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Exploitation of Power-to-Gas for Ancillary Services Provision in the Netherlands

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SUMMARY

In the future energy system, hydrogen as an energy carrier will play a role of increasing importance. Electrical energy can be converted into hydrogen locally by electrolysers and stored for a relatively long period. Then, the hydrogen can be used by final consumers like the transportation system or industries, as conceptually illustrated in Fig. 1. The flexibility of electrolysers offers promising possibilities for electrical grid support by the provision of ancillary services. Currently, a pilot power-to-gas facility with a 1-MW electrolyser is installed in the northern part of the Netherlands. A larger electrolysis plant of 300 MW may be installed in this area later. The feasibility of this large-scale plant, its impact on the stability of the electrical transmission network and the possibilities for ancillary services provision are currently being investigated in the project TSO2020 [1].

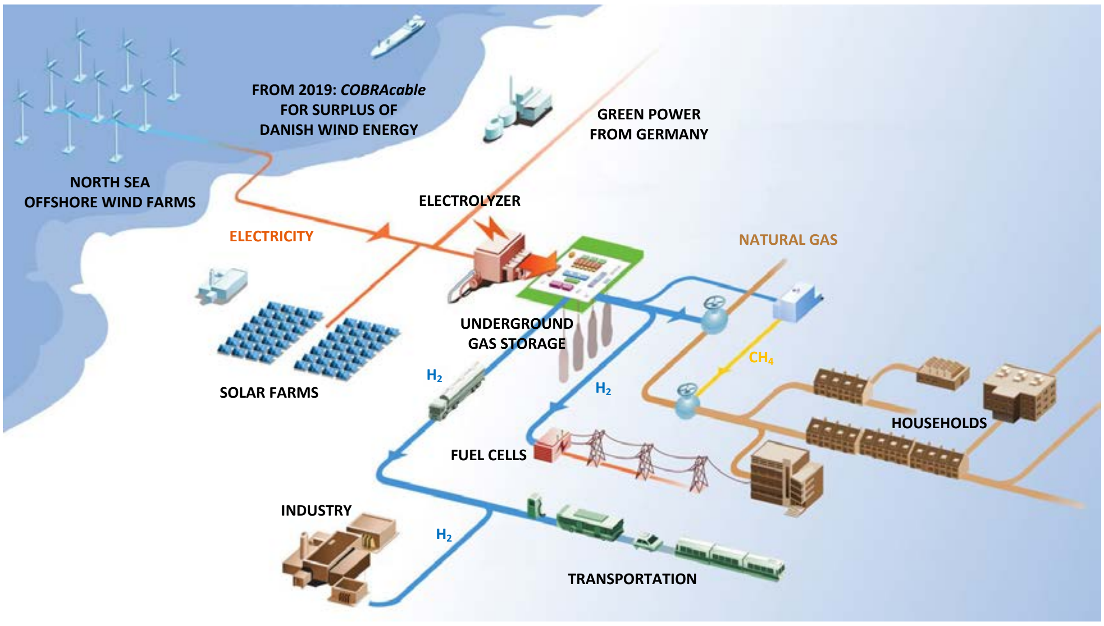

Fig. 1: Conceptual illustration of TSO2020 (figure adapted from [1]).

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TSO2020 (Electric “Transmission and Storage Options” for 2020) consists of several activities, including a Cost-Benefit Analysis (CBA), the pilot 1-MW electrolyser, an analysis of the scale-up to mass production and a study on the impact on power system stability including the possibilities for ancillary services provision. This last activity is divided into several tasks:

- Development of an electrolyser model for real-time simulation
- Development of the network model for real-time simulation
- Analysis of the impact of electrolysers on power system stability
- Hardware-in-the-Loop (HIL) tests of the electrolyser rectifier and controller
- Investigation of the possibilities of ancillary services provision by electrolysers
- Development of control schemes for ancillary services provision

The stability analyses of this activity will be performed in real time on the Real-Time Digital Simulator (RTDS). As models of large (>1 MW) electrolysers have not been described in literature yet, electrical models of the 1-MW and 300-MW electrolysers have been developed specifically for this project in RSCAD, to be simulated on the RTDS. These models also include the controls required for ancillary services provision. The performance of the electrolyser models are validated against data from existing literature and against field measurements of the 1-MW pilot electrolyser in the Netherlands. The transmission network of the northern Netherlands has been modelled in RSCAD as well and includes the 700-MW HVDC NorNed connection (to Norway), the 700-MW HVDC COBRAcable (to Denmark), the 600-MW GEMINI offshore wind farm and several conventional generators.

