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Offering water electrolysers' flexibility to European grid service markets

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Abstract

Sustainable production of hydrogen is a key element of the European energy transition agenda, especially for seasonal and mobile energy storage purposes. The technology is about to enter the market, as the economy of the solution has considerably improved over the years. The water electrolyzer (WE) as a key element of such hydrogen production can offer its high operational flexibility for grid services such as frequency control. Servicing those markets as a byproduct, the WE achieves a value that is relevant to bridge the gap towards market parity.

The article reports on best opportunities for European grid service markets to be served by WEs. The results of the research, supplemented by a survey amongst transmission system operators (TSO) and distribution system operators (DSO) conducted in 2017/2018, are summarized. Financial and business logic data is available for 25 European countries incl. Norway and Switzerland. 85 TSO grid services within 12 countries are commercially and technically feasible candidates.

With four such cases a more detailed economic analysis is made for a WE with daily storage capacity. Offering the WE's flexibility to the grid service markets can reduce the levelised cost of hydrogen at the WE outlet (LCOH) by up to 10% under ideal conditions, i.e. at a WE size of 500 kW and more operating at 6000 full load hours (FLH) or more, without sharing the margin between the balancing service provider (BSP) and the WE owner.

Introduction

Aggregation of smaller scale, distributed renewable energy systems for the provision of grid services already is in place in a series of European countries. Others report to adapt their market rules in order to comply with the harmonization effort of the EU [1]. Thereby, opportunities open for water electrolyzers (WEs) to achieve an additional income from the provision of grid services. WEs, as a key element of sustainable hydrogen production, can offer high operational flexibility for grid services such as frequency control. Servicing those markets as a by-product, the WE achieves a value that is relevant to bridge the gap towards market parity. For the European project QualyGridS, the best opportunities for the European grid service markets to be served by WEs have been identified. Data is available for 25 European countries including Norway and Switzerland.

Balancing market survey

Due to a lack of reliable market data in the literature, a survey was conducted. The survey was based on written questionnaires, one specifically for TSOs, and a second one specifically for DSOs. The TSO questionnaire asked about grid service product information and prices for the year 2016. It was sent to 36 TSOs from 30 countries (28 EU countries plus Switzerland and Norway) and a selection of DSOs in winter 2017/2018.The results were cross-checked with available literature, mainly from [2], [3], and [4]. If necessary for clarification of the answers, the respondents of the survey were contacted multiple times during 2018. Results are summarized in Figure 1.

