


# Influence of Power-to-Fuel Plant Flexibility Towards Power and Plant Utilization and Intermediate Hydrogen Buffer Size

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Conversion of intermittent renewable energy into synthetic fuels and chemicals is required to secure long-distance transport and feedstock for chemical industry. Due to the fluctuating energy generation, process intensification and feed flexibility are essential. This contribution investigates the importance of feed flexibility on the buffer size with applying a 20:80 scenario of wind/solar energy generation. The degree of power and plant utilization are calculated. With the capability to accept a lower load bound of 17 % after only 10 min, a minimum tank capacity of only 1.3 h is calculated to avoid a fuel plant stop throughout a calendar year. Additional tank capacity for peak power compensation in the range of ~10 h is beneficial for the utilization degree of power and under the prerequisite of a load-flexible fuel plant.

**Keywords:** Fischer-Tropsch synthesis, Microchannel reactors, Plant flexibility, Power utilization, Renewable energy

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## 1 Introduction

Energy transition to avoid massive climate changes will need huge efforts to replace fossil fuels, not only in electricity generation but also with regard to all kinds of transport and chemical industry [1]. Nevertheless, this is a large chance for innovative chemical engineering to work on the substitution of fossil feedstock.

To bring significant quantities of alternative synthetic fuel into the market, several aspects have to be considered. The biofuel approach plays only a minor role in this discussion, since the current demand for fuels exceeds the available biomass resources and massive expansion of intensive agriculture is not straightforward [1]. In all applications where high energy density of the fuel is required, only hydrocarbon-based fuel can meet the challenge and, thus, a carbon source is essential for the production of synthetic fuel for long-distance transport. Significant amounts of carbon are available in the form of CO<sub>2</sub> from industrial processes and can be extracted from the atmosphere on the long term. By the latter approach, the carbon cycle can be closed and the increase in CO<sub>2</sub> concentration in the atmosphere can be avoided while all the advantages of hydrocarbon-based fuels can be utilized [2].

Only a few processes are currently able to produce required materials such as kerosene or diesel substitutes that meet the current fuel standards. One of the most promising processes among the Power-to-Liquid (PtL) processes is the Fischer-Tropsch (FT) synthesis [3]. In this scheme,

hydrogen from renewable energy via electrolysis together with carbon dioxide can be used to produce long-chain hydrocarbons, which can be converted into clean synthetic fuel in accordance with the specifications using known refinery technology. Synthetic fuels based on FT synthesis are known for some time based on natural gas or coal and are approved for blending up to 50 % according to ASTM D 7566 [4] in the case of synthetic kerosene and are in line with EN15940 in the case of paraffinic diesel. The absence of aromatic compounds in the FT products, which currently dictates the limit in blending for substitution of fossil jet fuel, allows a significant reduction of particle emissions and, thus, a reduction of the particle-induced climate effect caused by its combustion [5].

Important issues in synthetic fuel production are the price for renewable electricity, the price for CO<sub>2</sub>, and plant costs (CAPEX). The electricity price depends on the location (availability of sun or wind) and the development of installation costs per peak power of renewable energy. The

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same applies to the source of CO<sub>2</sub> and the costs for its purification. The plant costs normally scale with the installed capacity. Until now, most plants under construction are still demonstration plants.

The cost price per kilowatt hour of renewable electricity in Germany [6] is currently 4–7 ct kWh<sup>-1</sup> for solar power and about 4–8 ct kWh<sup>-1</sup> for wind (onshore). In more favorable regions, about 1–2 ct kWh<sup>-1</sup> are conceivable, taking into account cost reductions. Exemplarily considering a conversion loss of up to 50 % in the generation of the synthetic fuel and an average calorific value of 10 kWh per liter results in an electricity price share of, e.g., 40 ct L<sup>-1</sup> or 500 € t<sup>-1</sup> at 2 ct kWh<sup>-1</sup>.

