electrolyzer capacity in scenario 2, as the differences between min and max values are rather small. For example, if the capex is 200 €/kW, the electrolyzer capacity varies within only 42 MW (347-389 MW), which is 10.8% of the maximum. There is more variation in other scenarios.

In scenario 1, higher optimal electrolyzer capacities are obtained (Fig. 5a). For a capex of 200 €/kW, the median electrolyzer capacity is 469 MW, compared to 373 MW in scenario 2. The difference increases with higher capex. Scenario 3 behaves differently, as the decisiveness of the capex decreases with decreasing capex value (Fig. 5a). There is a very large range (396–739 MW) for the percentiles 25–75 of the electrolyzer capacity when capex is 200 €/kW, so other parameters in addition to capex have a big role in the optimal solution. This range decreases to 247–258 MW when the capex is 1400 €/kW.

As the total methanol production is fixed, the total hydrogen production is also fixed. Therefore, the full-load hours (Fig. 5d) of the electrolyzer are directly resulting from the electrolyzer capacity. High capacity leads to low full-load hours, and vice versa.

In contrast to electrolyzer capacity, the capex of electrolysis does not affect substantially the synthesis capacity, as seen in figure 5b. The ranges are decreased slightly by increasing capex, but the medians are about the same. Interestingly, there are no big differences between the scenarios. The main difference is the large ranges in scenario 1, as the optimal synthesis capacity extends over 150 MW and the full-load hours can be well below 6000 h in some cases (Fig. 5e). Overall, the median full-load hours for synthesis are close to 8000 h in all scenarios and for all electrolyzer capex. This means that in many cases, it is almost a steady-state operation.

The ranges for hydrogen storage (Fig. 5c) are very large in all scenarios, but the trend is for smaller storage with high electrolyzer capex. This is due to smaller electrolyzer capacity and higher full-load hours (Fig. 5d). The largest median is obtained for scenario 3 with the lowest electrolyzer capex, which might be due to extensive use of cheap grid electricity with large electrolyzers. Because the synthesis must be operated all the time with only wind and solar in scenario 1, the overall storage level is a bit higher compared to other scenarios.

The cost of methanol (Fig. 5f) has a clear and rather obvious trend for electrolyzer capex: high capex leads to higher cost. However, there are plenty of other parameters affecting the cost, so the ranges are very large. Enabling more grid electricity decreases the cost, as cheaper electricity compared to wind and solar from certain hours can be utilized.

The optimal capacities of wind and solar power and the consequent shares of them of the total electricity usage are shown in figure 6. In scenario 1, high capex leads to higher median capacities, both for wind and solar. The increase is larger for wind, from 544 MW to 632 MW, as for solar the change of medians is only from 525 MW to 532 MW. The range between minimum and maximum values is also significantly larger for wind capacity.

In scenario 2, there is less variation for optimal wind capacity. Even for the overall min and max values including all capex values, the range is only between 484 and 531 MW. Solar capacity has more variation, median being decreased from 543 MW to 447 MW by increasing capex from 200 €/kW to 1400 €/kW. It might be that the grid electricity is so valuable, that it is maximized by the limits of the RFNBO rule.

Then in scenario 3, electrolyzer capex does not seem to affect much how wind and solar are utilized. The ranges for each capex are huge, as already the 25 percentile starts from zero, except if the electrolyzer capex is 1400 €/kW. This proposes that there is some other parameter that is more decisive.

Due to increased wind capacity with high electrolyzer capex, the surplus (Fig. 6c) increases in all scenarios. If looking only at the median values, scenario 2 has the highest surplus, as a high surplus enables a high amount of grid power (by the RFNBO rule). In scenario 1, without grid electricity, the ranges for surplus are very large, up to over 35%. If unlimited grid electricity is enabled (scenario 3), the surplus is decreased a lot. Still, there is a rather large range with high electrolyzer capex, up to over 20% at the maximum.