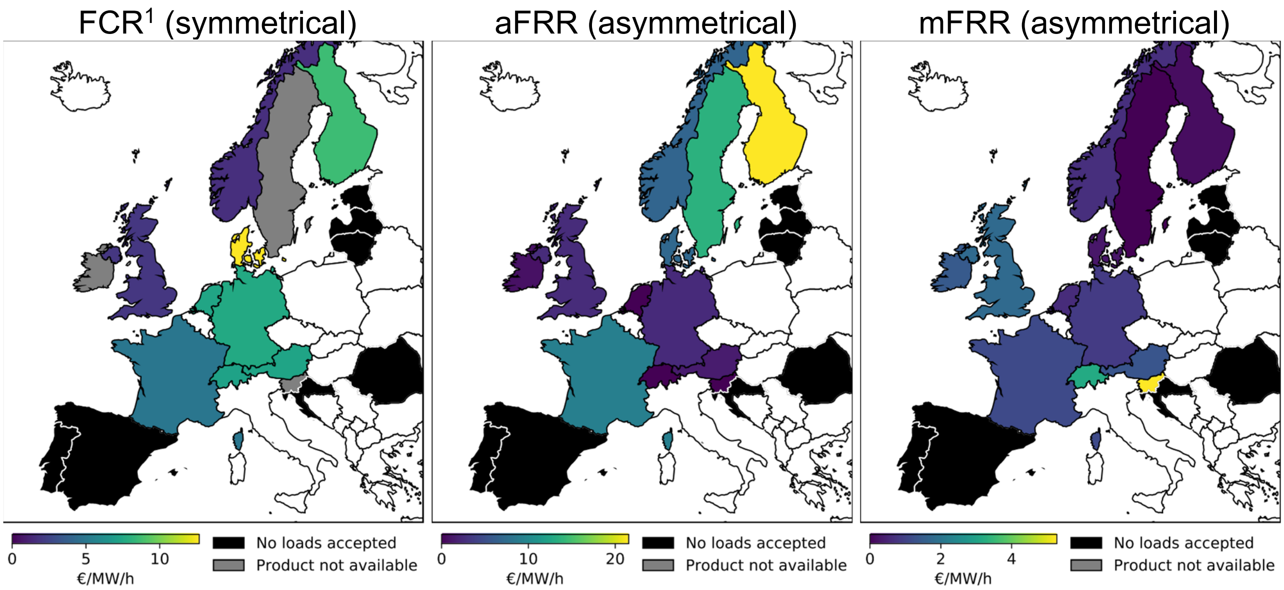

Figure 1: Results of the survey (average availablilty prices of 2016)

Evaluation of the most attractive grid services

Based on the survey results, a few attractive grid services are selected to be evaluated and compared in more detail. Therefore, the levelised cost of hydrogen at the WE outlet (LCOH) is calculated. As a base case, it is assumed that a WE operator buys the required electricity on the day-ahead market. He takes care to keep costs as low as possible and purchases

[1] Where FCR-N and FCR-D were available, FCR refers to FCR-N

electricity in the cheapest hours of the day. The next step is to formulate the influence of various network services on the WE operator's strategy. The aim of this strategy is to minimize electricity cost. This allows for an evaluation of different grid services by examining the difference of the LCOH "grid services" and LCOH "base case" (no grid service).
Today's profitable WE business-cases[2] are characterized by a more or less stable hydrogen production target over the course of a few hours or days even. This restriction is considered in the following evaluation. The calculations for the base-case as well as for all grid service cases are based on historical data of the years 2016 and 2017.

Grid services overview

the following TSO grid service products are analyzed in more detail:
Positive and negative automatic frequency restoration reserve (+/- aFRR) in Germany (asymmetrical): The availability and utilization are paid as bid. If a tenderer[3] gets called for availability, he can, at a next stage, offer utilization. As for 2016 and 2017 there are two weekly products, an off-peak and a peak product [5].
Positive and negative manual frequency restoration reserve (+/- mFRR) in Germany (asymmetrical): The availability and utilization are paid as bid. Again, if a tenderer gets called for availability, he can, at a next stage, offer utilization. The products are characterized by a contract duration of 4 hours [5].
Frequency containment reserve (FCR) in Germany (symmetrical): The availability is paid as bid and traded as a weekly product.
Positive manual frequency restoration reserve (+mFRR) in Norway (asymmetrical): Availability (national name: RKOM) and utilization (national name: RK) are paid-as-cleared. There are two weekly availability products, an off-peak (12 pm – 6 am) and a peak (6 am – 12 pm) product. Furthermore, RKOM is split into RKOM-H and RKOM-B, where RKOM-H is characterized by stricter requirements regarding activation duration and flexibility [6].

Combining selected TSO grid services with WE applications

Today's profitable WE business-cases are characterized by a more or less stable hydrogen demand over the course of a few hours or days. Such cases could be identified in the application categories "industry with limited constant demand of hydrogen" and "distributed hydrogen fueling stations". [2] Hence, it can be assumed that the WE's flexibility is restricted with regard to daily production targets of hydrogen.
The impact of the grid service business for these two application categories is evaluated by considering the following cases:

- a base case in which the WE is operated without participation in the grid service business,
- offering asymmetric power reserve products (aFRR, mFRR) and
- offering a symmetric FCR product.

Changes in CAPEX and WE efficiency due to part- and over load resulting from the grid services are neglected. Further CAPEX/OPEX assumptions are depicted in Table 1. The calculations for the base-case as well as all grid service cases are based on historical data of the years 2016 and 2017. The following sections detail the conditions under which the respective calculations are based. Thereby asymmetric and symmetric products are considered separately, since the conditions under which a WE can provide these differ significantly.

