DynEl Report

Revenue opportunities for solid oxide electrolysis cell systems selling up-regulation on primary reserve markets

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Introduction

Electricity is traded on day-ahead market and intra-day markets[1]. Like ordinary markets, the market price is where supply and demand volumes meet each other. Based on incoming bids and the forecasted demand, the market price is found by the transmission system operator (TSO). In Denmark the TSO is Energinet.

Electrolysis can in principle be used for electricity arbitrage on the day-ahead and intra-day markets since electrolysis can convert e.g. H_2O to H_2 which can be stored and later converted back to electricity. However, the conversion efficiency is rather low and less than 50% round-trip-efficiency should be expected. For this reason, the capacity factor (i.e. the fraction of activated hours where the electrolysis system is operated) will be very low. In principle, the solid oxide cell technology can be used to make systems reaching 80% round-trip efficiency (1). This could potentially make electricity arbitrage profitable (2). This is however a long-term market due to rather limited profits and the requirements for multi-MW systems with advanced features such as internal methane formation in the cells. Therefore electricity arbitrage on the day-ahead and intra-day markets are not considered profitable in a nearby future.

The increasing electricity production from wind and solar power increases the requirement for services that can mitigate unforeseen imbalances between the production and the consumption. Such services can generate substantial revenues to the service provider. Dynamically operated electrolysis systems can simultainously produce H_2 while providing the mentioned services. Compared to Alkaline Electrolysis Cells (AEC), and Proton Exchange Membrane Electrolysis Cells (PEMEC), SOEC cells are noted to have superior dynamic capabilities (3). The presented analysis focus on the quantifying the revenue from dynamically operated SOECs selling regulation capacity to the reserve markets.

Stabilization of the Danish Electricity grid

As mentioned, the increasing electricity production from wind and solar power increases the requirement for services that can mitigate unforeseen imbalances between the production and the consumption.
Ancillary services are services required by the TSO or distribution system operator (DSO) to maintain the integrity and stability of the transmission or distribution system as well as the power quality. Some of the anclillary services are traded on electricity markets like Nord Pool. Other ancillary services such as short-circuit power, inertia, reactive reserves and voltage control are not traded on a market. Energinet may instead choose to advertise the procurement of these services at different notices and durations. Since these services are not regularly traded we will not analyze the potential revenue from these services.

[1] In the modern electricity market trading is possible several years ahead physical delivery (also with the use of purely financial deals) and can continue until one day before delivery. Competitive and liquid forward electricity markets are essential for market participants (equally, producers as well as consumers) to hedge their short-term (e.g. day-ahead) price risks and uncertainties.

The services traded on Nord Pool are segmented into various reserve markets with different response time and size. Fast responses within a few seconds are provided by the primary reserves. In Jutland and Fyn (the DK1 area) this is provided by the FCR market. In Sjælland (DK2) this is provided by the FCR-N market. If an unforeseen imbalance between production and consumption exceed size of the primary reserves, the larger secondary reserves can provide the required regulation capacity to reestablish the balance. In DK1 the secondary reserves is traded on the aFRR market and in DK2 on the FCR-D market. Even larger imbalances are handled by the manual reserves. The manual (or tertiary) reserves are traded on the mFRR markets.
In general, if the production cannot meet the consumption, the frequency drops below 50 Hz. Figure 1 and Figure 2 provides a schematic overview of the activation of the DK1 and DK2 markets in case of a frequency dip.

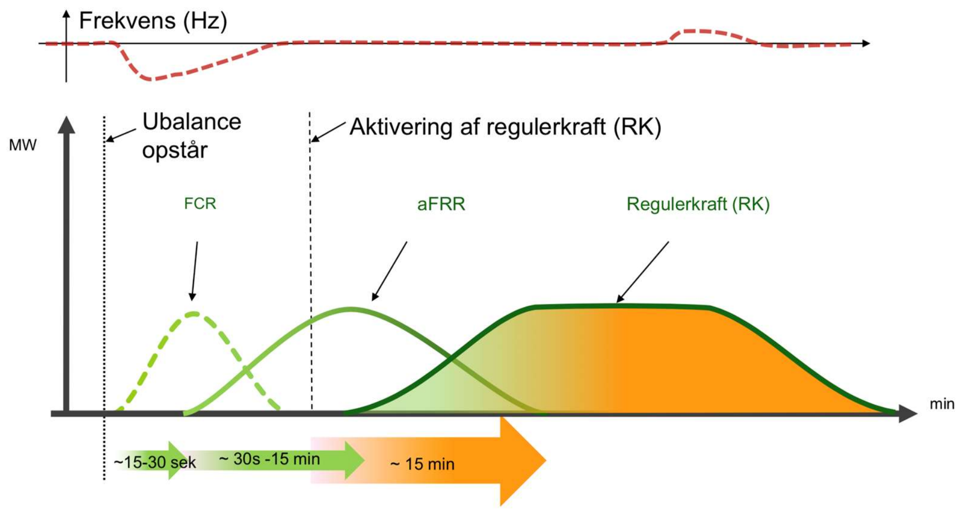


Figure 1. Activation of the various markets in DK1 to reestablish balance between electricity production and consumption. Illustration from Energinet.

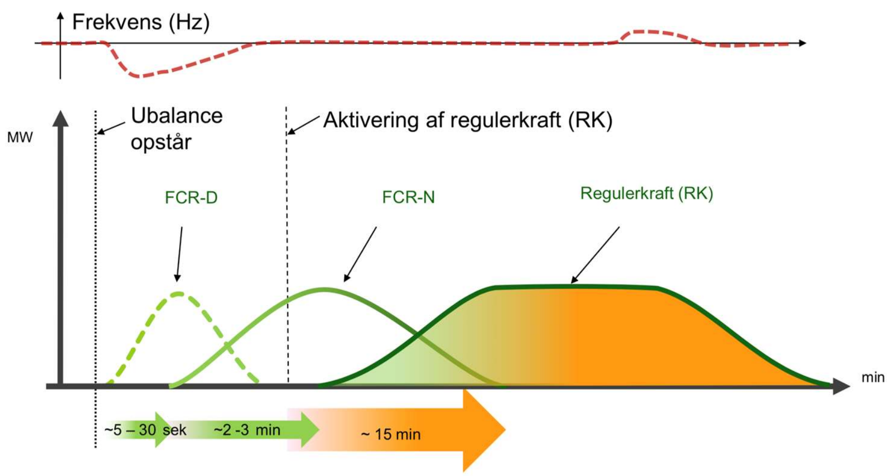


Figure 2. Activation of the various markets in DK2 to reestablish balance between electricity production and consumption. Illustration from Energinet.

Overview of the Technical Requirements for the Danish Reserve Markets

An overview of the technical requirements for the ancillary services traded on Nord Pool is shown in Table 1. The ancillary service markets are the FCR-N and FCR, FCR-D, aFRR and mFRR. The minimum bid size varies from 0.3 to 5 MW. The FCR markets has a narrow frequency range around 50 Hz and a relatively short required response time of a few seconds. The required duration varies from 15 minutes to continuous operation. Besides the symmetric FCR-N market, the markets are separated in up- and down-regulation markets.

Table 1. Overview of the technical requirements for traded ancillary services in Denmark

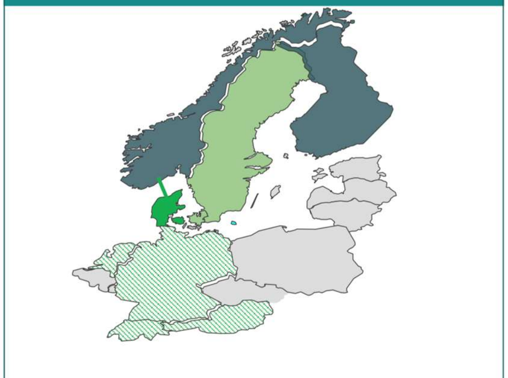
Market	Region	Minimum bid size (MW)	Frequency range	Required response time	Required duration (hours)
Frequency Containment Reserve (FCR)	DK1	0,3	± 200 mHz. Deadband: ±20 mHz	50% in 15 sec, the remaining within 30 sec	0,25
Frequency Containment Reserve for Normal operation (FCR-N)	DK2	0,3	± 100 mHz. Deadband: none	150 seconds	1
Frequency Containment Reserve for Disturbances (FCR-D)	DK2	0,3	± 500 mHz. Deadband: ± 100 mHz	50% in 5 sec, the remaining within 25 sec	1
automatic Frequency Restoration Reserve (aFRR)	DK1	1	n.a.	15 minutes	Continunous
Manual Frequency Restoration Reserve (mFRR)	DK1	5	n.a.	15 minutes	Continunous

Harmonization Plans and Market Sizes

Over the coming years Energinet will be changing the primary reserve markets for DK1 and DK2. From 2019 and onwards Energinet are working on FCR (DK1) to become a part of a common market together with Germany and FCR-D (SK2) and FCR-N (DK2) to become a common market with Sweden as illustrated in Figure 3. The harmonization of the FCR market is expected to bring about symmetric bids and a required duration of 1 hour.