The share of grid power (Fig. 6f) is not relevant for scenario 1, as it is not available. In scenario 2, grid share is clearly increasing with increasing electrolyzer capex,

Scenario→	Wind capacity 1	2	3	Solar capacity 1	2	3	Electrolyser capacity 1	2	3	Synthesis capacity 1	2	3	Hydrogen storage 1	2	3	Full-load hours of electrolyser 1	2	3
Due to electrolyser capex	14	7	100	1	18	100	26	33	59	2	3	1	8	42	69	26	33	59
Due to H2 storage capex	11	1	4	2	3	10	6	10	11	21	17	10	86	96	97	6	10	11
Due to PPA cost	15	0	100	5	0	100	18	0	26	2	0	1	18	0	55	18	0	26
Due to CO2 price	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Due to synthesis minimum load	3	1	0	3	2	3	1	0	0	20	9	6	72	49	45	0	0	0

Scenario→	Full-load hours of synthesis 1	2	3	Surplus from wind and solar 1	2	3	Share of wind 1	2	3	Share of solar 1	2	3	Share of grid 1	2	3	Cost of produced methanol 1	2	3
Due to electrolyser capex	2	2	1	67	58	100	4	7	100	12	17	100	0	59	57	31	28	38
Due to H2 storage capex	20	17	10	45	22	44	1	1	5	4	4	13	0	25	2	14	4	7
Due to PPA cost	2	0	1	62	0	100	3	1	100	8	4	100	0	0	78	43	42	28
Due to CO2 price	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	15	17
Due to synthesis minimum load	20	9	6	23	1	15	3	1	2	8	4	13	0	0	4	6	1	2

Figure 4 Overview of the effect of each parameter on the KPIs, shown with the relative difference (%) of the medians. The color scale is highlighting the value, increasing from green to yellow to red.

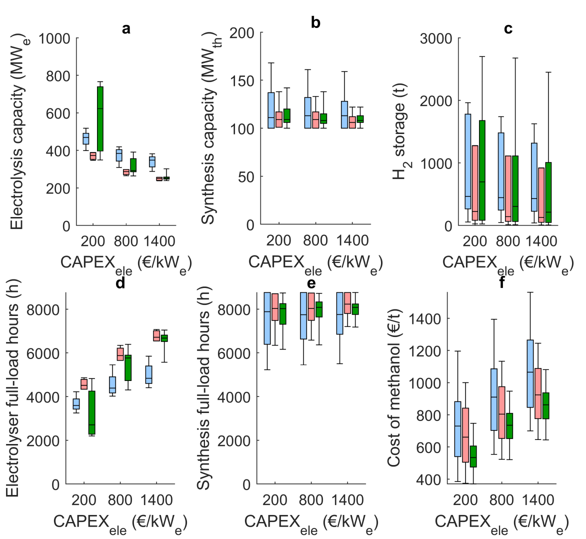

Figure 5 Effect of electrolyzer capex on the optimal capacity and full-load hours of electrolyzer and synthesis, hydrogen storage capacity and cost of methanol. Legend: (blue) Scenario 1, (red) Scenario 2, (green) Scenario 3.

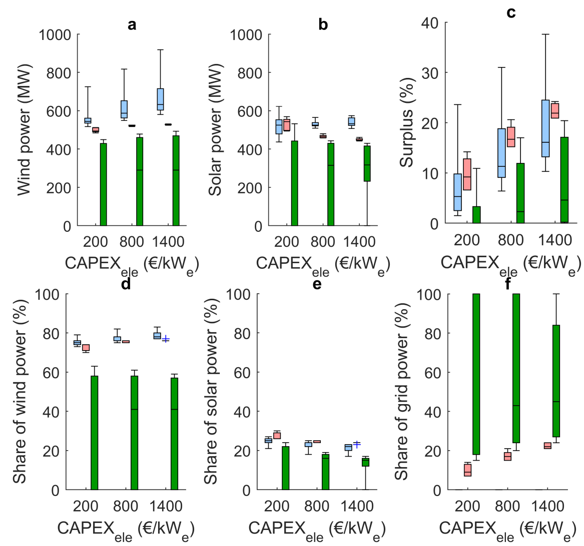

Figure 6 Effect of electrolyzer capex on the optimal capacities and surplus of wind and solar, and the share of each electricity source. Legend: (blue) Scenario 1, (red) Scenario 2, (green) Scenario 3.

up to over 20%. This equals the surplus, as the surplus is utilized via virtual battery to represent the RFNBO rule. If unlimited grid electricity is available (Scenario 3), electrolyzer capex has only a small impact. High capex seems to narrow the range of grid share.