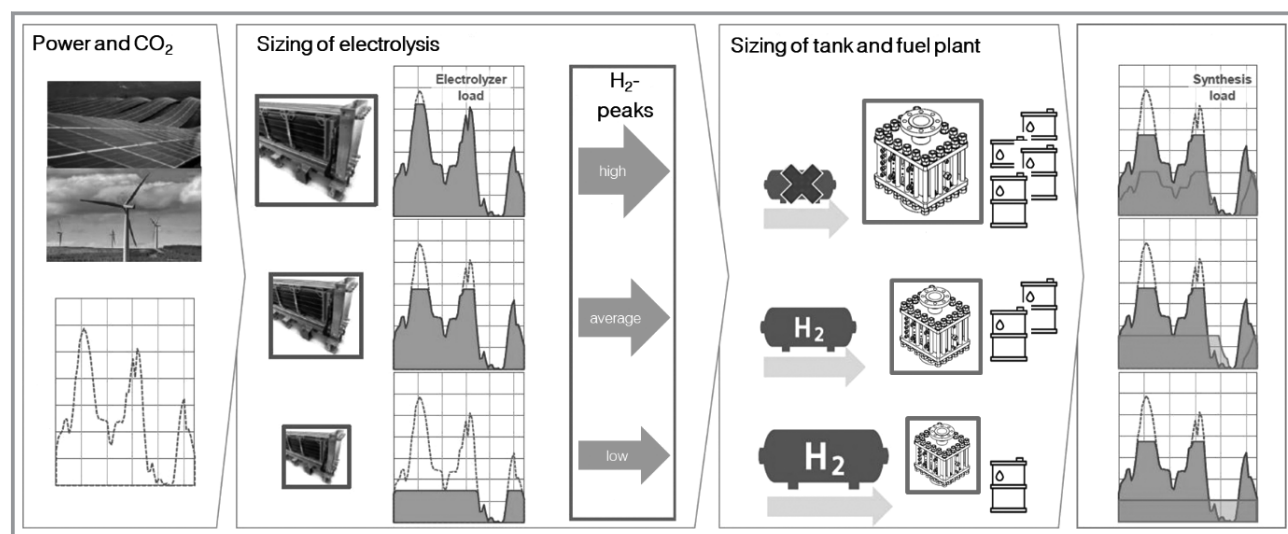
The contribution of carbon dioxide to fuel costs is similar to that of electricity, except that if the process is optimized, almost 100 % of the carbon from CO<sub>2</sub> ends up in the fuel and, therefore, no conversion losses need to be considered. CO<sub>2</sub> can be purchased for about 80–100 € t<sup>-1</sup> from ethanol production. The price of CO<sub>2</sub> from the cement industry in Germany is 33 € t<sup>-1</sup> [7]; for Iceland, the price for CO<sub>2</sub> from cement is 17 € t<sup>-1</sup> [7]. If CO<sub>2</sub> does not originate from biogenic sources but from industrial point sources, carbon dioxide is only used a second time; therefore, CO<sub>2</sub> avoidance is only creditable once and, thus, of limited interest from an economic point of view. Only CO<sub>2</sub> extraction from the air or sustainable biogenic sources creates climate neutrality. According to the Agora study [7], the current price is 145 € t<sup>-1</sup> and will develop towards 100 € t<sup>-1</sup> by 2030. The conversion factor for fuel costs is calculated from the molecular mass of CO<sub>2</sub> versus the basic block chain molecule –CH<sub>2</sub>– and 80 € t<sup>-1</sup> CO<sub>2</sub> directly results in a contribution of about 250 € t<sup>-1</sup> fuel.

From the point of view of the use of point sources of carbon dioxide, local and temporally fluctuating supply of electricity, and the avoidance of grid costs, the establish-

ment of a multitude of decentralized plants is the fastest way to build up significant capacities and to reduce CAPEX while power and fuel spots can be commissioned in very short time. Typical power classes could be 10 MW (electrical input for hydrogen generation) and larger. Thus, the annual FT output is > 3000 t a<sup>-1</sup>. The Agora study [7] assumes total production costs of PtL products of 9 to 13 ct kWh<sup>-1</sup>, i.e., 90–130 ct L<sup>-1</sup> or 1125–1625 € t<sup>-1</sup> in the future. This is of course higher than the current price of fossil fuels today and several decisions need to be taken on political basis to boost these technologies and to make them attractive.