To investigate the possibilities of ancillary services provision by electrolysers, the current regulations of the Dutch and European market have been reviewed, thereby concentrating on frequency balancing, voltage control and congestion management. Based on this review, it is expected that electrolysers have the largest potential in providing frequency support, especially in the short term by participating in Frequency Containment Reserve (FCR). Under certain conditions, electrolysers could also participate in Automatic Frequency Restoration Reserve (aFRR) and voltage control.

Several simulations have been performed, in which the response of the power system to a selection of possible contingencies was studied. These contingencies include the disconnection of generators, wind farms and submarine interconnections, and some short-circuit faults. These initial simulations show that the frequency response of the system improves if part of the FCR is provided by electrolysers instead of conventional generators.

Future work includes the validation of the electrolyser model against field measurements. Also, further simulations will be performed, considering also voltage and frequency support by electrolysers operating at lower (than rated) capacities. The provision of ancillary services will be investigated further and control schemes for this purpose will be developed. General recommendations for the provision of ancillary services will then be given.

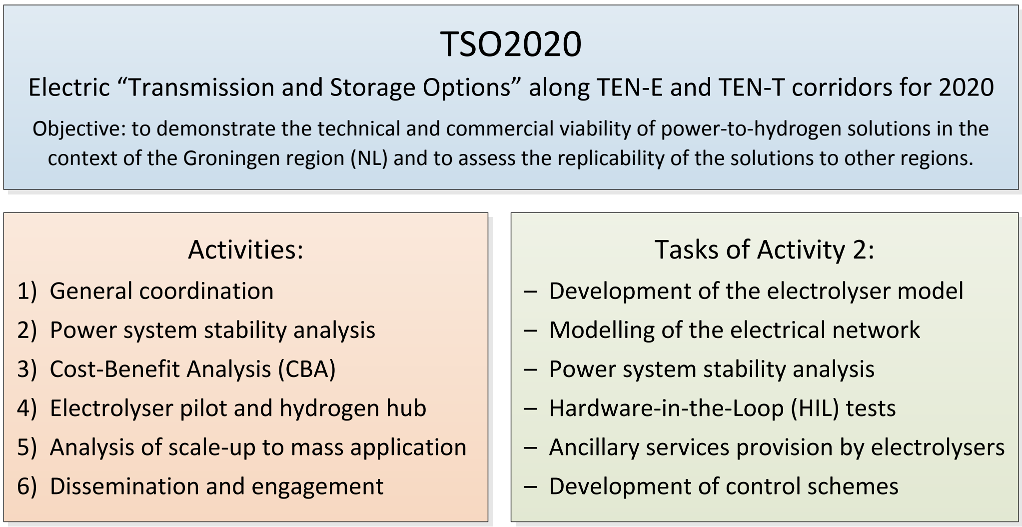
KEYWORDS

Ancillary Services – Electrolyser – Power System Stability – Real-Time Simulation

1. INTRODUCTION

In the transition towards a more renewable energy supply, various solutions are currently being investigated. In the generation of electricity, the share of offshore wind and solar photovoltaics is already continuously increasing. At the same time, industries, households and the transport system are searching for alternatives for fossil fuels like natural gas. In this context, a highly promising synergy between electric power systems and natural gas systems is created in the form of hydrogen. By electrolysis, water is converted into hydrogen and oxygen, thereby converting electrical energy into chemical energy. Hydrogen can be converted back to electricity by fuels cells, but also offers the possibility to be used as fuel in the transport system and in industries. Hydrogen can even be converted to syngas, which can be injected into the natural gas network to supply households.

As hydrogen can be stored for longer periods, electrolysis solves the issue of long-term electricity storage, which can effectively be applied to absorb excess electricity from fluctuating renewable sources. In addition, electrolysers could support the operation of the power system by participating in electrical ancillary services. Currently, a pilot 1-MW electrolyser is installed in the northern part of the Netherlands, while a larger electrolysis plant of 300 MW may be installed in this area later. The feasibility of these electrolysers, their impact on the stability of the electrical transmission network and the possibilities for ancillary services provision are currently being studied in the project TSO2020 [1].



TSO2020

Electric “Transmission and Storage Options” along TEN-E and TEN-T corridors for 2020

Objective: to demonstrate the technical and commercial viability of power-to-hydrogen solutions in the context of the Groningen region (NL) and to assess the replicability of the solutions to other regions.