6.2. *PPA cost*

The PPA cost of wind and solar has the most significant effect on the cost of methanol, as seen in figure 7f. However, it affects also the optimal capacity of the electrolyzer (Fig 7a) in scenarios 1 and 3. In scenario 1, high PPA cost increases the electrolyzer capacity, which enables better utilization of the wind resources by decreasing costly surplus (Fig. 8).

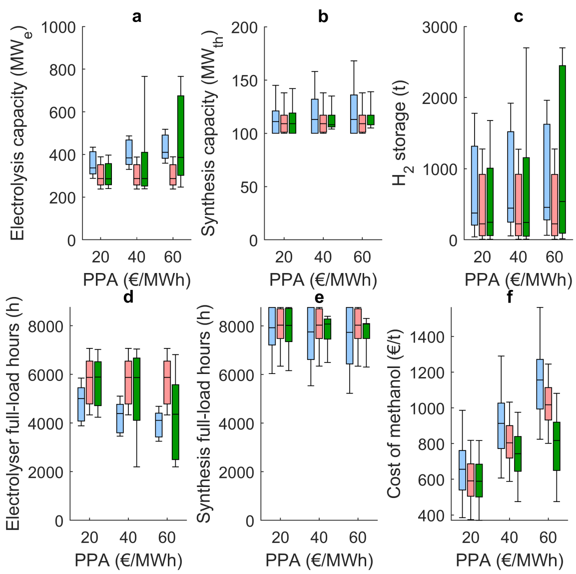

Figure 7 Effect of PPA cost on the optimal capacity and full-load hours of electrolyzer and synthesis, hydrogen storage capacity and cost of methanol. Legend: (blue) Scenario 1, (red) Scenario 2, (green) Scenario 3.

With unlimited grid electricity (Scenario 3), low PPA cost decreases the range of optimal electrolyzer capacity (Fig. 7a). With a PPA of 20 €/MWh, the maximum observed capacity is below 400 MW, but it increases up to over 700 MW with a PPA of 60 €/MW. This could be explained at least partly with the high shares of wind and solar power (together nearly 80%) when PPA is 20 €/MWh (Fig. 8d). As the 20 €/MWh is cheap compared to the grid electricity, there is no economic benefit to having a huge electrolyzer capacity for charging hydrogen storage with the cheapest grid electricity. In contrast, almost no wind or solar is used when PPA cost is 60 €/MWh, thus a larger capacity electrolysis and hydrogen storage is needed to shift the hydrogen production to moments of low-cost grid electricity.

The capacity and full-load hours of the synthesis do not change much according to PPA cost. Hydrogen storage has also a large variation, but increasing PPA cost also increases the optimal storage size in scenarios 1 and 3.

The cost of methanol is heavily depending on the PPA cost, as expected (Fig 7f). The effect is smaller when grid power is enabled, especially with unlimited grid power. Without grid power (scenario 1), the median cost of methanol goes from 656 to 1156 €/MWh when the PPA cost is increased from 20 to 60 €/MWh. In scenario 3, the increase is much less: from 589 to 817 €/MWh.

In addition to the cost of methanol, the PPA cost clearly affects to the optimal wind and solar capacities, and consequently the shares of wind, solar, and grid power (Fig. 8). With the lowest cost PPA, 20 €/MWh, the median grid share is around 20% (Fig. 8f). There is no big difference if the RFNBO rule is in use or not. Surprisingly, the PPA cost does not really affect the wind and solar capacities in scenario 2 (Fig. 8a, 8b). In contrast, low-cost PPA leads to higher capacities in scenario 1. In this case, additional cost from increased surplus (Fig. 8c) is compensated by the benefits of increased full-load hours (Fig. 7d). When there is no limit for grid power usage, PPA cost (relative to grid electricity cost) affects heavily the share of grid power. A high PPA cost of 60 €/MWh pushes the optimal wind and solar capacities to zero, except in a few cases marked with a blue cross.