One important issue when discussing plants operated on renewable energy is the intermittent nature of the renewable source. It leads to discussions on the correct sizing of the electrolysis, i.e., the sizing with respect to the highest power peak occurring in the time scale of milliseconds or seconds (Fig. 1). Furthermore, longer time scales lead to fluctuation, which either requires a hydrogen buffer system or a high flexibility of the fuel plant, i.e., a reverse shift and a FT synthesis stage, to reduce the buffer size (Fig. 1). Both aspects are addressed in the BMWi project PowerFuel and the associated research from which this article results from.

Off-grid solutions depend strongly on the capability of the fuel plant to operate feed flow flexible. Only a small number of studies have been devoted yet towards the investigation of the influence of flexibility on the output and utilization degree, which arises from certain assumptions. Some researchers have investigated the possibility of performing alternative processes for energy storage via molecules like methane (synthetic natural gas) under dynamic boundary conditions [9–12]; mostly catalyst stability and the challenges for describing the reactor system have been investigated there. Major obstacles are under-stoichiometric hydrogen supply in unsteady-state operation leading to catalyst deactivation. Thus, hydrogen and CO<sub>2</sub> need to be



**Figure 1.** Aspects sizing and flexibility of electrolysis with regard to fluctuation of power as well as sizing and flexibility of fuel synthesis along with fuel yield; aspects as investigated in the BMWi project PowerFuel; figure adapted from [8].

fed both dynamically. In Fischer-Tropsch synthesis, the catalyst deactivation is less important as can be found in some studies varying the  $H_2/CO$  or  $H_2/CO_2$  feed ratio [13–18], but the reactor needs to be secured from complete hydrogen consumption, which on the other hand requires fast control over the reactor temperature [14, 15]. However, all of these studies only considered the operation of the FT reactor or synthesis chain alone.

In the current study, the focus is on the utilization of the peak power neglecting the time difference between power and hydrogen generation but with special focus on the hydrogen buffer size, its filling level in conjunction with the capacity ratio between mean power and fuel plant capacity as well as the flexibility of the fuel plant. The fuel plant consists of reverse water-gas shift stage producing the syngas and the Fischer-Tropsch synthesis. Indications of flexibility of fuel plants equipped with microstructured reactors are provided to show the importance of flexibility.

## 2 Approach

As an example, an electricity park in Baden-Württemberg with a wind/PV ratio of 20:80 was selected. The power curve of the power park was resolved in 10-min time scale. Thus, it has been concluded that electrolysis such as PEM or alkaline can follow the available power in this time range. The data set has been received from the FVT at Ruhr-University Bochum and was generated from an analysis of weather data [19]. The relative supplied power was normalized to the mean of the year according to Eq. (1).

$$P_{\text{rel}} = \frac{P_{\text{el}}(t)}{\frac{1}{1a} \int_{1a} P_{\text{el}}(t) dt} \quad (1)$$