[2] Other application categories such as "industry with high demand of hydrogen" and "power to gas connected to the natural gas grid" turn out to be unprofitable.

[3] A tenderer in this context refers to a Balancing Service Provider (BSP) that tenders grid service products to a TSO.

Operation strategy without power reserve products (base case)

In the base case scenario, the WE operator is assumed to minimize the electricity cost without making use of the option to offer grid service products. The operator is assumed to follow a daily production target. The lowest electricity costs are achieved when the WE operates at nominal power during the hours with the lowest electricity prices. It is further assumed that the WE operator purchases electricity at the day-ahead-spot-market.

In order to calculate the electricity costs, historical hourly day-ahead-prices of the years 2016 and 2017 are used. These prices are available at EPEX SPOT SE [7] and Nord Pool AS [8] for Germany and Norway, respectively. In Norway's case, different bidding zones exist. In order to further minimize the electricity costs, it is assumed that the WE is located within the bidding zone with the lowest average price, which is NO 4 (Tromsø). The average price in this region in 2016 and 2017 was 25.39 €/MWh, whereas the average price in Germany with 31.58 €/MWh was about 6 €/MWh higher.

Operation strategy with asymmetric power reserve products (aFRR, mFRR)

The base case as described above is now extended by offering the WE's flexibility as asymmetric power reserve to the BSP. It is assumed that the BSP accepts quarter-hourly offers for aFRR as well as mFRR , and the WE operator offers positive power reserve products during operation (i.e. the WE reduces its power) and negative power reserve products during the stand-by time (i.e. the WE increases its power). The stand-by power consumption is neglected in this analysis. The impact of these grid service products on the electricity cost and the operation time is shown in Figure 2. The figure shows the sorted day-ahead prices of one day (in ascending order). The red hatched area represents the base case for which the WE does not profit from reduced energy costs due to the compensation for its availability and utilization offerings.

Positive power reserve products are offered for the hours scheduled for operating at nominal power. For those hours, the availability price ($P_{Availability}$) is interpreted as a reduction to the electricity cost. When positive reserve is called ('utilization of control reserve'), the costs are further decreased by a utilization compensation. However, the positive utilization reduces the operational time and as a result, lowers the hydrogen production accordingly. The actual net cost for electricity corresponds to the blue hatched area in Figure 2.

The negative products affect the net cost analogous to the positive products. However, a BSP, and therefore the WE operator too, usually pay the TSO for negative utilization. [4] As a result, the WE operator pays for the called utilization on the one hand, but increases the hydrogen production on the other hand.

The requirements imposed on WEs participating in these grid service markets, such as the minimum contract duration as well as the minimum power, are lowered by the BSP aggregating WEs in a virtual power plant (VPP). Hence, it is assumed that whenever the WE runs, it offers its nominal capacity for mFRR positive. In the high price hours however, when the WE is not operating, mFRR negative is offered at nominal power. In order to estimate the influence of utilization, German average utilization prices paid by the TSO as well as average utilization amounts (duration and frequency) are assumed. It is important to keep in mind that the amount of utilization varies depending on the bidding strategy, which in turn has an impact on the business case. However, the effect on the business case is expected to be minor since a higher utilization comes with lower revenues per MWh utilization (due to the merit-order principle of the pay as bid mechanism) and is therefore neglected.

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[4] I.e. the BSP and with that the WE operator pay for the energy consumed. However, the price typically is lower than the regular market price, which makes the case commercially attractive.