In 2018 the market size of the FCR market was 13 MW with an average price of 209 kr / MW h. In 2020 the market size will be 22-23 MW and in from 2021 the market size will be 180 MW including the German market.

Hurtig frekvens regulering (FCR)



Markeds setup	Forventet udvikling
DK1 dagsmarked	~2019 Fælles europæisk indkøb
SE-DK2 dagsmarked (FCR-N/FCR-D)	>2020 Fælles nordisk marked

Figure 3. Forthcoming changes on the primary reserve markets. Illustration from Energinet.

Produkt	Indkøbt i antal timer	Gns. Mængde (MW)	Gns. Pris (kr/MW/h)
mFRR (DK1)	8760	290	7
mFRR, erstatning (DK2)	610	105	627
mFRR 5 årig aftale (DK2)	8760	638	310
aFRR (DK1)	692	97	551
FCR – op (DK1)	8760	13	209
FCR – ned (DK1)	8760	13	11
FCR-N (DK2)	8760	-	274
FCR-D (DK2)	8760	-	128
Spec.nedregulering (DK1)	1964	567	-70

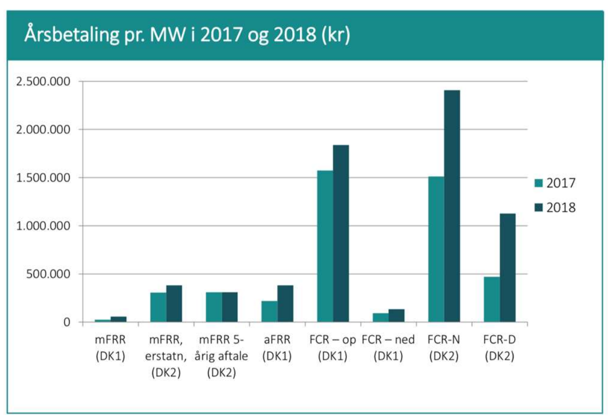


Figure 4. Current market sizes for balancing markets in Denmark for 2018. Illustration from Energinet.

Potential Revenues for Service Providers

Figure 4 shows the average price the Transmission system operator (TSO) pays for the balancing services. The average price is higher than the average revenue that service provides can obtain. This is in part because the TSOs are free to choose the service provider on market conditions. In other words, the service provider will not always be able to sell the service, in particular if the provider demands a too high price for the service.

The figure shows that the primary reserve markets as well as the FCR-D market has substantially higher prices than the secondary (except for FCR-D) and the tertiary reserve markets. For this reason the analysis of the possible obtainable revenue focus on the FCR, FCR-N and FCR-D markets. The primary reserve markets are relatively small compared to the secondary and tertiary markets. Therefore the primary reserve markets can serve as a step-stone for upscaling and maturing the electrolysis technology.

Technical Description for the FCR, FCR-N and FCR-D services

Ancillary service conditions in the DK1 and DK2 regions are described in the document "Ancillary services to be delivered in Denmark. Tender conditions", which can be downloaded at Energinet.dk. The description of the individual services below provides a brief summary of each service.

Payment for grid services

Energinet Elsystemansvar A/S procures ancillary services in order to ensure effective balancing of the electricity system. Today, all reserve products and balancing services are provided via a balance responsible party (BRP). This means that all suppliers of reserves products or balancing services (balancing service provider - BSP) must sign a contract with a BRP to provide services in and to the market.
A contract with the BRP, NEAS Energy, cost approximately 3000DKK/month for the BSP.
A contract with the BRP, Energi Danmark, do not have a fixed monthly fee, and different payment and trading setups can be made with Energi Danmark.
Recently Energinet.dk made a call for tenders for pilot projects for the FCR/FCR-D without contract with a balance responsible party. The tender deadline was 1st of January 2019 and requires a test period starting from 1st of march 2019.

FCR-N (DK2)

The frequency controlled regulation - normal reserve (FCR-N) regulation is provided in the East Denmark (DK2) region. In 2017, the average requirement was +/- 23 MW.

Technical conditions:

Figure 3 shows the droop characteristics for the FCR-N market. The control system must support a deviation of up to ± 100 mHz relative to system frequency of 50 Hz. The regulation does not permit a deadband. During upward regulation, Power (-Pbid) is delivered for frequency deviation between 49.9 – 50 Hz. During downward regulation, Power (Pbid) is absorbed for frequency deviation between 50 – 50.1 Hz. For frequency above 50.1 Hz and below 49.9 Hz, the maximum contracted power is absorbed or delivered respectively.

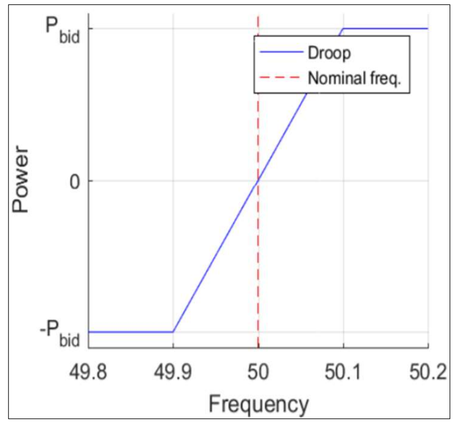


Figure 5. FNR droop characteristics

The reserve must as a minimum be supplied linearly at frequency deviations of between 0 and 100 mHz. The activated reserve must be supplied within 150 seconds, regardless of the size of the deviation, and it must be possible to maintain regulation continuously. In case of incidents, which mean that the reserve system cannot supply frequency-controlled normal operation reserve, the reserve must be re-established within 30 minutes.

Market conditions:
In order to participate in the market, a minimum bid of 0.3 MW is required. The bids must state an hour-by-hour volume and a price for the day of operation. The volume stated is the number of MWs that the bidder is offering to make available. If the player uses block bids, the volume must be the same within each block. The bids can be submitted 2 days before the operation (D-2) and one day before operation (D-1). All accepted bids for frequency-controlled normal operation reserves receive an availability payment corresponding to the player's bidding price (pay-as-bid).

Market analysis:
The market analysis is based on historical data from the FCR-N market from 2018. The income is calculated as the probability based on the historical data set of winning the bid, times the bid price, i.e. it reflects the performance of an average bidder. A low bid gives a high chance of winning but a low income on the pay-as-bid market. A high bid yields a low change of winning but a high income. The optimum bid is the bid price that yields the highest income. The bids are separated into 24 1-hour segments. Using a fixed bid of e.g. 200 DKK/MW throughout the day yields an average income around 77 DKK/MW. The maximum income for a fixed bid strategy is an average hourly income around 90 DKK/MW at a fixed bid around 140 DKK/MW.

The optimum bid (hour-by-hour) and maximum income for the optimum bid are shown in Figure 6 and the Income vs bid for each hour-segment for FCR-N is shown in Figure 7. An average hourly income of 107 DKK/MW can be obtained from this market using the hourly optimum bid.

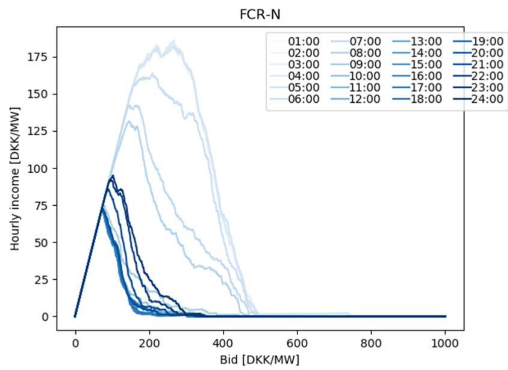


Figure 6. Optimum bid (hour-by-hour) and maximum income for the optimum bid.

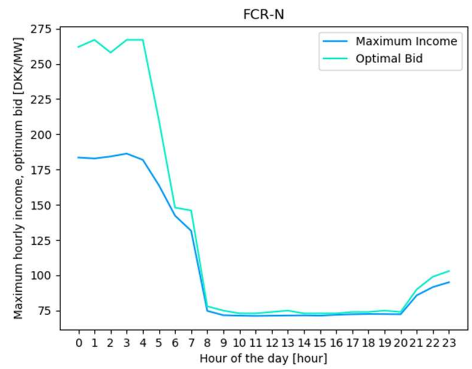


Figure 7. Income vs bid for each hour-segment for FCR-N.