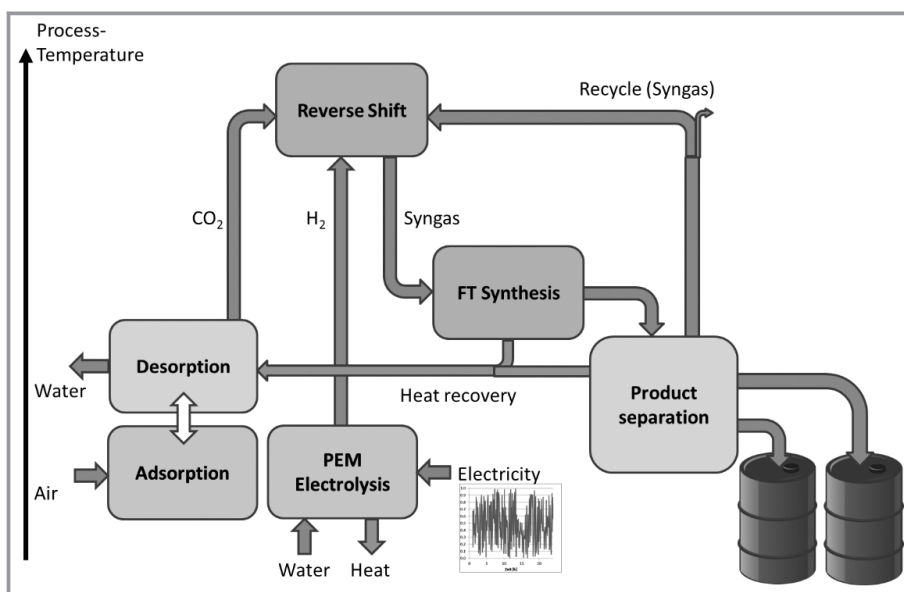
The aim of the investigation applying these data should be to evaluate, on a normalized basis, the required size of a hydrogen buffer tank and fuel plant in dependency on the renewable power characteristics at the plant location and the fuel plant flexibility. The plant configuration according to the BMWi project PowerFuel in Fig. 2 is considered: electrolysis is delivering hydrogen immediately when it is produced; such assumption seems valid with regard to the applied time resolution of the power curve. Hydrogen is buffered in a tank and is further fed with  $CO_2$  in required stoichiometry conditions to a reverse shift stage and sent to the Fischer-Tropsch stage. After

the FT stage, the product is condensed and most of the gaseous products and residual unconverted reactants are recycled.  $CO_2$  is delivered in this scheme from direct capture from air (as part of the PowerFuel project) but with regard to the following flexibility analysis, the source of  $CO_2$  is not important.

The following parameters are applied:

- Hydrogen consumption at plant minimal hydrogen load  $f_{\text{min}}$ : the parameter  $f$  is the hydrogen feed in relation to the nominal hydrogen feed (design load) and ranges between 0 and 1;  $f_{\text{min}}$  is known from one single module of INERATEC's fuel plants as 0.17.
- Time for load change of INERATEC's fuel plants: a) change from design load to minimum operation  $f_{\text{min}}$  requires 10 min, b) change back to the design load ( $f = 1$ ), 60 min are required

Generally, the faster the fuel plant can react to load changes, the less intermediate hydrogen tank capacity must be made available to compensate for system inertia. The requirement to operate the overall plant with as little as possible imported power (dependent on the plant location) results in the minimum hydrogen tank capacity  $t_{\text{min}}$ . Its value is determined from the fuel plant capacity and the power profile at the site. With hydrogen from the tank, the fuel plant should be able to operate continuously at the minimum operating point ( $f_{\text{min}}$ ) over the longest time of expected power lack. Thus, the power profile has been screened towards the largest power lack. To provide a value for  $t_{\text{min}}$ , the fuel plant capacity  $F_{\text{max}}$  has to be selected (see next item) for a given power profile. To be able to generalize the obtained data, all given values for tank sizes are provided in the unit of operating hours of the fuel plant in nominal load ( $f = 1$ ).



**Figure 2.** Plant scheme and process temperature for the PtX process under analysis in the PowerFuel project.

Two dependent parameters can be varied upon the economics:

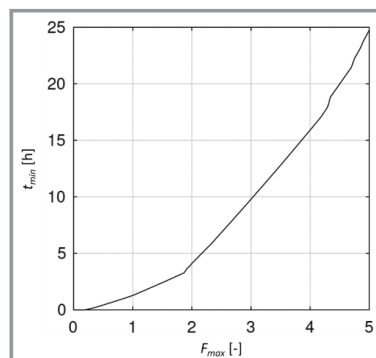
- The normalized fuel plant capacity  $F_{\max}$ : It is handled in the analysis as a ratio of fuel plant capacity in relation to the mean power available at the site, which is determined by integration of the power profile (Eq. (1)). Thus, a value lower than 1 corresponds to less hydrogen consumption of the fuel plant than can be produced from the mean power with electrolysis. The smaller the PtL plant is designed, the more often the electrical power of the site may be in excess. Power must eventually be sold or even be discarded in an off-grid solution assuming no hydrogen buffer tank. Thus, power utilization  $\eta_{\text{Power}}$  will certainly increase with fuel plant capacity. With increasing fuel plant capacity, however, more hydrogen will be consumed in minimum operation, which increases again the required minimum tank size  $t_{\min}$ . The respective numbers of the utilization will be provided in Sect. 3.
- Additional tank capacity for compensation of peak power  $t_{\text{peak}}$ : Additional tank capacity can be applied for intermediate storage of hydrogen in phases of peak load power to increase the power utilization  $\eta_{\text{Power}}$  and the fuel plant utilization  $\eta_{\text{Plant}}$ . If the power output and, consequently, the hydrogen flow from the electrolysis drops after phases of peak load to below the design load of the fuel plant, the fuel production could still be operated at the design point, which means that, e.g., the day-night cycles of photovoltaics (PV) can be compensated.