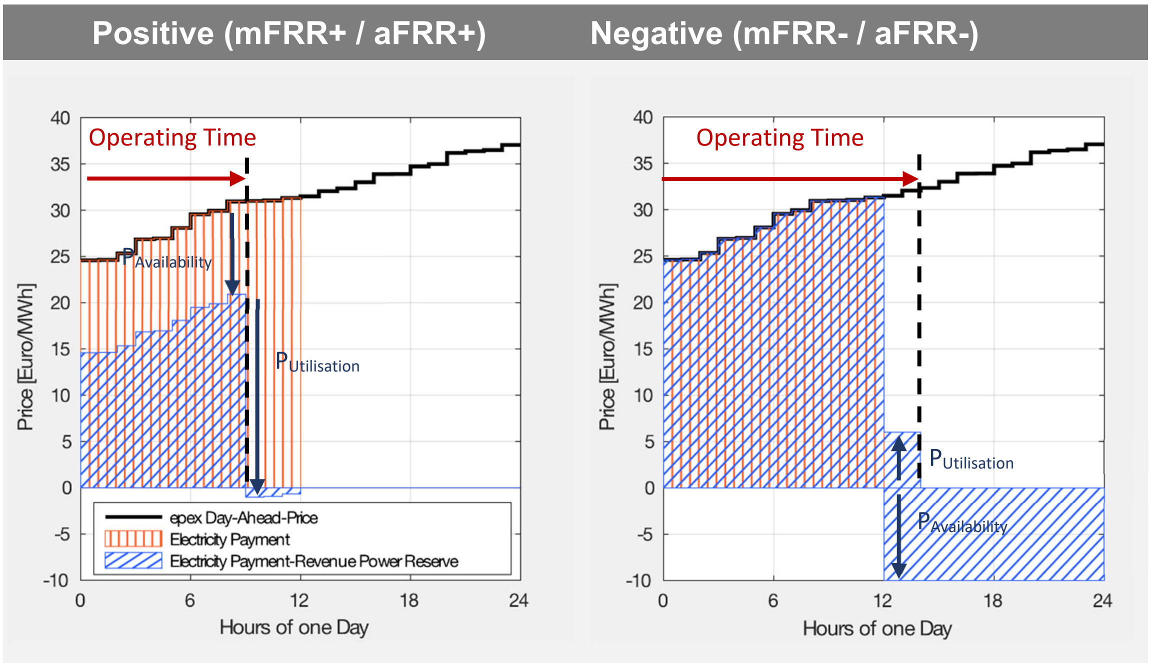

Figure 2: The effect of the asymmetric power reserve product on the business case (example of a nominal 12 hours operation schedule per day)

The impact of these power reserve products on the electricity cost is computed with historical ¼ - hourly values of 2016 and 2017. Regarding Germany, the relevant data is available from the Bundesnetzagentur [9]. The availability prices used for the analysis were derived from the published German average prices for availability in a given time-slot as €/MW/h.[5] In regard to utilization, these average values are used for the utilization price as well as for the amount. By dividing the total utilization (MWh/15min) by the total reserved capacity (MW) for each 15-minute slot, a relative utilization amount per 15-minute slot is derived. By knowing the reserved WE capacity and the relative utilization amount, the absolute average utilization of the WE can be estimated for every 15-minute slot.

Turning to Norway, mFRR is called Tertiærreserver. In the Nordic power supply system, the mFRR utilization is published by Nordpool, a common market place for energy trades. Nordpool refers to it as Regulating Power, while within the Norwegian TSO Statnett it's called Regulerkraftmarkedet (RK). As for availability (Regulerkraftopsjonsmarkedet, RKOM), data is published by Statnett [10]. Again, data for the period 2016, 2017 is being used. Please note that the time-series consists of weekly contracts only. Hence, seasonal contracts are neglected. Furthermore, the price for the negative availability is assumed to be zero. This is due to the fact that positive availability is traded only. In order to convert the availability prices to Euro, the official daily exchange rate time series from Nordpool is used [8]. As for utilization, a common market exists among all Nordpool zones [10]. Hence, the average utility price per ¼ hour is calculated by dividing the sum of all zones of the regulating bids volume by the sum of regulating volumes for each hour.