Activities:

1) General coordination
2) Power system stability analysis
3) Cost-Benefit Analysis (CBA)
4) Electrolyser pilot and hydrogen hub
5) Analysis of scale-up to mass application
6) Dissemination and engagement

Tasks of Activity 2:

– Development of the electrolyser model
– Modelling of the electrical network
– Power system stability analysis
– Hardware-in-the-Loop (HIL) tests
– Ancillary services provision by electrolysers
– Development of control schemes

Fig. 2: Activities of the TSO2020 project and tasks of Activity 2 (based on [2]).

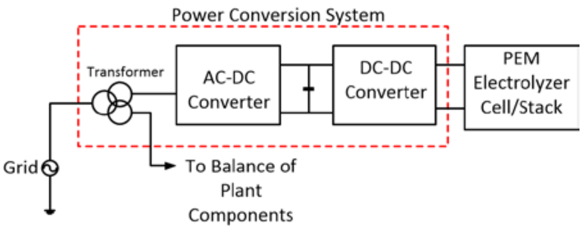
As shown in Fig. 2, TSO2020 consists of several activities. Activity 2 is performed by Delft University of Technology and concentrates on the impact of electrolysers on power system stability and the possibilities for ancillary services provision by electrolysers. This includes the modelling of the electrolysers and the electrical network, real-time simulations and Hardware-in-the-Loop (HIL) tests, and the investigation of the possibilities of ancillary services provision. This paper aims at giving an overview of the current status and initial results of Activity 2. First, the modelling of the electrolyser is discussed in section 2. Then, the modelling of the electrical transmission network of the northern part of the Netherlands is described in section 3. Section 4 gives an overview of the possibilities for ancillary services provision by electrolysers. The results of several simulations to study the impact of electrolysers on the power system stability are then discussed in section 5. Finally, general conclusions and future work are discussed in section 6.

2. MODELLING OF THE ELECTROLYSER

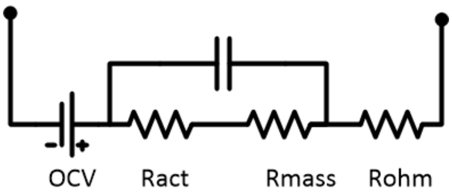
Although some electrical models of small electrolysers exist, practical models of large (>1 MW) electrolysers have not been described in literature yet. As it is important that the dynamics of these electrolysers are understood well, suitable models must be developed to aid the studies of grid dynamics with electrolysers. Therefore, for this project, electrical models of the 1-MW and 300-MW electrolysers have been developed in RSCAD [3]-[5], to be used in real-time simulations on the Real-Time Digital Simulator (RTDS). These models are based on existing literature describing the working principles of electrolysers [6]-[12].

According to [8], four types of electrolysers exist: Polymer Electrolyte Membrane (PEM) electrolysers, alkaline electrolysers, Solid Oxide Electrolysers (SOE) and Anion Exchange Membrane (AEM) electrolysers. Currently, both PEM and alkaline electrolysers are commercially available. AEM electrolysis has a limited range of applications, whereas SOE technology is at the early stage of development. Among the technologies, alkaline electrolysis is the most mature, while PEM is in its initial commercial phase. Although alkaline technology is well suited for smaller applications, PEM electrolysis shows significant promise for future, large-scale applications [6], [13]. It holds the highest promise for the lowest capital cost along with higher power densities, smaller footprint, larger dynamic range and a scalable design. The models developed in this study are therefore based on PEM technology.