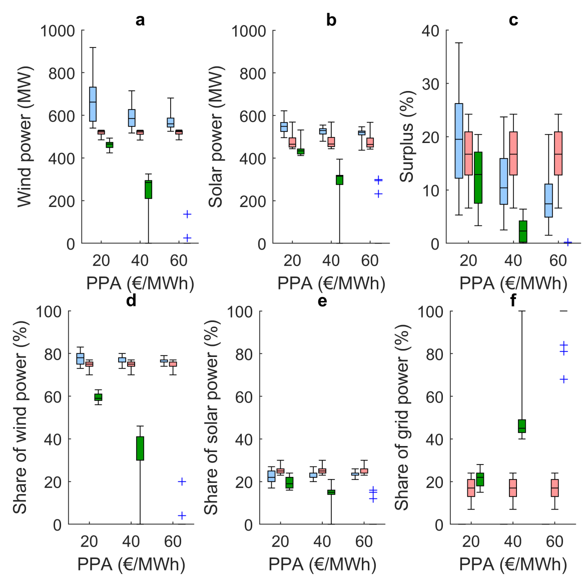

Figure 8 Effect of electrolyzer capex on the optimal capacities and surplus of wind and solar, and the share of each electricity source. Legend: (blue) Scenario 1, (red) Scenario 2, (green) Scenario 3.

In scenarios 1 and 3, the surplus of wind and solar power is clearly decreasing with increasing PPA cost, as shown in figure 8c. The grid share (Fig. 8f) is obviously linked to shares of wind and solar. As discussed previously, the share is not affected by the PPA cost, but electrolysis capex (Fig. 6f). In contrast, the effect is dramatic in scenario 3, where cheap PPA leads to a very low grid share, and costly PPA results in a 100% grid share in nearly all cases. Only 3 cases out of 243 have some wind and solar (blue crosses).

6.3. Hydrogen storage capex

The investment cost for hydrogen storage has the biggest impact on the optimal storage capacity (Fig. 9c) as expected. In all scenarios, low-cost storage leads to a large capacity. Because scenario 1 is relying only on wind and solar power and synthesis must be operated constantly, there is a technical demand for some capacity. This can be seen as a difference between another scenario when the storage capex is 500 €/kg, as the optimal capacities in scenarios 2 and 3 are nearly negligible. Scenario 1 has a large variation in storage capacity with lower capex, which might originate from the utilization of the occasional cheap grid electricity. In other cases, storage is used more for hydrogen produced by wind and solar.

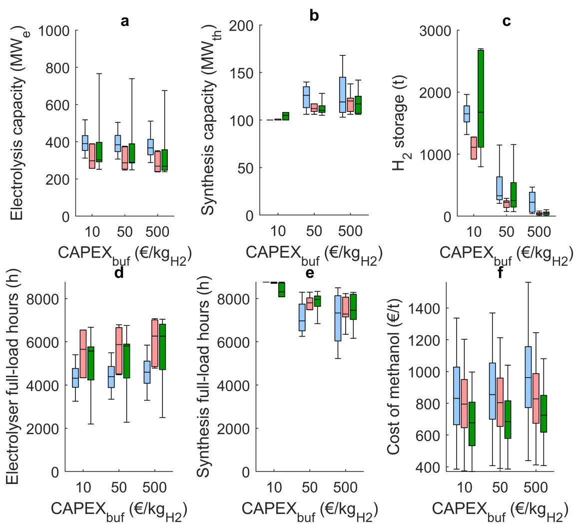

Figure 9 Effect of hydrogen storage capex on the optimal capacity and full-load hours of electrolyzer and synthesis, hydrogen storage capacity and cost of methanol. Legend: (blue) Scenario 1, (red) Scenario 2, (green) Scenario 3.