The value a WE provides to a BSP depends not only on speed, reliability and power, but also on the time of day or time of week at which the WE operator is willing to offer its services. This can be understood based on the following considerations:

mFRR (Germany) and aFRR (Germany) / mFRR (Norway) are traded as daily 4-hour and weekly off-peak/peak products, respectively. For any further analysis, and to make the cases comparable, it is assumed that the product delivery period is split into 15-minute slots by the aggregator, and that there is no minimal requirement regarding contracted power. The difference in the contract duration between the actual products and the assumed 15-minute

[5] Price in € per MW and hour of availability.

duration plays a role when it comes to assessing the value of WEs providing these products. This is due to the fact that the day-ahead prices affect the tenderer's willingness to offer power reserve products [11]. The operator of a flexible power-plant, for example a storage hydro power plant or a gas power plant, usually plans its schedule to maximize its profit. Hence, the higher the day-ahead prices, the more attractive it gets to produce and sell electricity. As a result, the operator offers negative power reserve products for the time slots with high day-ahead prices (when the turbines run) and positive products for the slots with low prices. The willingness to offer negative power reserve during low price hours usually is low and therefore characterized by high offering prices and vice versa. Usually, weekend day-ahead energy prices are lower, due to a decreased demand of electricity.

However, aFRR and mFRR (Norway) are weekly products. Hence, a BSP gets compensated for a whole week (either for peak or off-peak hours) with one price. If a power plant operator offers a weekly product, let's assume aFRR negative, he commits to let the turbines run even during the unfavorable weekend hours. On the other hand, when evaluating the value of reserve offerings over shorter durations, in our case ¼ hours, the correlation between energy and flexibility prices should be considered.

For reasons of data availability, the effect of the contract duration on the value of power-reserve is estimated based on data from Germany. This is done by estimating the German mFRR (4-hour products) prices as if mFRR (Germany) had been traded as weekly products, assuming the effect is similar for mFRR and aFRR in Germany as well as in Norway:

The historical availability prices of mFRR (Germany) are aggregated over the same hours where aFRR products were traded. As there are two weekly products in Germany, this is done by calculating two average mFRR (Germany) availability prices for each week, a peak and an off-peak price. The impact on LCOH is then calculated for this synthetically aggregated mFRR (Germany) time-series as well as for the historical time-series with the 4-hour products. By comparing the relative savings on LCOH, we now are able to estimate the impact of this aggregation. By assuming that the impact was similar for Germany and Norway as well as for aFRR and mFRR, we can now calculate the reduction on relative LCOH savings on aFRR and mFRR (Norway) due to splitting the weekly product into 4-hour products and derive a more realistic result.

It is worth mentioning that we assume contract durations of 15 minutes, and therefore we are likely to still overestimate the revenues due to mFRR as well as aFRR. However, since there is no historical data available for neither mFRR nor aFRR with contract durations for less than 4 hours, this effect cannot easily be quantified.

Operation strategy with symmetrical power reserve product (FCR)

As next, the base case as described above is extended by offering the WE's flexibility as FCR, which is a symmetric power reserve product. In order to evaluate the economic potential of the symmetrical FCR product, the full capacity of the WE can be used for the provision of FCR. In that case, as the WE operator has to guarantee the symmetrical power reserve, the WE can maximally operate at half of its maximum power, which then is considered its nominal power.

Offering FCR not only is generating an additional revenue, but also yielding opportunity costs. These opportunity costs are caused by the fact that the WE has to operate on part-load while selling the symmetrical grid service product. As a result, the WE gives up the opportunity to produce hydrogen at maximum power during the best day-ahead price hours. This reduction needs to be compensated by operating at more expensive hours[6] that originally were not scheduled for operation.

[6] Operating at 50% of nominal power.