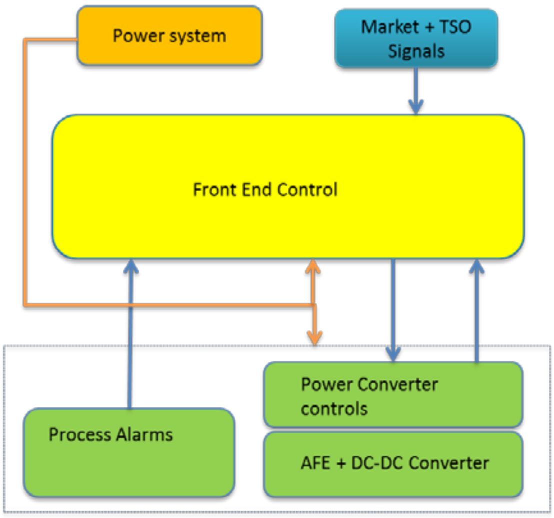
In electrolysers, the electrochemical process of water electrolysis is performed, in which electricity is applied to split water into hydrogen and oxygen. An electrolyser plant mainly consists of three parts: (i) the electrolyser stack, in which the electrolysis takes place; (ii) the Balance of Plant (BoP) components, which support the operation of the stack (e.g. feedwater and circulation pumps); and (iii) the power conversion system, which connects the stack to the electric power system (i.e. rectifier, DC/DC converter and transformer). Fig. 3a shows the electrical connection of an electrolyser, as it is modelled in this study. The AC/DC and DC/DC converters are implemented in a number of ways by different manufacturers. In this study, the AC/DC conversion is implemented with a 3-phase active rectifier in series with a DC/DC converter. The BoP components are modelled by a constant load, as it can be assumed that most of these have a fixed power consumption.



(a) components of the power conversion system



(b) electrical equivalent of the PEM cell



(c) implemented control of the electrolyser

Fig. 3: Modelling of the electrolyser and its associated controls.

Fig. 3b shows the electrical model of the PEM electrolyser stack. Electrolysis requires a Direct Current (DC) source that must overcome a reversible voltage in order to trigger the chemical reaction of water splitting into oxygen and hydrogen. Losses within the PEM stack increase the required voltage and are modelled as overpotentials. The representation by the electrical equivalent shown in Fig. 3b is widely used in current literature [11]. The reversible voltage is represented by a fixed DC voltage (OCV). Ract, Rmass and Rohm represent the activation, mass transport and ohmic losses, respectively. The double layer capacitance of the cell is represented by a capacitor. A further simplification of the model can be made by neglecting the activation and mass transport losses and the double layer capacitance. The electrical model then becomes a series connection of the open cell voltage and ohmic losses, which can be estimated from the slope of the I-V curve between the boundaries of the upper and lower operating current densities for a given cell area.

The electrolyser model is implemented with a control system as illustrated in Fig. 3c [3], [5]. Controls systems in commercially available electrolysers are primarily designed to support plant automation for the production of hydrogen gas. In order to optimise the electrolyser system to support additional objectives such as provision of ancillary services, an additional control layer is required. The Front End Controller (FEC) is this additional high-level control and integrates with low-level controls to form a hierarchical control scheme with extended capabilities, such as the capability to simultaneously respond to market price signals, the condition of the power system and internal signals like electrolysis process alarms.

The performance of the electrolyser model has been studied by simulating the response to typical process commands. As an example, Fig. 4 shows the response of the model to a step increase/decrease command of the hydrogen production, which is determined by the stack current. Comparison with electrolyser responses from literature shows that the developed model accurately replicates the response of a typical electrolyser [4], [15]. The response of the developed electrolyser model will be validated against field measurements of the 1-MW pilot electrolyser installed in the northern Netherlands. Based on these measurements, the parameters of the model will be adjusted.