Storage capex is also affecting the optimal synthesis capacity. Cheap, and consequently large storage enables smaller synthesis that operates at nearly steady-state (Fig. 9b, 9e). If storage is more expensive, it seems to be beneficial to use higher synthesis capacity and ramp it down when needed.

There is also a small effect on electrolysis capacity. High storage cost leads to smaller electrolysis capacity (Fig. 9a) and higher full-load hours (Fig. 9d). The cost of methanol is also increased with higher storage capex (Fig. 9f), but not very much. In scenarios 2 and 3, the increase of median cost of methanol is only 33 and 48 €/t, when the storage capex increases from 10 to 500 €/kg. In scenario 1, storage has a larger role and the methanol cost difference is 131 €/t.

Wind and solar capacities are affected differently between scenarios. In scenario 1, high storage capex leads to higher wind capacity (Fig. 10a), compensating smaller storage (Fig. 9c). In scenario 2, high-cost storage decreases wind capacity, and there is negligible effect in scenario 3. For solar power, the effect of storage capex is smaller, and not very clear. The same applies to the shares of wind and solar.

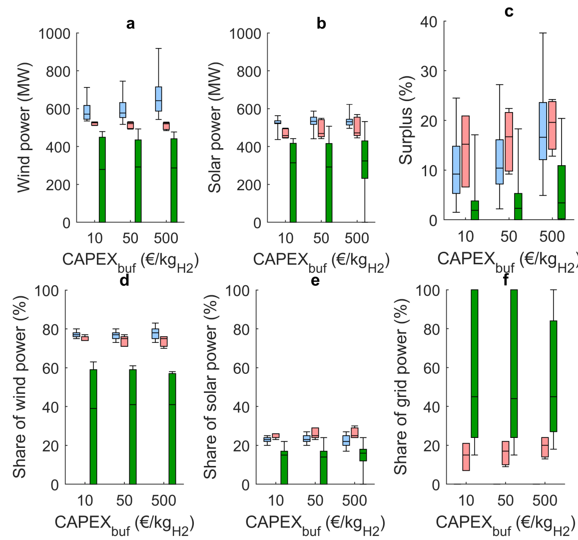

Figure 10 Effect of hydrogen storage capex on the optimal capacities and surplus of wind and solar, and the share of each electricity source. Legend: (blue) Scenario 1, (red) Scenario 2, (green) Scenario 3.

Surplus from wind and solar increases with increasing storage capex in all cases (Fig. 10c). This is logical, as the benefit of avoided surplus is decreased by the increased cost of storage.

The highest capex (500 €/kg) seems to add solar share in scenario 3, as the range of percentiles 25–75 narrows closer to the median. In general, the optimal electricity mix in scenario 3 is not much affected by storage capex, as the obtained ranges for shares are very large.

6.4. Minimum load of synthesis

As the minimum load of the synthesis has a relatively small effect on many parameters (Fig. 4), not all the details are presented here. As shown in figure 11, optimal electrolysis capacity and operation are not affected by the synthesis minimum load. Instead, the synthesis operation is affected quite a lot. If the minimum load is small, the median synthesis capacity increases, and the median full-load hours decrease (Fig. 11b ,11e). The effect is strongest in scenario 1, as it must provide flexibility either with synthesis part load or hydrogen storage. Other scenarios have also the option of grid electricity.

As hydrogen storage is the other main flexibility option in scenario 1, its capacity is also increased for a high minimum synthesis load (Fig. 11c). Between minimum loads of 20% and 80%, the median storage capacity changes from 265 to 931 t. There is less change in other scenarios, as the median is maintained below 386 t.