The overall tank size is finally the sum of  $t_{\min}$  and  $t_{\text{peak}}$ . The load setpoint of the plant ( $f$ ) in the time-resolved simulation to determine tank volumes and power and fuel plant utilization is performed in the following approach: as soon as the tank filling falls below  $t_{\min}$  in one of the time steps (10 min), the fuel plant should operate at  $f_{\min}$  (case 1). On the opposite, as the tank filling exceeds in one time step the value of  $t_{\min}$  by at least 1 % (case 2), the value of the load setpoint  $f$  is increased to reach  $t_{\min}$  in the following time step again. The required load change is always calculated and compared to the value the plant could follow. If the required load change is above the value of the plant flexibility, then the load setpoint is increased or reduced to the minimum or maximum load setpoint, for case 1 and case 2, respectively.

Finally, it should be noted, that the tank size does not refer to the storage state of hydrogen. Hydrogen could be stored under pressure or liquefied. Both options would cost additional energy if electrolysis is operated near ambient; presumably, electrolysis at  $> 40$  bar would be beneficial to operate the full process chain at up to 30 bar and to allow a pressure change in the tank. However, this would imply an additional tank size, which cannot be utilized as soon as the tank pressure reaches the synthesis pressure. This would increase the overall  $t_{\min}$  and  $t_{\text{peak}}$  by up to factor of  $\sim 4$ .

### 3 Results

In Fig. 3, the influence of the plant capacity  $F_{\max}$  on the minimum tank capacity  $t_{\min}$  is shown. The larger the plant is designed, the larger gets the minimum tank capacity. In the progression of the curve, several bends can be seen. This results from the fact that with increasing hydrogen demand in minimum operation of the fuel plant multiple smaller power lacks can merge into a single, larger lack.



**Figure 3.** Influence of the plant capacity  $F_{\max}$  on the minimum tank capacity  $t_{\min}$  at a wind/PV ratio of 20:80.

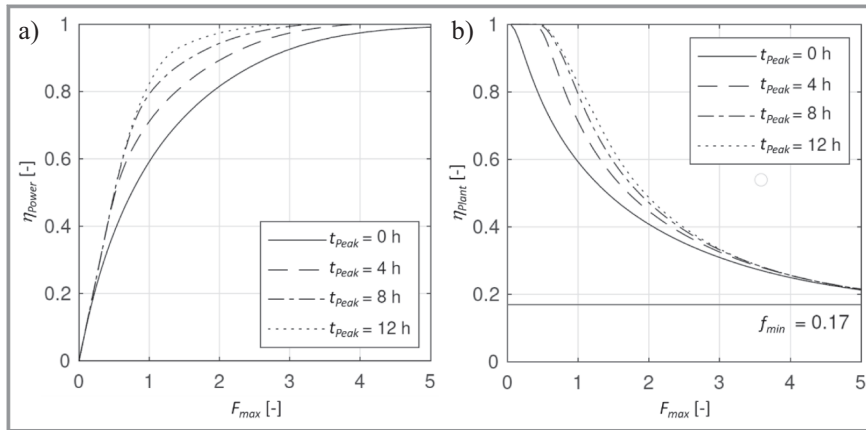
Furthermore, two different gradient sections are visible, which are separated by the bend at  $F_{\max} = 1.9$ . The period in which the fuel plant could be operated in minimum load from the tank without any production of hydrogen  $t_0$  can be derived from the simulation via Eq. (2):