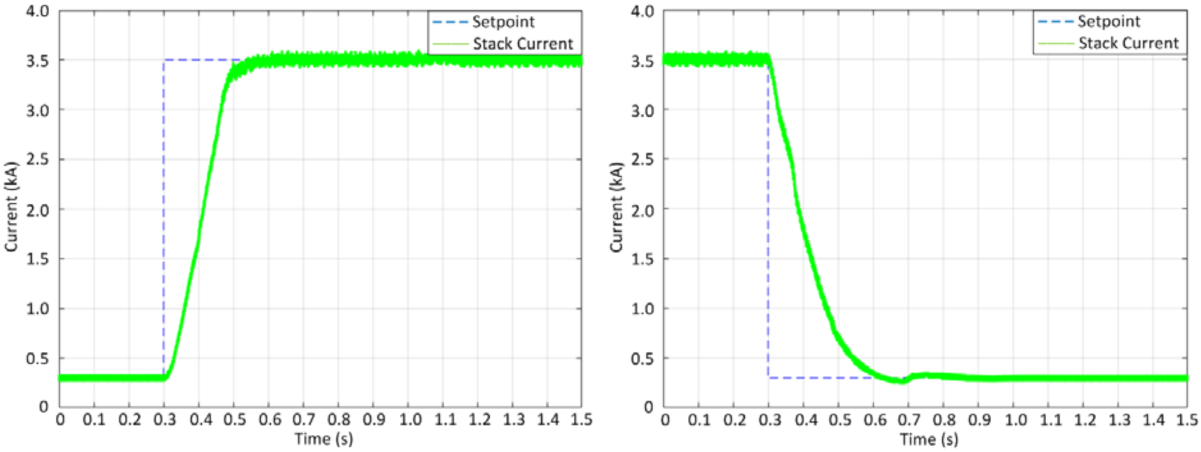
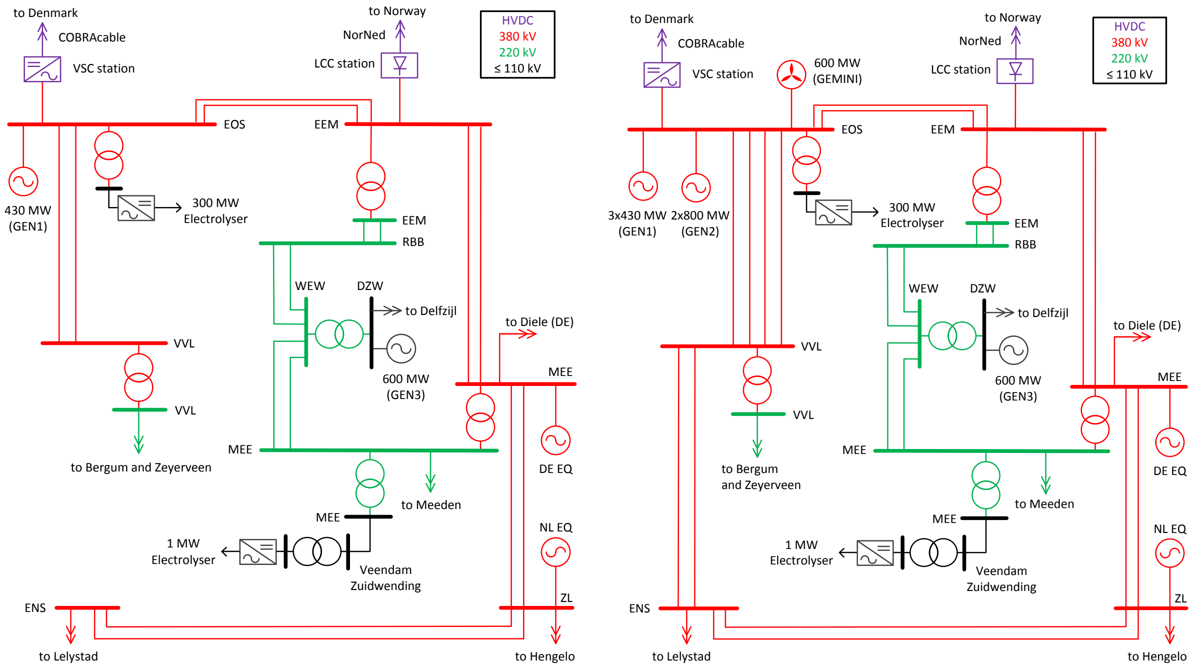


Fig. 4: Response of the electrolyser to a step up (left) and step down (right) command.

3. MODELLING OF THE TRANSMISSION NETWORK

For the real-time simulations, the transmission network of the northern part of the Netherlands has been modelled in RSCAD as well, based on a model in PSS/E. For validation and comparison, a simplified version of the network has also been modelled in PowerFactory. This northern part of the Dutch transmission network is particularly suitable to study the impact of electrolysers, as this part of the network contains several large-scale facilities which will interact with the electrolysers. The network model therefore includes the 700-MW HVDC NorNed connection (to Norway), the 700-MW HVDC COBRAcable (to Denmark), the 600-MW GEMINI offshore wind farm, and almost 3 GW conventional generation.

As illustrated in Fig. 5, two different topologies of the Northern Netherlands Network (N3) are considered. First, in the intermediate situation, only two circuits between EOS-VVL are in service, while the 380-kV connection between VVL-ENS has not been installed yet and only one 430-MW generator linked to EOS is operative. For the final situation, the four 380-kV circuits between EOS-VVL and the 380-kV connection between VVL-ENS are in service, while all the generating capacity is operative. For the year 2030, both network topologies are considered, while for the year 2040, the final network topology is selected.



intermediate topology

final topology

Fig. 5: Considered network topologies: intermediate (left) and final (right).