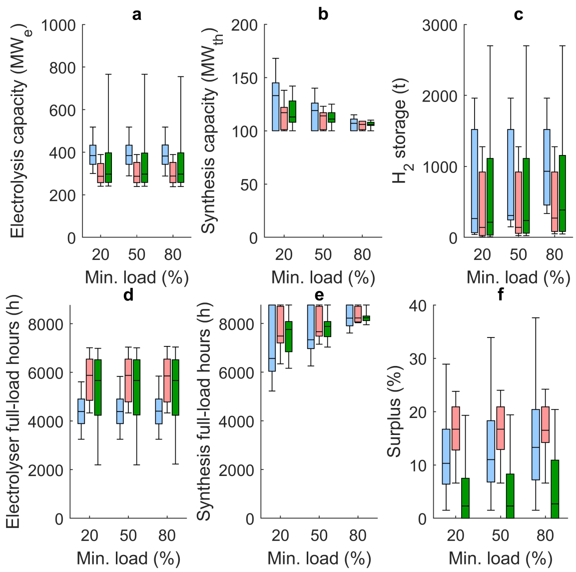

Figure 11 Effect of synthesis minimum load on the optimal capacity and full-load hours of electrolyzer and synthesis, hydrogen storage capacity and surplus. Legend: (blue) Scenario 1, (red) Scenario 2, (green) Scenario 3.

The surplus is slightly increased in scenario 1 if the minimum part load is increased, as more wind capacity might be required to provide the hydrogen demand. There is still a very large range for surplus, as also electrolysis capex, storage capex, and PPA cost affect this. The impact is lower in other scenarios.

6.5. *CO_2 price*

The CO_2 price does not affect the capacities or operation of the plant, but only the methanol cost (Fig. 4). Therefore, the details are shown only for the methanol cost in figure 12. The cost increase is rather large, even larger compared to the impact from the capex of hydrogen storage. Therefore, it is important to concentrate on efficient CO_2 sources for this kind of application.

7. CONCLUSIONS

In this study, the aim was to show which parameters have the highest importance for the results of techno-economic analysis for a Power-to-Methanol plant. A global sensitivity analysis was conducted to explore all the possibilities within the studied parameters.

It was found that many parameters had a large effect on optimal capacities, system operation, and cost

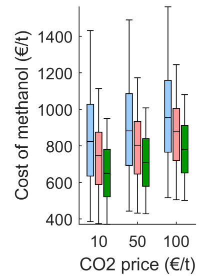

Figure 12 Effect of CO_2 price on the cost of methanol. Legend: (blue) Scenario 1, (red) Scenario 2, (green) Scenario 3.

of methanol. Similarly, many KPIs experienced no or low impact from some of the parameters. This type of analysis can help decisions regarding assumptions of further studies. To make a concrete and clear techno-economic analysis, many parameters must be constant. This kind of pre-sensitivity analysis can be used to decide which parameters can be fixed, and which are both uncertain and important to be included in some sort of scenarios or sensitivity analysis.

The main costs of Power-to-Methanol are originating from electricity (wind, solar, grid) and the investment cost of electrolysis. Depending on the relations between these, wind and solar might not be used at all, if unlimited grid electricity is permitted. Hydrogen storage is also a very important component from the design and operational point of view, but not affecting so much the final cost of methanol.

The RFNBO rule limits the benefit of the grid electricity. One must bear in mind that unlimited grid electricity might seem to produce the lowest cost methanol, but it is not certified as green or renewable based on REDIII. However, if the specific CO_2 emissions of the grid electricity are low enough, significant emission reductions could be still achieved. Therefore, this could be more of an issue about subsidies or distribution obligation, if the final product is eligible for those.

The minimum partial load of the synthesis affects mainly the operation of the synthesis and optimal hydrogen storage capacity.

The cost of CO_2 does not affect the optimal capacities or operation of the plant, but the effect on the final cost of methanol is at the same level compared to hydrogen storage. Possibilities for economic and efficient CO_2 capture should be considered in the future, for example in the form of heat integration.

The limitations of this study are related to the number of studied parameters, and the level of detail in the analysis. Due to time limitations, the number of studied parameters was limited. In further studies, parameters such as ramping rate, interest rate, different years, and transmission costs could be considered in the global sensitivity analysis. The current approach also limits the analysis of single cases, as the focus is more on the KPIs.

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