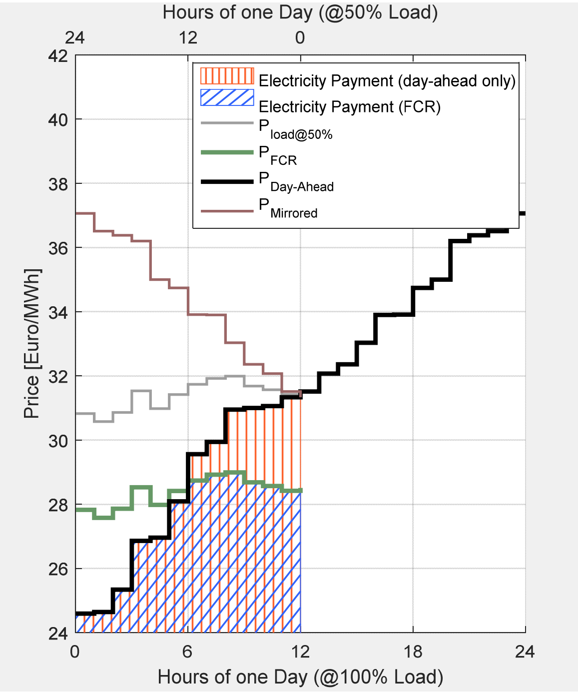

Figure 3: The effect of the symmetric power reserve product FCR (example of a 12 hours operation schedule per day at nominal power)

With this mechanism in mind, a procedure is derived in order to identify the hours, in which an FCR offering is advantageous while operating the WE on part-load. This procedure as well as the impact on the cost of electricity is depicted in Figure 3. The figure again shows the sorted day-ahead prices of one day (in ascending order). As an example, if the WE operator intends to offer FCR for 2 hours a day, the two hours during which FCR is most advantageous consist of the hour with the highest day-ahead-price that was at the same time scheduled for operation in the base-case (not offering GS) and the hour with the lowest price that was originally not scheduled for operation. In the example of Figure 3, these hours would be hour 11-12 and hour 12-13. This is due to the fact that the difference between the average day ahead price during these two hours (50% load) and the day ahead price for hour 11-12 (100% load) is the lowest possible difference, and therefore causes the minimal opportunity cost. To operate at 50% load during the two hours 11-13, the cost for electricity equals to the average price of these two hours multiplied by the two hours of 50%-load:

$$P_{load@50\%}(t) = \left(P_{Mirrored}(t) + P_{Day\ Ahead}(t)\right)/2$$

These costs $P_{load@50\%}$ are represented by the grey line in Figure 3 (electricity price if the load is operated at 50% and the missing production must be made up at a time with the next cheapest energy price). The opportunity-costs can now be derived by looking at the difference between the grey line and the bold black line (day-ahead price). As can be seen, for the example of a 12 hours base operation schedule with 2 hours of FCR offering,[7] the lowest opportunity costs are found in hour 11-12 and increase towards the left side. I.e. the more FCR hours are to be offered, the higher the opportunity costs are. If we now subtract the revenue of FCR-availability, the actual electricity price (green line) of offering FCR is obtained. Lower values of the green line, as compared to the day-ahead-curve, imply that an FCR offering is advantageous. In the example of Figure 3, with an FCR availability compensation of 3 €/MW/h, this is the case if the day-ahead-price is in the range from 29 to 34 €/MWh. If the day-ahead-price is lower than 29 €/MWh, the opportunity costs are too high and it is more advantageous to operate the WE at nominal power instead of offering FCR. The cost reduction due to FCR is reflected by the difference between the red and the blue area in Figure 3.

Deriving the levelised cost of hydrogen

Deriving the LCOH produced by a WE in Germany, no EEG surcharge is considered. The costs for water are assumed to be 0.03 € per kg hydrogen [12]. Further assumptions for the Alkaline as well as PEM WEs are based on [13] and depicted in Table 1.

[7] In this example 12 hours means operation as base case, i.e. operation without FCR. Offering FCR for 2 hours in fact extends the effective operation time to 13 hours: 11 hours at P_{nom} plus 2 hours at $P_{nom}/2$. The number of hours in which the WE operates at 50% load and offers FCR is indicated in the upper x-axis.