Table I gives an overview of the operational scenarios that are considered in this study. As shown in the table, three generation scenarios are considered for 2030, while one scenario is considered for 2040. Scenario 1 is based on the intermediate network topology shown in Fig. 5, in which generation and demand are reduced due to some of the circuits not being available. Scenarios 2 and 3 apply to the final network topology. For the 2040 case study, the generating capacity from Scenario 2 in the 2030 model is modified. The 800-MW coal-fired power plants (GEN2) are assumed to be refurbished to biomass, respecting the same power rating, but dispatched at 500 MW. Also, a second offshore wind farm of 600 MW is installed at EOS substation, in similar fashion to GEMINI.

Table I: Operational scenarios in the N3 area for the years 2030 and 2040 (in MW).

Generator / HVDC link	Year 2030 Scenario 1	Year 2030 Scenario 2	Year 2030 Scenario 3	Year 2040 Scenario 2
GEMINI wind farm (EOS)	0	600	450	2 × 600
GEN1 (EOS)	430	3 × 430	3 × 430	3 × 430
GEN2 (EOS)	0	2 × 800	2 × 800	2 × 500
GEN3 (DZW)	400	233	233	233
NorNed import (EEM)	700	700	700	700
COBRAcable import (EOS)	300	700	-700	700
Total	**1830**	**4890**	**3490**	**4890**

The network shown in Fig. 5 contains two synchronous generators that represent the remainder of the Dutch network (NL EQ) and a section of the German network (DE EQ), respectively. These were added to make the frequency response in the simulations more realistic. The inertia values of these equivalent generators were estimated from the PSS/E grid model. The control structure and parameters of the generators within the N3 network are directly adapted from the PSS/E model of interconnected European countries.

The system load in this region is about 2 GW and is projected from 2018 to the years 2030 and 2040, considering the estimated growth proportion obtained from the Quality & Capacity Plan 2017 (KCD 2017) published by TenneT [16]. Tables AI and AII in the appendix show the distribution of the load over the three provinces in this region, together with the aggregation of the load to the higher voltage levels.

A selection of possible contingencies was defined to study the impact of electrolysers on power system stability. Table II gives an overview of these severe contingencies. Because of the network configurations and the generator dispatches, not all contingencies are simulated for all scenarios. In particular, the disconnection of 2 generators at EOS is not included for the year 2030, since this disturbance would be too severe in comparison with the total frequency support reserve assigned in the studied part of the network, and therefore, the electrolyser influence cannot be determined accurately for such contingency.

Table II: List of the contingencies considered for each scenario.

Contingency	Year 2030 Scenario 1	Year 2030 Scenario 2	Year 2030 Scenario 3	Year 2040 Scenario 2
Disconnecting COBRAcable	✓	✓	✓	✓
Disconnecting NorNed	✓	✓	✓	✓
Disconnecting GEMINI	–	✓	✓	✓
Disconnecting 1 generator at EOS	✓	✓	✓	✓
Disconnecting 2 generators at EOS	–	–	–	✓
Tripping 2 circuits between EOS-VVL	–	✓	✓	✓
3-phase short circuit at VVL	✓	✓	✓	✓

4. ANCILLARY SERVICES PROVISION BY ELECTROLYSERS

Real-time power system operation is challenged by numerous disturbances such as faults, demand alterations and fluctuating renewable energy, which can induce undesired frequency, voltage or congestion issues in the grid. Ensuring an effective and reliable operation is handled by Transmission System Operators (TSOs), in part, through the procurement of ancillary services. As electrolysers could participate in these ancillary services in the future, the possibilities for this have been investigated [17], [18]. Up until the last few years, the framework of ancillary services markets in European countries has been subjected to the specific rules of the corresponding national TSOs [19]. As the definition of the offered services, contracting methods, instructing procedures, remuneration settlement rules and prequalification requirements differ from one country to the other, it is hard to develop a joint analysis. This study therefore concentrates on the situation in the Netherlands, while also considering the possible development of the European market.