$$t_0 = \frac{t_{\min}}{f_{\min} F_{\max}} \quad (2)$$

For  $F_{\max} = 1.9$  and  $f_{\min} = 0.17$  with  $t_{\min} = 3.3$  h, a value of 10.2 h can be calculated. As the assumption of zero power is conservative, the lower branch of the curve is obviously dominated by the daily power cycles, while in the upper branch fluctuations of the wind power need to be compensated in addition to the day-night cycles of the PV power. If data with higher wind/PV ratio of 20:80 would be used,  $t_{\min}$  may increase up to a certain level of wind/PV.

Fig. 4a shows the power utilization and Fig. 4b shows the plant utilization with four different tank sizes for peak power  $t_{\text{peak}}$ . The two parameters provide opposite trends: a larger fuel plant can handle more peak loads at the site and the site utilization increases, but at the same time, plant capacity is withdrawn because the fuel plant can be operated less frequently at nominal load. The maximum simulated tank size for peak power is 12 h, which roughly corresponds to the expected day-night cycle. Utilization rates can be increased by using additional tank capacity, especially with regard to the contribution of wind power.

The influence of tank sizes for peak power  $t_{\text{peak}}$  on power utilization and fuel plant utilization can be seen in Fig. 5 for three different plant capacities of  $F_{\max} = 0.5, 1,$  and  $1.5$ . With increasing tank size, its influence on plant and power



**Figure 4.** a) Power utilization  $\eta_{power}$  and b) fuel plant utilization  $\eta_{plant}$  as a function of tank sizes for peak power  $t_{peak}$  and plant capacity  $F_{max}$ .

utilization decreases. This indicates that from a certain tank size on, most fluctuations in the day-night cycle can be covered and the remaining fluctuations are on a longer time scale. The remaining fluctuations are due to climatic and seasonal variations, which are explained, e.g., by fewer hours of sunshine in winter or by winter storms during which the wind turbines have to be switched off. These fluctuations depend on the installation site. In Chile or Morocco, tank sizes that buffer the day-night cycles therefore promise higher power and plant utilization than in Baden-Württemberg. If power and plant utilization should be 100 % at the same time, then very large tank capacities are required to run the fuel plant permanently at full load. Even seasonal fluctuations would have to be buffered and this would significantly increase the investment costs. Power utilization and plant utilization can only be both at 100 % if  $F_{max}$  is 1 – as from its definition. For all three fuel plant capacities, a bend in the graphs of utilization can be seen, which is consistent with Fig. 3 and the analysis of the average power lack via Eq. (2).

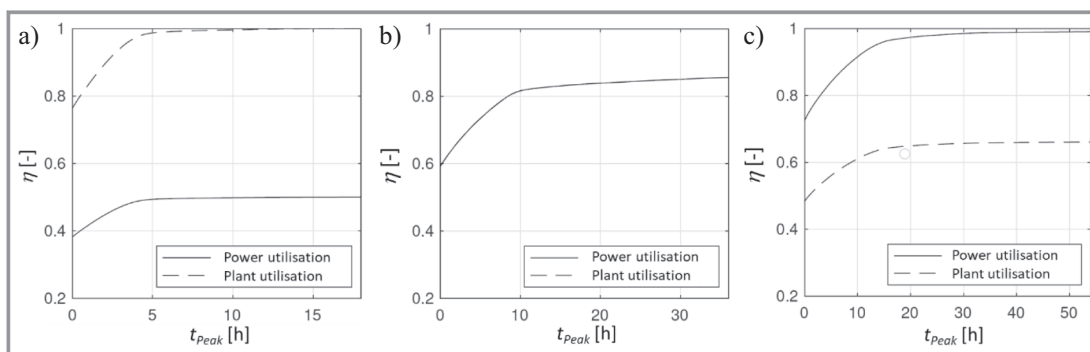
An investment in additional tank volume that buffers day-night cycles is favorable. Still, the selection of the appropriate fuel plant capacity depends on the given condi-

tions at the site. If selling surplus electricity is beneficial, it may be worthwhile to choose a smaller fuel plant capacity that can be run at nominal load for a longer time period. Nevertheless, tank size easily can get to a major hurdle in the installation of plants  $\gg 1$  MW and caverns suitable for hydrogen storage are rare.