	ALK	PEM
Nominal Power	1MW	
Maximal Power	1MW	
Maximal Power (Positive Sensitivity)	1MW	2MW
Power Consumption	58 kWh$_e$/kg	63 kWh$_e$/kg
Lifetime - System	20 Years	
Stack - Lifetime	80'000 h	40'000 h
Degradation	not considered	
CAPEX - System	1'200€/kW	1'500€/kW
CAPEX - Stack replacement	420 €/kW	525 €/kW
OPEX	4%/CAPEX	
Weighted average cost of capital (WACC)	8%	

Table 1: Assumptions

The costs for electricity are calculated according to the assumptions and methodology described above and implemented in a discounted cash flow model. In order to avoid unrealistic price jumps between different full load hour (FLH) scenarios, stack-replacement costs are calculated as annuity costs.[8] Based on the annuity payment equation and the present value of constant perpetuity, the annual payment due to stack replacement of a fictional WE with infinite operation years can be calculated as:

$$PV = \frac{S_c}{r} \qquad \textit{Eq. 1} \quad [14]$$

$$PV = \frac{S_c}{(1+WACC)^k - 1} \qquad \textit{Eq. 2}$$

$$\text{Where: } k = \frac{S_r}{flh} \qquad \textit{Eq.3}$$

$$Annuity\ Payment = PV \cdot \frac{WACC}{1-(1+WACC)^{-n}} \qquad \textit{Eq. 4} \quad [15]$$

$$if\ n \to \infty$$

$$Annuity\ Payment = PV \cdot WACC \qquad \textit{Eq. 5}$$

$$Annuity\ Payment = \frac{S_c}{(1+WACC)^{\frac{S_r}{flh}} - 1} \cdot WACC \qquad \textit{Eq. 6}$$

k	=replacement period in years
$WACC$	=Weighted Average Cost of Capital
r	=interest of stack replacement period
PV	=Present value of stack replacements over n years (Euro)
S_c	=Stack replacement costs (Euro)
S_r	=Replacement rate (hours)
flh	=Full-Load-Hours a year (hours)
n	=years of annuity

In order to evaluate the impact of grid services, the LCOH is calculated.[9] By forming the difference of the LCOH derived from the base-case (optimal scheduling without grid services) and cases with grid services, the cost reduction due to the grid services can be expressed as savings on LCOH, where LCOH is defined by:

$$LCOH = \frac{\sum_{t=0}^{n} \frac{C_t}{(1+WACC)^t}}{\sum_{t=0}^{n} \frac{H_t}{(1+WACC)^t}} \qquad \textit{Eq. 7} \quad [15]$$

[8] This corresponds to the amount the WE-operator has to spend every year in order to keep the stack in new-like-condition.

[9] Only the cost in Table 1 were considered and any other costs for the storage and its ancillary (compressor and so on) are neglected.

$WACC$ =Weighted Average Cost of Capital
C_t =Costs in year t (Euro)
H_t =Hydrogen production in year t

Results

By implementing the procedures and model assumptions defined above and testing them on the historical data for 2016 and 2017, it is possible to derive the costs of hydrogen production depending on different setups. The influence of different grid services can best be examined by looking at the LCOH savings shown in Figure 4.