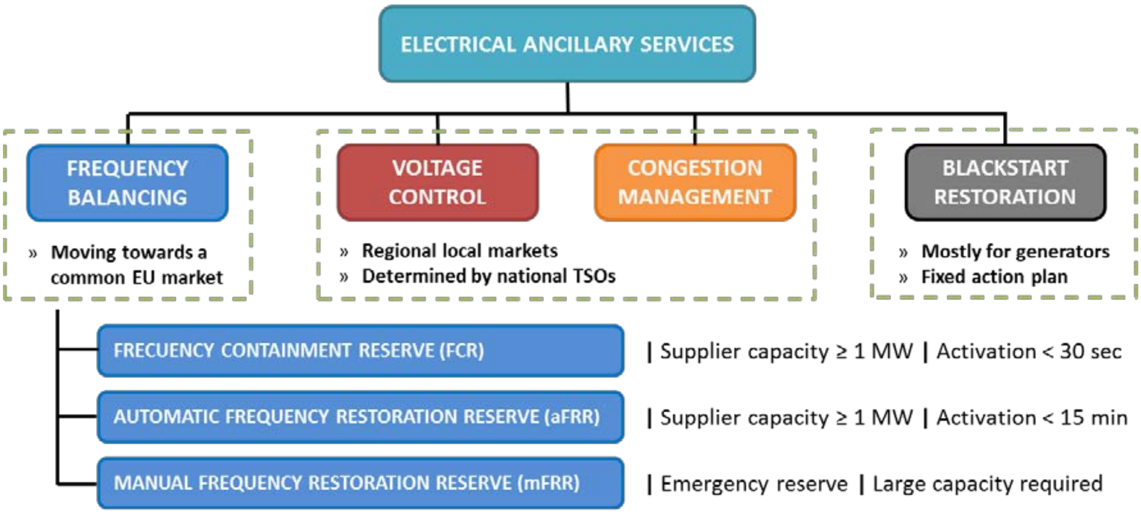


Fig. 6: Organisation of electrical ancillary services.

Fig. 6 gives an overview of the ancillary services considered in this study. Starting on the right, blackstart restoration plans are fixed action plans, mainly designed for generators. Electrolysers could participate in these action plans as loads that are switched in at a certain moment. Voltage stability and network congestion are local issues and are addressed by local relief actions, determined by national TSOs. In contrast, frequency variations affect every control area in the power system and therefore, the development of a common European frequency balancing market is being pursued in the short term [20]. In such scenario, mitigation of renewable energy uncertainty will be more effective and at the same time, a harmonised market playing field across Europe is created. As shown in Fig. 6, frequency balancing consists of three parts: Frequency Containment Reserve (FCR), Automatic Frequency Restoration Reserve (mFRR) and Manual Frequency Restoration Reserve (aFRR).

Frequency Containment Reserve (FCR), commonly known as primary frequency control, serves as the first barrier against active power imbalances. This service is designed to limit frequency excursions within the first 30 seconds after a disturbance. In the synchronous area of continental Europe, an overall capacity of ±3000 MW is allocated for FCR, further divided proportionally among the member states [21]. As of 2018, there is a shared European market with a total size of ±1400 MW, gathering TSOs from Germany, the Netherlands, Austria, Switzerland, Belgium and France. Denmark is involved in the cooperation group and able to join the market anytime [22]. In the Dutch control area, the size of FCR was ±110 MW in 2017 [23]. Out of the overall FCR capacity, 30% is auctioned exclusively for Dutch providers, while 70% is auctioned in the shared market [23].

The FCR market is constructed around a symmetric capacity product. The minimum bid size is ±1 MW and the maximum bid size is the prequalified volume. The auction takes place once a week, and generators and loads are able to participate in it. The product resolution lasts for an entire week, for which the providers must commit. Remuneration is based on a pay-as-bid settlement rule, favouring the cheapest offers available [23]. Technically, FCR requests activation of the full bid within 30 seconds in case of a ±200 mHz frequency deviation. For providers without a limited energy supply, FCR support must persist for the entire deviation period. The control implementation is decentralised and follows a classic droop characteristic, such that the change in active power is proportional for smaller frequency deviations [34]. An overview of the framework of the joint FCR market is depicted in Fig. 7.

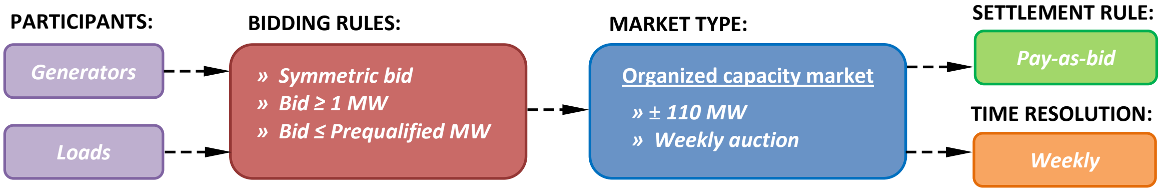


Fig. 7: Current FCR market framework in the Netherlands [17].