Operation activity:
The operation activity on the FCR-N market is relatively high due to the lack of a dead band. The frequency resolved energy content per MW is shown in Figure 8 below. The total hourly energy content is the sum of the negative and positive energy content which was 364 kWh / MW h in March 2017. The energy content varies from hour to hour, but is not readily available at the Energinet.dk webpage. For the optimal income, the activation probability is 69%. Table 2 shows the analysis results for the FCR-N market.

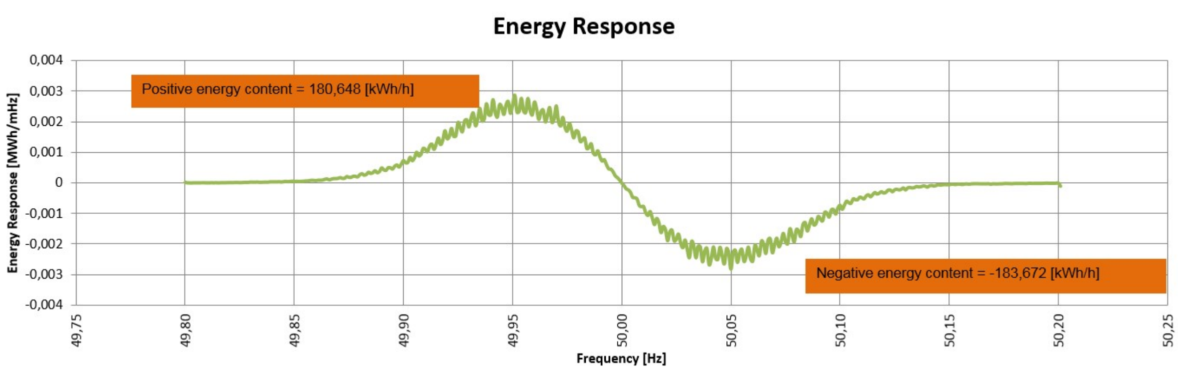


Figure 8. Frequency resolved energy on the FCR-N market in March 2017 for 1 MW capacity.

Table 2. Analysis results for modelling the FCR-N market

Frequency market parameters – FCR-N		
Name	Variable	Value
Energy charge	E_{Ch}	181 kWh / MW h
Energy discharge	E_{Disch}	184 kWh / MW h
Income with optimal bid	I_{FCR-N}	107 DKK / MW h
Bid probability	P_F	69%

Frequency Containment Reserve for Disturbances FCR-D – DK2

The frequency controlled disturbance reserve (FCR-D) regulation is provided in the East Denmark (DK2) region. In 2017, the average requirement was +/- 150-180 MW.

Technical conditions:

For major system disturbances, frequency controlled disturbance reserve (FCR-D) is used to provide system stability. FCR-D is only provided as an upward regulation. Figure 4 shows the droop characteristics for FCR-D.

The activated reserve should supply for the frequency deviation between 49.5 – 49.9 Hz.

The negative power shown in the figure is the power delivered to the grid when the frequency fluctuates between 49.4 – 49.9 Hz.

The response time for the control system prescribed is that the first 50% of the response should be supplied in 5 seconds and the remaining 50% of the response within 25 seconds. In case of incidents where the plant is not able to supply the contracted reserve, the plant must re-establish within 30 minutes.

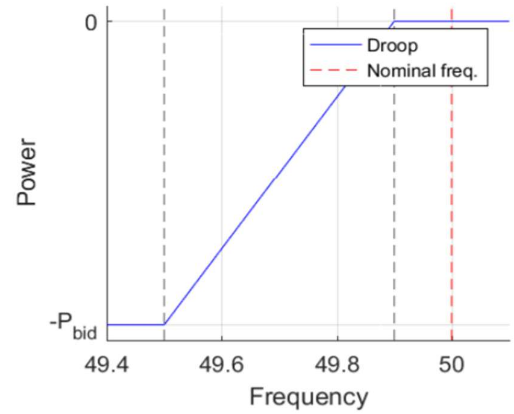


Figure 9. Droop characteristics for FDR

Market conditions:

In order to participate in the market, a minimum bid of 0.3 MW is required. The bids must state an hour-by-hour volume and a price for the day of operation. The volume stated is the number of MWs that the bidder is offering to make available. If the player uses block bids, the volume must be the same within each block. The bids can be submitted 2 days before the operation (D-2) and one day before operation (D-1). All accepted bids for frequency-controlled normal operation reserves receive an availability payment corresponding to the player's bidding price (pay-as-bid).

Market analysis:

The market analysis is based on historical data from the FCR-D market from 2018. An average hourly income around 40 DKK/MW can be obtained from the FCR-D market using the hourly optimum bid. The income is calculated as the probability based on the historical data set of winning the bid, times the bid price, i.e. it reflects the performance of an average bidder. A low bid gives a high chance of winning but a low income on the pay-as-bid market. A high bid yields a low change of winning but a high income. The optimum bid is the bid price that yields the highest income. The bids are separated into 24 1-hour segments. Using a fixed bid of e.g. 200 DKK/MW throughout the day yields an average income around 15 DKK/MW. The maximum income for a fixed bid strategy is an average hourly income around 35 DKK/MW at a fixed bid around 90 DKK/MW.

The optimum bid (hour-by-hour) and maximum income for the optimum bid are shown in Figure 10 and the Income vs bid for each hour-segment for FCR-D is shown in Figure 11. The income for FCR-D is significantly lower than FCR-N with an approximately income on 40 DKK/MW per hour.

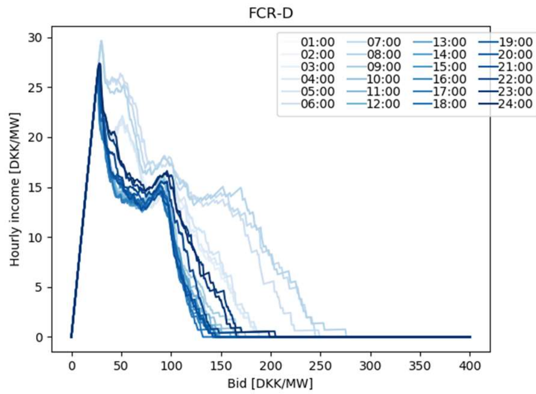


Figure 10. Optimum bid (hour-by-hour) and maximum income for the optimum bid for FCR-D.

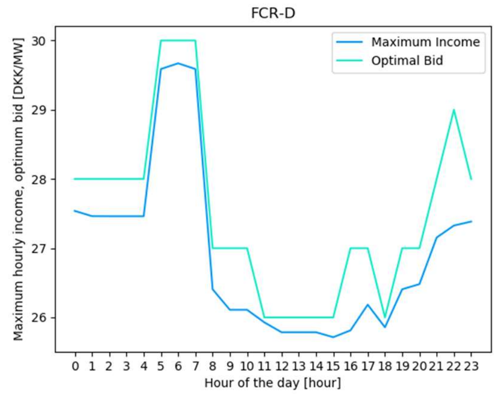


Figure 11. Income vs bid for each hour-segment for FCR-D

Operation activity:

The operation activity on the FCR-D market is low due to a 100 mHz deadband. The frequency resolved energy content is shown in Figure 12 below. The total hourly energy content is the sum of the negative and positive energy content. This is 1.4 kWh/h per MW. The energy content may vary from bid activation to bid activation, but the activation energy response is not monitored by Energinet on an hourly basis. For optimal income the bidding is at every hour 24-7 in the lifetime of the battery and the bidding probability for the FCR-D market is set to be the same as FCR-N: 69%.

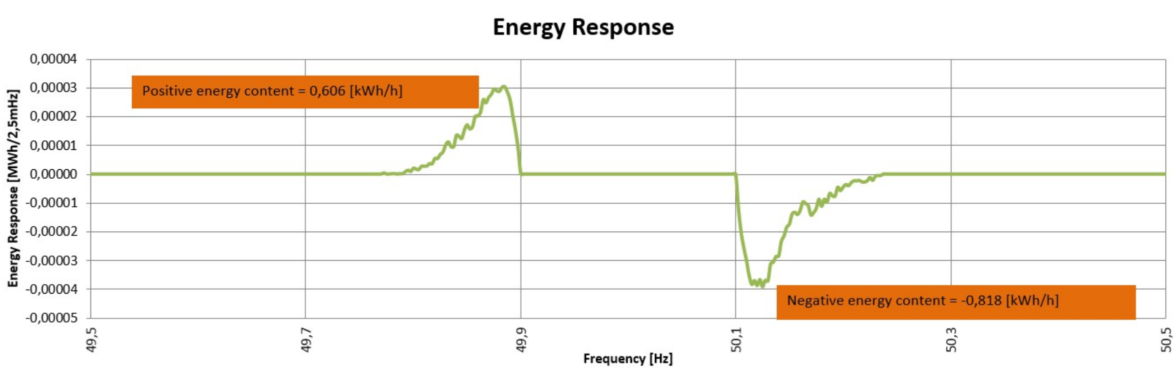


Figure 12. Frequency resolved energy content per MW in the FCR-D market in March 2017.