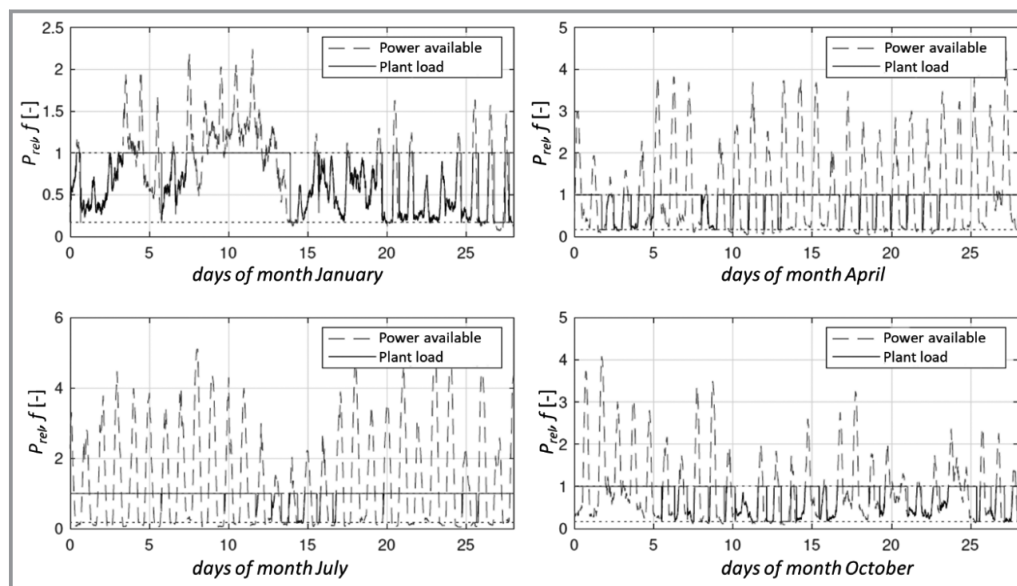
All modeling here rests on the flexibility of the fuel plant as introduced in Sect. 2. Looking at Fig. 6, where electric power and load state of the fuel plant are plotted for a selection of months, it becomes clear that this flexibility generates a high benefit, since the fuel plant needs to be

ramped several times in relatively short time frame. The minimum tank capacity of 1.3 h is applied here to avoid any shutdown during the year. This minimum capacity is needed only in some days of the year, see, e.g., the dip at January 27 or during nights in July. Generally, changes in the tank filling level on a daily basis occur mainly in summer, when solar radiation is high. That way, the plant can be operated on nominal load for almost all the days of July. In winter, the filling level of the tank has been observed to be at the lower boundary over several days (January 15 to January 29) at days with low wind. On the other hand, high wind velocities in winter can lead to a larger number of consecutive days of nominal operation (January 7 to January 13).

Finally, the influence of the flexibility of the plant on the power and fuel plant utilization was investigated. A reduction of the flexibility from the minute scale towards the range of hours reduces both the power and fuel plant utilization degree by roughly 10 % (absolute). Only if the additional tank size for peak power is chosen 12 h or even higher, the difference disappears as the flexibility of the plant gets less important. However, if the plant flexibility is reduced also, the minimum tanks size would drastically



**Figure 5.** Power utilization  $\eta_{site}$  and fuel plant utilization  $\eta_{plant}$  as a function of tank sizes for peak power  $t_{peak}$  for fuel plant capacity  $F_{max}$  a) 0.5, b) 1, and c) 1.5.