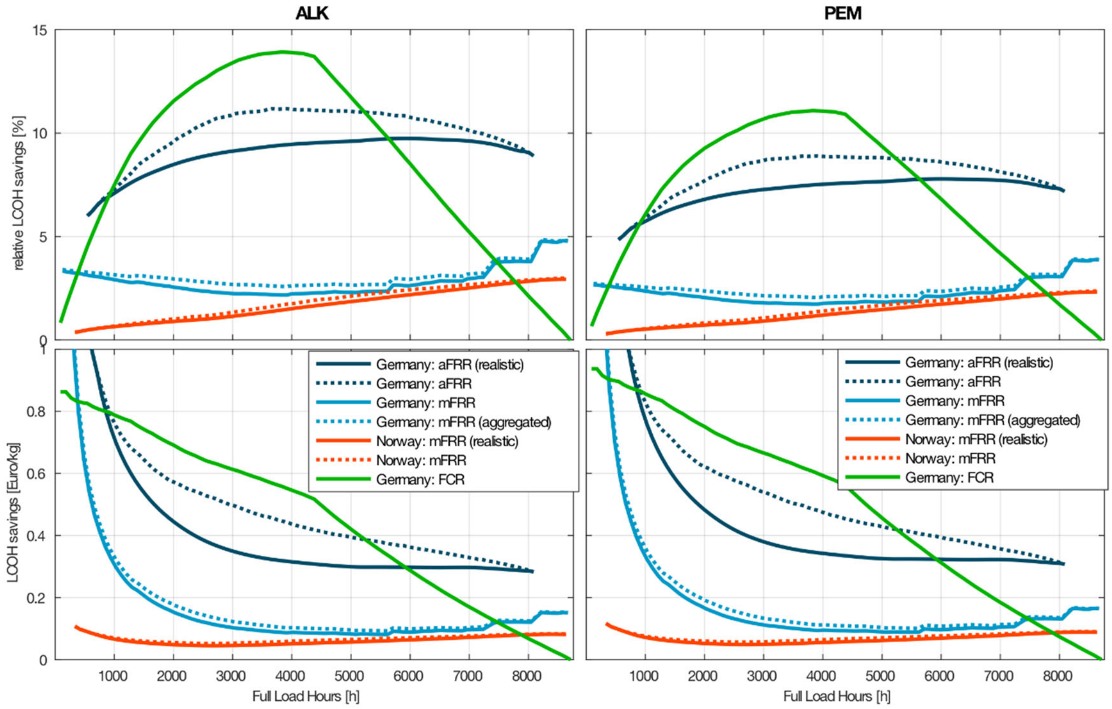

Figure 4: Relative LCOH-savings (upper) and absolute LCOH-savings (lower) due to grid services for ALK-WE (left) and PEM-WE (right). The cases "realistic" refer to the synthetically calculated 4-hour contracts, which consider the effect of contract duration on the value of GS, as explained in section Operation strategy with asymmetric power reserve products (aFRR, mFRR). Full load hours are to be understood as annual full load hours, where it's assumed they are equally mapped to daily full load hours.

Looking at the absolute FCR savings in Germany, the highest impact is found at low FLH scenarios (for the lowest FLH scenario 0.94 €/kg (PEM) and 0.86 €/kg (ALK)). As the operating hours increase, this value decreases steadily and reaches 0.56 (PEM) and 0.52 (ALK) €/kg at the 4380 FLH scenario. This decrease is caused by the opportunity costs of not having the possibility to concentrate the production during the lowest price hours. If the FLH are further increased, the number of hours available for part load (50% of nominal power) declines and restricts therefore the revenues of FCR even more. As a result, an even steeper decrease can be observed for FLH higher than 4380.
More constant relative savings over all possible FLH scenarios can be observed for aFRR and mFRR in Germany. Over all FLH, the average savings are with 7.2% (PEM) and 9.0% (ALK) substantially higher for aFRR than for mFRR (Germany) with 2.3% (PEM) and 2.8% (ALK).
Due to the inexistence of a negative mFRR availability market in Norway, the relative savings of mFRR (Norway) steadily increase from almost zero for low FLH scenarios to 2.4% and 2.7% for PEM and ALK-WE for high FLH, respectively.

As can be seen for PEM as well as for ALK WEs, the least promising grid services are mFRR (Germany) and mFRR (Norway). At less than 1000 FLH, aFRR shows the highest saving potentials with about 7% and 5% of savings on LCOH for ALK and PEM WEs, respectively. Above 1000 FLH, FCR influences the LCOH even more and reaches relative savings of 13% and 11% on LCOH for 4380 FLH. Between 5700 and 8760 FLH aFRR is the dominant grid service product in terms of saving potential.

Conclusion

Providing services to the grid service markets, WE operators can reduce their LCOH in many European markets. Detailed calculations show that especially German aFRR and FCR are suitable products with which WEs can reduce production costs considerably. It is worth mentioning here, that many effects, which limit savings from grid services, could not be considered at this stage of the analysis. These effects include the costs of additional storage facilities and lower availability revenues due to the temporal splitting of availability contracts (4-hour contracts have to be split into 15-min contracts). Furthermore, the WE operator has to offer grid service products through an aggregator who has to be compensated for its services, too. Hence, the results show an optimistic picture and should only be used to compare the grid service products relative to each other.

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