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Table 3 shows the analysis results for the FCR-D market.

Table 3. Analysis results for modelling the FCR-D market

Frequency market parameters – FCR-D		
Name	Variable	Value
Energy charge	E_{Ch}	0.61 kWh / MW h
Energy discharge	E_{Disch}	0.82 kWh / MW h
Income with optimal bid	I_{FCR-D}	40 DKK / MW h
Bid probability	P_F	69%

Frequency Containment Reserve for Disturbances FCR – DK1

In the event of frequency deviations, the primary reserve regulation must ensure that the balance between production and consumption is restored, stabilizing the frequency at close to, but deviating from 50 Hz. In DK1 the primary reserve FCR is regulated by means of automatic control equipment that responds to grid frequency deviation. In 2017 the average requirement was +/- 20 MW.

Technical conditions:

Figure 13 shows the droop characteristics of FCR. The control system must support a deviation of up to ± 200 mHz relative to system frequency of 50 Hz. The regulation permits a deadband of ± 20 mHz.

During upward regulation, Power ($P_{bid,up}$) is delivered for frequency deviation between 49.8 – 49.98 Hz. During downward regulation, Power ($-P_{bid,dw}$) is absorbed for frequency deviation between 50.02 – 50.2 Hz.

For frequency above 50.2 Hz and below 49.8 Hz, the maximum contracted power is absorbed or delivered respectively.

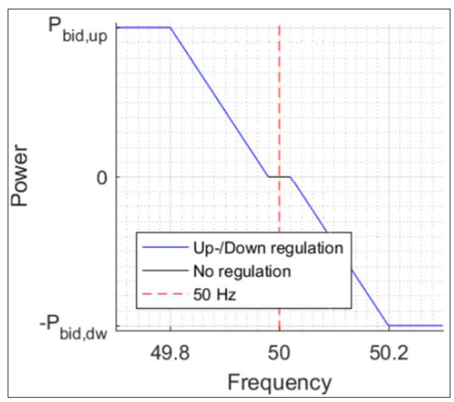

Figure 13. FCR droop characteristics

The first half of the activated reserve must be supplied within 15 seconds and the remaining half to be delivered completely within 30 seconds. It must be possible to maintain the regulation until the automatic and manual regulating reserve can take over; however, minimum 15 minutes. Following the end of the regulation, the reserve must be reestablished after 15 minutes. Only if the integral energy deviation equals 15 minutes at full charge/discharge, it is allowed to reestablish the reserve. In other words, for a 1 MW bid, it is allowed to re-establish the reserve if the energy-imbalance within the given hour exceeds 250 kWh. Re-charging/discharging the 250 kWh energy imbalance must be finished at latest 15 min after the aFRR reserve is activated.

Market conditions:

In order to participate in the market, a minimum bid of 0.3 MW capacity is required. The regulation allows to bid for upward and downward regulation separately. An auction is held once a day for the coming day of operation. For the purpose of the auction, the 24-hour period is divided into six equally sized blocks of four hours each. In case of incidents where the plant is not able to supply the contracted reserve, the plant must re-establish within 30 minutes. No calculation is made of energy volumes supplied from primary reserves. Supplies of energy from primary reserves are settled like ordinary imbalances.
The FCR service works as a retail market. This means all bids for upward regulation accepted will receive an availability payment corresponding to the price of the highest bid for upward regulation accepted (marginal price). The same applies with regard to downward regulation.

Market analysis:
The market analysis is based on the historical data from the FCR (DK1) market from 2018. The FCR market is a retail market which means the average income can be estimated as the median across the analyzed data. The median is 163 DKK/MW.

Operation activity:
The operation activity on the FCR market is low due to a 20 mHz deadband. The frequency resolved energy content per 1MW is shown in Figure 14 below. The energy content may vary from bid activation to bid activation, but the activation energy response is not monitored by Energinet on an hourly basis. For optimal income the bidding is at every hour 24-7 in the lifetime of the battery and the bidding probability for the FCR market is estimated to 69%. Table 4 shows the analysis results for the FCR market.

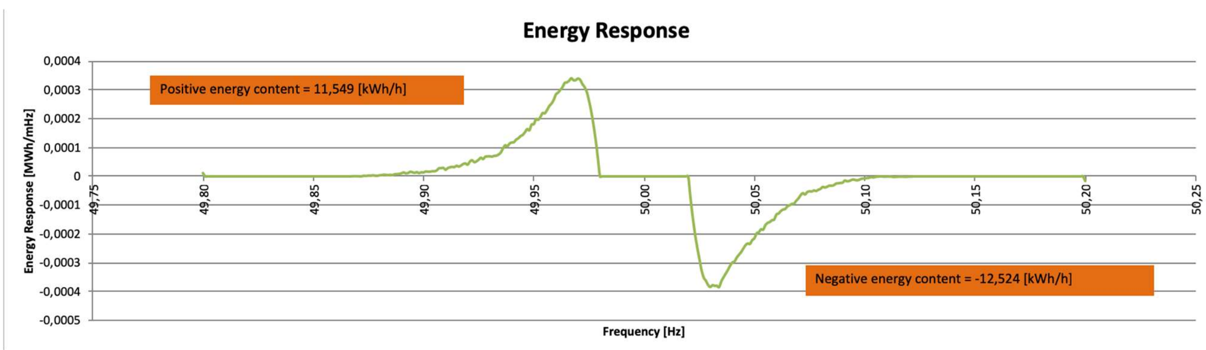

Figure 14. Frequency resolved energy content on the FCR market in March 2017 for a 1MW capacity.

It is noted that the deadband in the FCR market may be removed due to future harmonization with the EU continental and German markets. This will increase the energy content. The increased energy content w.o. the deadband is presented in Figure 15.

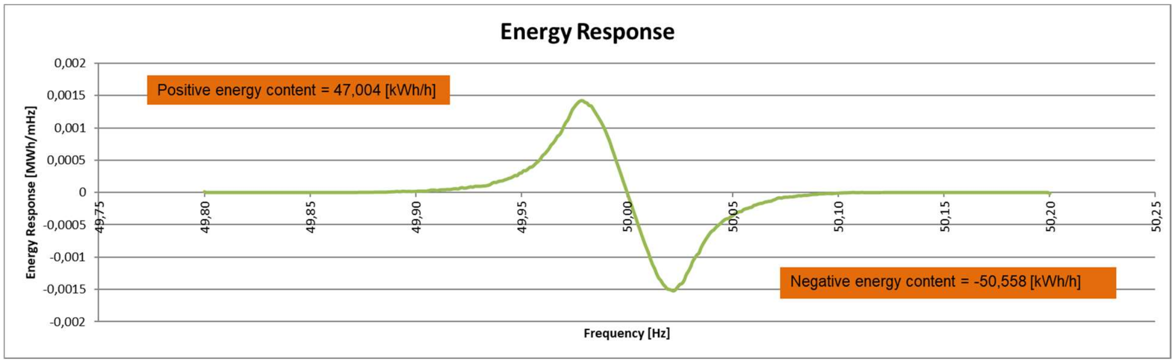

Figure 15. Frequency resolved energy content with a 1MW capacity w.o. deadband in the FCR market using March 2017 data.

Table 4. Analysis results for modelling the FCR market

Frequency market parameters – FCR		
Name	Variable	Value
Energy charge, today (in the future)	E_{Ch}	12 (47) kWh/h / MW
Energy discharge, today (in the future)	E_{Disch}	13 (51) kWh/h / MW
Income with optimal bid	I_{FCR}	169 DKK/MW /hour
Bid probability	P_F	69%

Discussion and Results

It is interesting to compare the TSO expenses presented in Figure 4 with the potential revenues outlined in Table 2-4. The TSO expenses are considerably higher than the potential revenues. A part of the explanation for this deviation related to the bid probability. Players on the reserve markets will not always win the bid and this lowers their average income. However, this does not explain the entire discrepancy. Professional Balance Responsible Parties (BRP) trading on the Nord Pool will have substantially more advanced bidding strategies involving e.g. weather forecasts, than the simple strategy used in the analysis presented here. Therefore the BRPs revenue are expected to be higher than the presented revenue assessments. This could explain the remaining part of the deviation between the assessed revenues and the average TSO expenses.