**Figure 6.** Relative electric power and load of the fuel plant for selected months at a fuel plant capacity  $F_{\max} = 1$ , a tank size for peak power  $t_{\text{peak}} = 10$  h, and a wind/PV ratio of 20:80. Minimum tank capacity  $t_{\text{min}} = 1.3$  h.

increase, since not  $f_{\text{min}}$  but almost full load of the plant needs to be considered during the largest power lack to avoid a shutdown leading to a value of  $t_{\text{min}} > 7.7$  h. The total hydrogen tanks size would reach values of days. Tab. 1 provides an illustration of the tank sizes in absolute numbers for a 10-MW(el) plant. For calculating the number of tanks, different considerations could be applied as stated in Sect. 2. Here, a pressurized electrolysis unit is considered to deliver hydrogen up to the maximum tank pressure.

Furthermore, the difference will further increase, when a complete analysis of a plant with off-grid installation would be performed. In this study, the data from Baden-Württemberg was applied, which levels out cloud influences which would occur on a more limited area for, e.g., only power supply by PV.

**Table 1.** Illustration of tank size in plant working hours by a 10-MW(el) plant (overall 50 % efficiency assumed) and number of tanks operating at pressure difference between 30 and 43 bar (rounded up to next integer; electrolysis assumed to operate at 43 bar).

Tank size	H <sub>2</sub> storage [m <sup>3</sup> <sub>(STP)</sub> ]	Number of 100-m <sup>3</sup> tanks [-]
Flexible plant $t_{\text{min}} = 1.3$ h	2166	2
Flexible plant $t_{\text{peak}} = 10$ h	16 661	13
Sum flexible plant = 11.3 h	18 827	15
Stationary plant $t_{\text{min}} = 7.7$ h	12 829	10
Stationary plant $t_{\text{peak}} = 12$ h	19 993	16
Sum stationary plant = 19.7 h	32 822	26

## 4 Conclusion

By applying sun and wind data from Baden-Württemberg and the high feed flexibility from fuel plants equipped with microstructured reactors, a minimum hydrogen buffer size of  $t_{\text{min}} = 1.3$  h could be calculated, which would be required to operate the fuel plant, i.e., the reverse shift and Fischer-Tropsch synthesis, 365 days per year without intermediate shutdown. Additional hydrogen tank capacity can be installed to utilize peak power and to smoothen the operation conditions. These extra tank sizes need to be in the range of 10 h to reach maximum power and fuel plant utilization. Economic evaluation needs to balance between tank costs and utilization. With conventional chemical plants, e.g., equipped with fixed-bed or bubble column reactors, these extra tank size would increase to be above 12 h. Furthermore, the minimum tank size of 1.3 h, which has been calculated for flexibility of a fuel plant

specific for INERATEC's technology, would increase by a factor of  $> 5$  ( $t_{\text{min}} > 7.7$  h) if load flexibility of a conventional plant in the range of days would be present. Assuming a commercial tank pressure of 43 bar (maximum filling pressure) and 100 m<sup>3</sup> inner tank volume, a flexible plant of 10 MW could be operated with only two tanks.

Without grid connection and a less leveled power profile, the advantages of the highly flexible

fuel plant technology over conventional technology become even clearer: a plant capacity of several MW (electricity consumption at full load) might already hinder any application with renewables due to size requirements for intermediate hydrogen storage and its price.

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### Symbols used

$f$	[-]	normalized operating load of the fuel plant
$F_{\max}$	[-]	normalized fuel plant capacity
$f_{\min}$	[-]	normalized minimum operating load which the fuel plant can operate
$P_{\text{el}}$	[W]	available power at time $t$
$P_{\text{rel}}$	[-]	normalized mean available power
$t$	[s]	time
$t_0$	[d]	possible operation time of the plant at $f_{\min}$ without $\text{H}_2$ production
$t_{\min}$	[d]	minimum required tank capacity based on $f = 1$ derived from the longest lack of power while operating at plant at $f_{\min}$
$t_{\text{peak}}$	[d]	additional installed tank capacity for compensation of peak power with the fuel plant operating at $f = 1$
$\eta_{\text{Plant}}$	[-]	fuel plant utilization
$\eta_{\text{Power}}$	[-]	power utilization for production of fuel

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