The primary reserve market in Denmark is of limited size. As mentioned earlier, in 2018 the market size of the FCR market was 13 MW. In 2020 the market size will be 22-23 MW and in from 2021 the market size will be 180 MW including the German market. The primary reserve market for the synchronously interconnected system of continental Europe is set by ENTSO-E at 3,000 MW, with each country contributing an agreed amount of capacity (4). Globally the primary reserve market is several GW.

For the R&D stage, the manufacturing learning rate for solid oxide fuel cells (SOFCs), which are very similar to SOECs, is previously noted to range are between 13% and 17% (5). If effects of economies-of-scale and automation are included, when combining all production stages the learning rate is expected to reach 35% (5). The high learning rate is reflected in the earlier estimate of price vs. production volume by Thijssen et al. (6), see Figure 16. The figure shows that the stack cost manufacturing cost levels off when the production volume exceeds around 50-100 MW per year.

Assuming a stack lifetime of 2 years, the annual production volume required to supply the European primary reserve market is 1.5 GW (3 GW divided by 2 years). In other words a fraction of the European primary reserve market is large enough to serve as a stepstone that could bring the SOEC technology above the first critical upscaling.

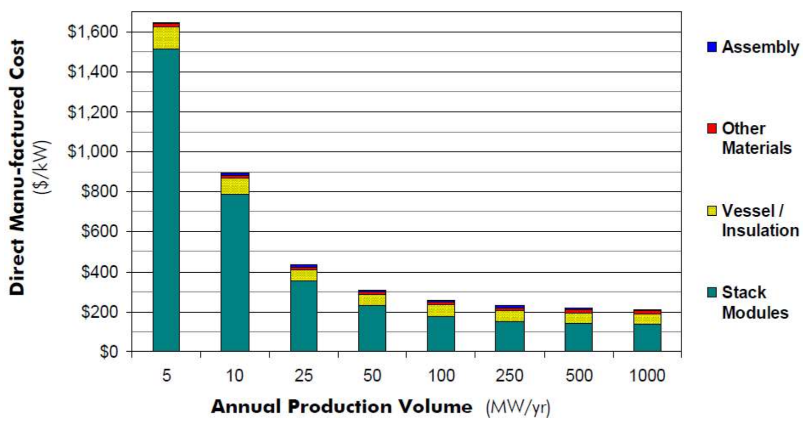

Figure 16. Effect of production volume on estimated direct manufactured cost ($/kW) for stacks with planar rectangular cells (6).

At a production volume of 250 MW/yr, the estimated SOFC stack price is around 225 $/kW (6), Figure 16. With an estimated income of 40, 107 and 169 DKK /MW h on the FCR-D, FCR-N, and FCR markets, the payback time for the for the stack alone is respectively 4.3, 1.6, and 1.0 years, on the three markets. Short SOEC stacks with lifetimes exceeding 2.3 years have already been demonstrated (7).

It is important to realize that the SOECs are best used for providing up-regulation, i.e. that the SOEC is operated in electrolysis mode most of the time, and can be brought to part-load or shut off to stand-by mode when there is a need for up-regulation. In markets with requirements for symmetrical bids, this means the SOECs should be used as a bundled system in conjunction with facilities that can turn on power to provide down-regulation. Looking at the prices for respectively

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up- and down-regulation in the FCR market (Figure 4), down-regulation only constitutes 5% of the cost for up-regulation. This means it is reasonable in the business case to assign the dominating income from the frequency regulation to the SOEC system.

The energy content required for up-regulation in the FCR-N, FCR-D and FCR markets is respectively 181, 0.61 and 12 (47) kWh / MW h (Table 2-4). With a bit probability of 69% this means the system will on average be shut off 12% , 0.04% and 0.83 (3.2) % of the operation time on the respective markets. In other words, the H2 production rate will decrease with these percentages when simultaneously selling up-regulation. This will negatively impact the added value from the H2 production. For a positive business case, the income from selling frequency regulation should exceed the loss related to the decreased H2 production.

Fossil based H2 cost in Germany is recently estimated to 5,3.5, and 2 $/kg equivalent to 0.128, 0.090, and 0.051 $/kWh (assuming 39 kWh/kg) for respectively small-, medium- and large-scale production (8). Further, a break-even price for Texas and Germany was respectively estimated to 3.23 $/kg and 3.53 $/kg (8). The values are listed in Table 5.

The average hourly electricity price on the day-ahead market in DK1 and DK2 excl. tax and tariffs was in 2018 respectively 328 and 344 DKK/MWh corresponding to around 0.05 $/kWh (9). Therefore an electricity cost of 0.05 $/kWh is used in the subsequent calculations.

Table 5. Fossil-based H2 production cost and SOEC system costs at small-, medium and large- scale

Production scale	H2 production scale in kg/day (MW; Nm3/h)	Fossil-based H2 price in Germany in $/kg ($/kWh)	SOEC system cost $/kW	SOEC system efficiency in % of Higher Heating Value	Stack life time in years	Stack cost in $/kW
Small (10)	200 (0.33; 93)	5 (0.128)	1400	96	2	225
Medium (11)	10.000 (16.7; 4600)	3.5 (0.09)	375	96	2	225
Large (12)	150.000 (250; 69500)	2 (0.051)	280	96	2	225

Table 6. Spot market prices, incomes and rate reductions on the FCR markets.

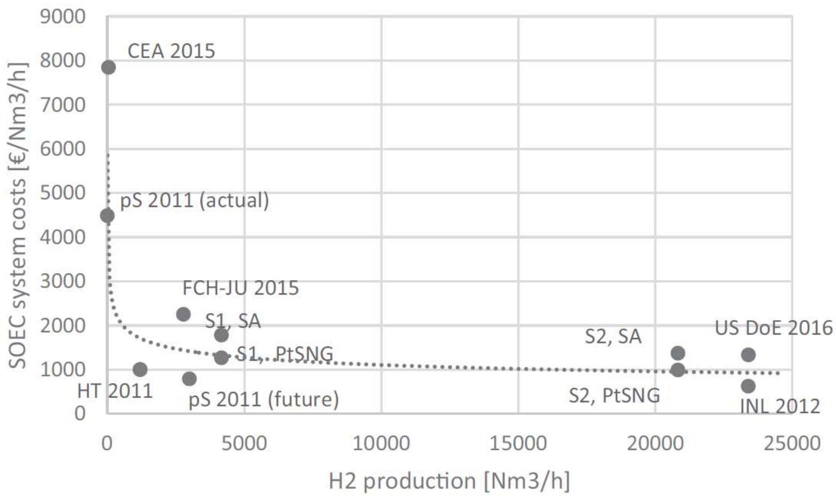
	Value	References
Spot market electricity price for DK1 and DK2 in Denmark in DKK / MWh ($/kWh)	328 (0.049), 344 (0.052)	(9)
Income from the FRC, FCR-N and FCR-D markets in DKK / MW h	169, 107, 40	(This work)
H2 production rate reduction at the FCR (FCR forecast), FCR-N and FCR-D markets in %	0.83 (3.2), 12, 0.04	(This work)

SOEC systems operating at 20 bar with a subsequent compression to 900 bar is expected to have a power-to-gas efficiency around 96% based on the higher heating value (HHV) (13). This means the H2 cost ascribed to purchase electricity on the DK1 (DK2) spot-market is equivalent to 2.1 $/kg.

For all power-to-hydrogen systems economy-of-size impact the production cost. The cost-size dependency for SOEC systems was recently analyzed by Anghilante *et al.* (14), see upper graph in Figure 17. A conversion factor of 3.6 kWh/Nm^3 H_2 was used. This means the system cost is expected to rapidly level off when the system size exceed app. 1.5 MW. A similar CAPEX vs size trends have been reported for Alkaline electrolysis systems, where the prices level off at around 1000 kg/day, as shown in the lower graph in Figure 17 (10).

An SOEC system size of 1.5 MW corresponds to a production rate of 900 kg H2 per day, and a cost of 624 $/kW. For comparison, Thijssen predicted a cost of 450 $/kW for a 3.1 MW SOFC system (6). The size of the small-scale SOEC systems is 200 kg/day (Table 5) which corresponds to 325 kW, i.e. a system size equal to that the current SOEC-based eCOs systems commercially available at Haldor Topsoe A/S which is capable of producing 96 Nm^3/h carbon monoxide. From Figure 17, the cost for the small scale SOEC system (200 kg/day H2) is estimated to 1400 $/kW.

Both the small- medium- and large scale systems are large enough to be used at the primary reserve markets without aggregation. To meet the requirement of a minimum bid of 0.3 MW, the small-scale system (0.33 MW) needs to provide a full regulation from around 10% to 100% power in order to participate as a stand-alone unit in the FCR markets. The size of the medium- scale plant (16.7 MW) is large enough to cover the entire DK2 FCR regulation requirement, however, if/when the FCR market is merged with the German market the medium-size SOEC system is less than 10% of the 180 MW regulation requirement of the merged market. The large-scale system (250 MW) exceed the merged FCR market. Further, it is important to note that the regulation is usually required on a more distributed scale than what can be provided with a large-scale SOEC system.



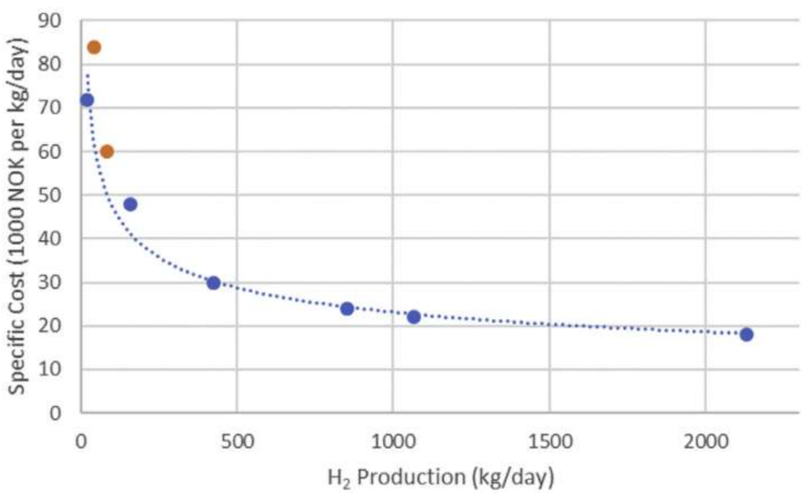


*Figure 17. **Top:** SOEC system costs vs. size (14). **Bottom:** Specific capital cost for various production volumes for respectively PEM (yellow) and Alkaline (blue) electrolysis systems (10).*

As mentioned, the cost to electricity is 2.1 $/kg H2. Since the income in the small- medium- and large- scale market is respectively estimated to 5, 3.5 and 2 $/kg H2, the possible revenue from the H2 production is 2.9, 1.4 and -0.1 $/kg H2, on the respective markets.

The net present value (NPV) calculated for the combined income from selling H2 at the small-, medium-, and large-scale markets while selling frequency regulation on the FCR, FCR-N, and FCR-D markets, is shown in Figure 18. The NPV calculation is conducted with an annual discount rate of 10% and takes into account the average decrease in the H2 production rate of respectively 3.2%, 12%, and 0.04%, on the FCR, FCR-N, and FCR-D markets. Further, a two-year stack lifetime, 225 $/kW stack price, and a system price as outlined in Table 5, is used in the calculation. It is seen that selling regulation capacity on the three FCR markets increases the NPV in particular for small-, and medium-scale SOEC systems. Operation on the large-scale market could make the NPV positive when operating on the FCR markets, however, the SOEC system size makes this case infeasible.

Since SOECs are still on a relatively low TRL, level the prices when fully matured are still uncertain. To address this, NPV calculations is shown in the Appendix for respectively 2 times higher prices for respectively SOEC stack, SOEC system, and SOEC system + stack. Further, to highlight the importance of a high conversion efficiency, NPV calculations for a 70% conversion efficiency is shown in the Appendix, Figure 22.

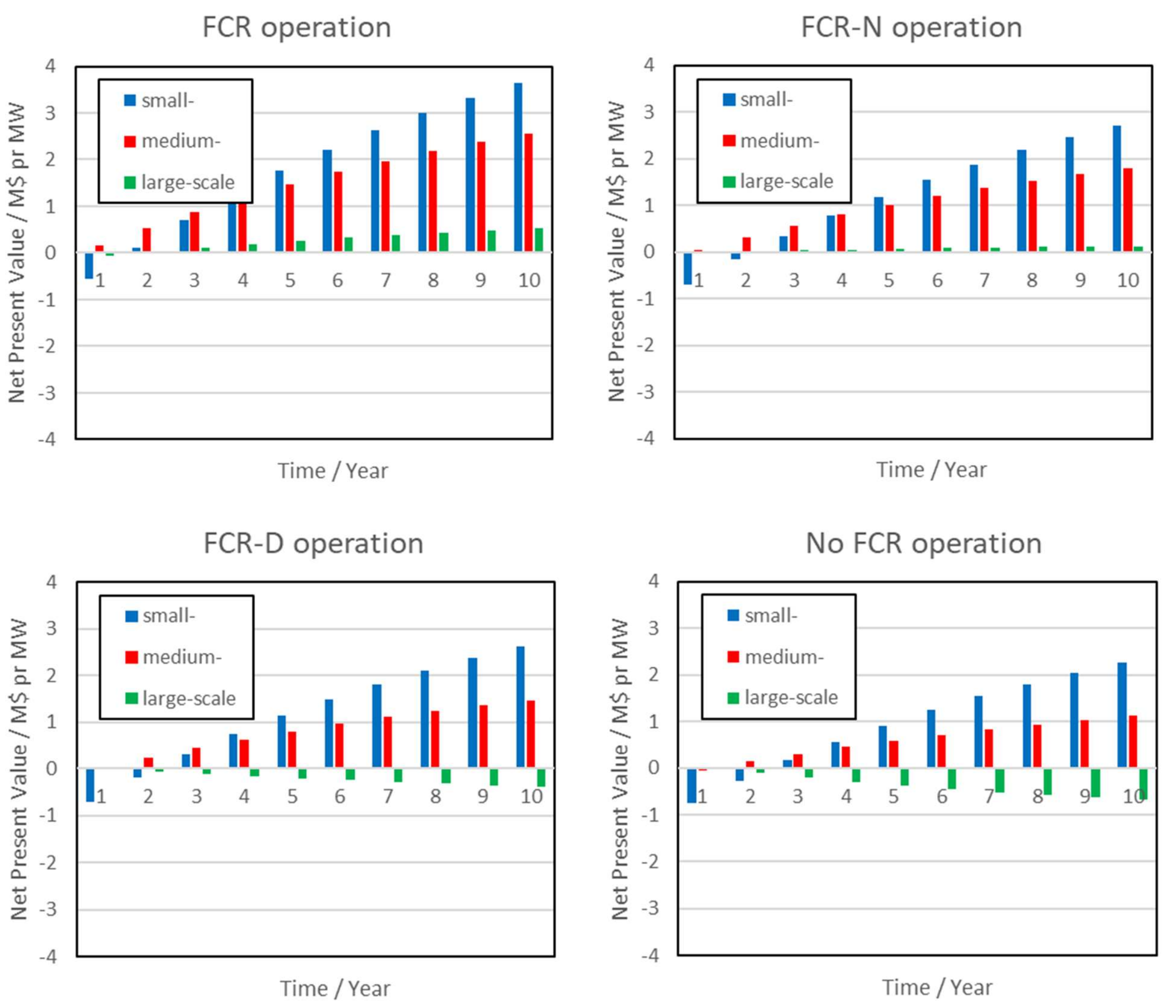


Figure 18. NPV for small-, medium-, and large-scale SOEC systems producing H2 while operating on the FCR, FCR-N, FCR-D, and without primary reserve market operation.

From the report conducted by AAU and DynElectro it was concluded that for large and medium systems the system price does not increase noteworthy by making the system capable of ACDC operation and in turn operation on the FCR markets. For small-scale systems, the system price is expected to increase by 10-20% due to the increased cost of the power electronics.

The energy constitutes around 20% of the electricity cost when taxes and tariffs are included. Therefore, if electrolysis plants have to pay full taxes, the electricity cost would be five times higher than what we used in the presented NPV calculation. Such a high electricity price leaves no room for a positive business case, not even for small-scale systems. Only if electrolysis plants can be exempted for tax and tariffs, or alternatively be operated “behind-the-meter”, the price level shows there is a reasonable margin for H2 production for small-, and medium-scale SOEC systems.

It is worth noting that by dynamic operation of the SOEC system in conjunction with e.g. wind farms, the SOEC system can help increasing the certainty of the forecasted production. This lowers the need for trading on the intra-day market, and therefore increases the marginal value sold wind power.

Conclusion

The potential income on the FCR, FCR-N, FCR-D and market was analyzed based on data from Energinet.dk. The income in the three markets was estimated to be respectively 169, 107 and 40 DKK / MW h. The primary reserve market size in Europe is around 3 GW. This means that if SOEC systems are used for only a small fraction of this market, the annual production volume can easily exceed 25-50 MW / year. Therefore the primary reserve market can serve as an interesting step-stone for upscaling the SOEC technology which are required to enter even larger markets.

The ACDC operation method enables improved dynamic operation capabilities for SOEC stacks, important for selling up-regulation capacity to the reserve markets. This is because the operation method enables a gradual decrease of the power consumption without introducing detrimental thermal gradients in the stack. The thermal gradients causes thermomechanical stress in the stack which results in loss of contact and decreases stack lifetime.

The presented analysis demonstrates that positive business cases seem possible for selling frequency regulation on the FCR, FCR-N and FCR-D markets using small-, and medium-scale SOEC systems. The analysis was made with a stack cost around 225 $ /kW and a stack lifetime around 2 years or more. Such a lifetime has already been demonstrated. The analysis also show that the production volume doesn't need to be more than around 50 MW/yr in order to realize a positive business case.

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Appendix

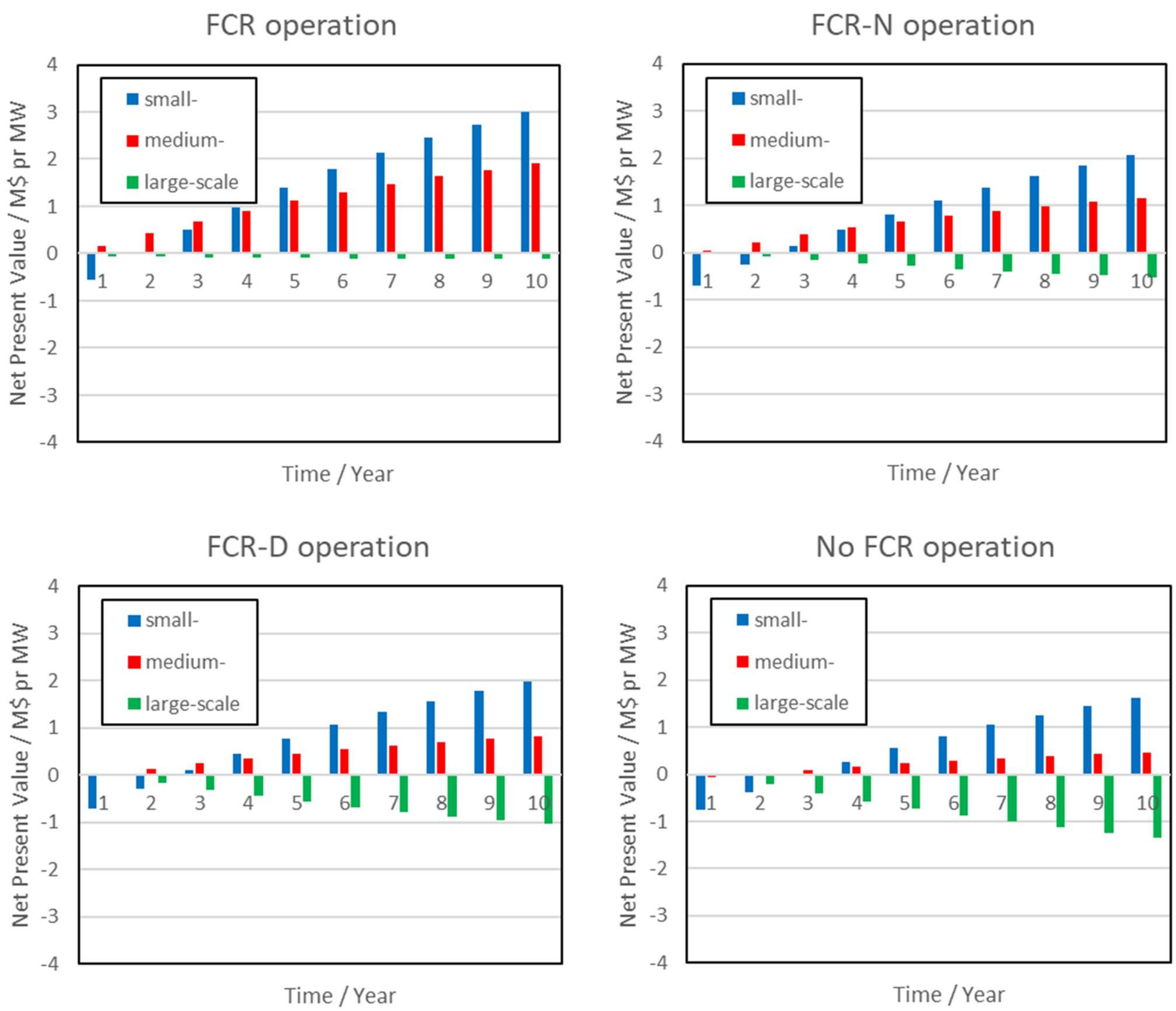

Figure 19. NPV with two times larger stack price compared to the values listed in Table 5.

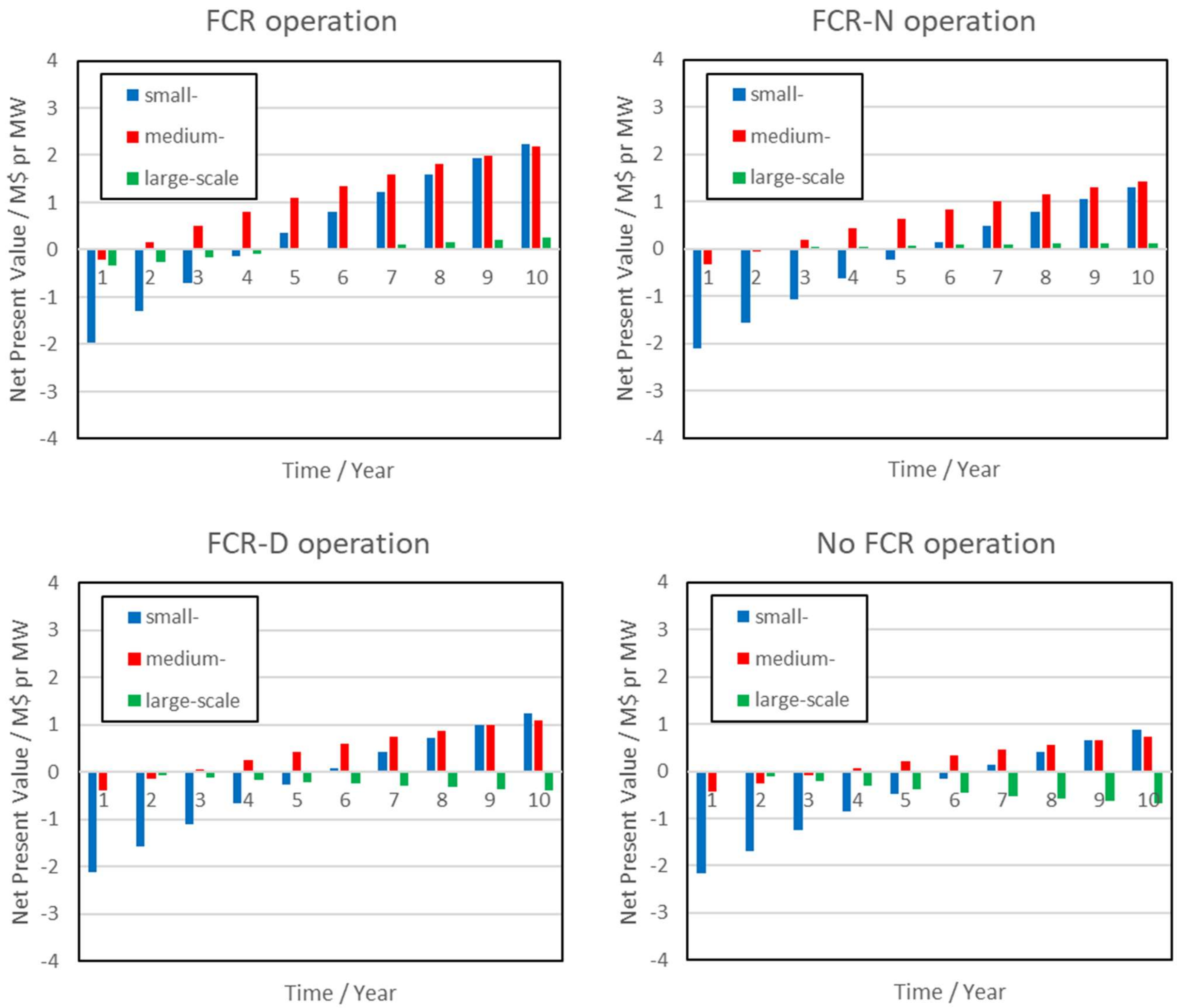

Figure 20. NPV for a two times larger system price compared to the values listed in Table 5.

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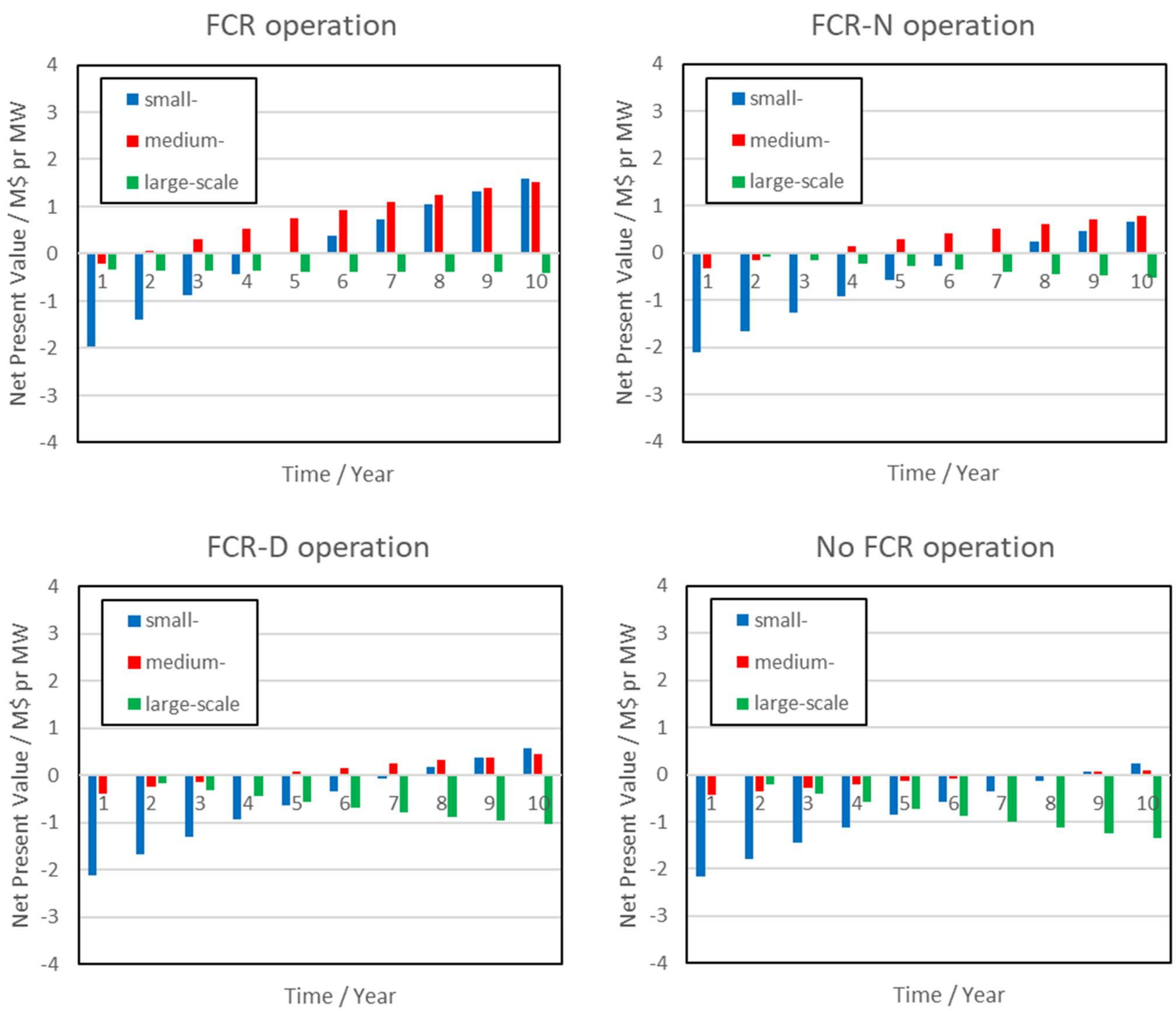

Figure 21. NPV with 2 times larger system and stack price compared to the values listed in Table 5.

To highlight the importance of the system conversion efficiency, Figure 22 shows the NPV with 70% efficiency, based on HHV.

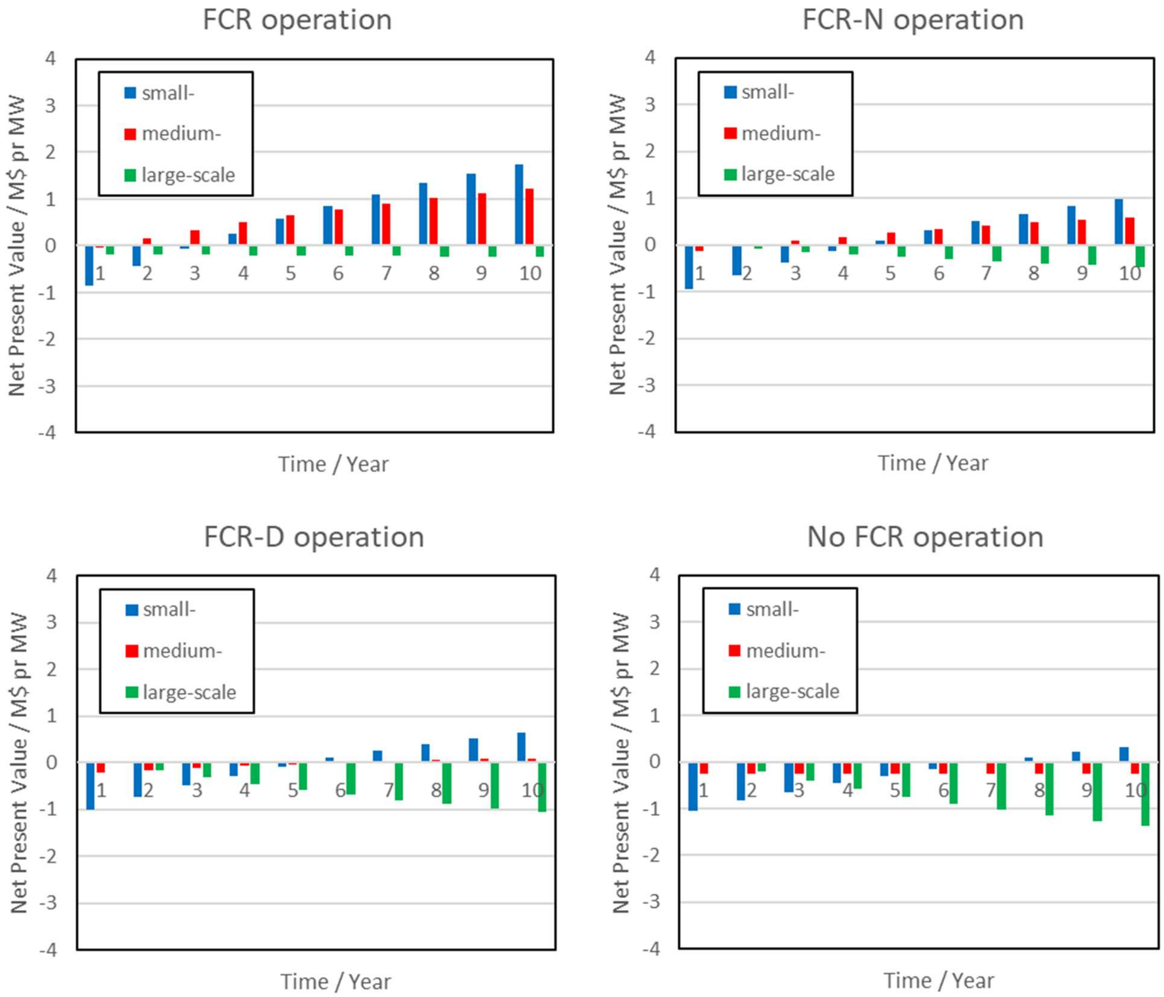

Figure 22. NPV with the system efficiency decreased to 70%.