By the end of 2020, the FCR framework will have been modified according to the recommendations of the member TSOs: the auction frequency will be daily, the product resolution will be shortened to 4 hours, and marginal pricing will be the settlement rule [22]. The shortening of the resolution will benefit the operational flexibility of electrolysers, as this offers the opportunity to provide FCR support while also exploiting cheap electricity (e.g. at off-peak hours or at night). The implementation of asymmetric bidding would enable to bid exclusively for either upward or downward regulation, which allows further operational flexibility. Nevertheless, asymmetric bidding is not planned for the next years because of the increase in market complexity [24]. In line with the planned regulatory market changes, it is probable that the technical requirements will become more stringent, either by shortening the full activation time or by incentivising the participation of faster technologies. Several countries, like the UK and Ireland [25], [26], are already creating new products for fast frequency regulation purposes. The fast speed performance of electrolysers indicates notable ability to participate in FCR, as any variation of demand can be achieved within just 1 second.

Automatic Frequency Restoration Reserve (aFRR), formerly known as secondary frequency control, acts right after FCR in order to restore the active power balance in every control area within 15 minutes after a disturbance. aFRR deployment is divided into Programme Time Units (PTUs) of 15 minutes each. Contrary to the FCR market, no common trading platform exists at the moment, making the framework disparity between countries more noticeable. In the Netherlands, a minimum of ±350 MW of aFRR capacity is required for 2018, effectively guaranteed via bilateral contracts of monthly or weekly duration [27]. The offered capacity must be symmetric with a minimum size of 1 MW and a maximum size of 999 MW [28]. Suppliers are remunerated on a pay-as-bid scheme [19]. For each PTU, all the contracted parties are obliged to bid their agreed capacity for upward and downward regulation. Additionally, non-contracted suppliers are allowed to send voluntary capacity bids, which in this case can be asymmetric and at least 1 MW in size. When all the bids have been received, they are inserted into a common bid ladder. In the event of an imbalance, the units are activated according to a merit order (i.e. cheapest bids first) [28], and the last participant unit sets the marginal price used to settle the energy usage in the PTU [19]. Power setpoints are realised in steps of 1 MW, a minimum ramp rate of 7% of the bid per minute must be provided, and full activation of the bid must be completed within 15 minutes [28]. The speed capabilities of electrolysers are well above the cited requirements, hence the provision of upward regulation aFRR by reducing consumption is a possibility. The structure of the complete aFRR market in the Netherlands is summarised in Fig. 8.

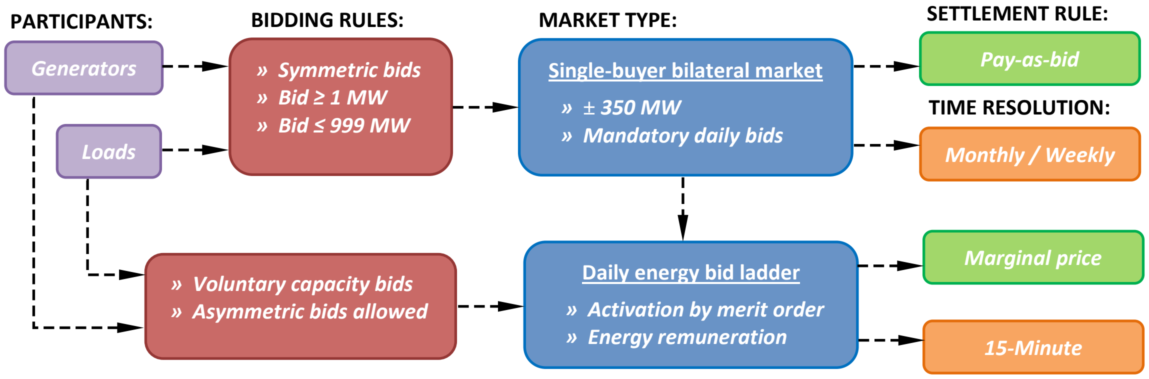


Fig. 8: Current aFRR market framework in the Netherlands [17].

For the next years, the harmonisation and development of a joint European aFRR framework is being targeted [29]. In such scenario, a common cross-border merit list would determine the order of energy activation, while cross-border marginal pricing would ideally become the settlement rule. Another focal point is the mitigation of the uncertainty of renewable energy sources, which will be addressed by shifting the market gate closure time as close as possible to real time and by shortening the full bid activation time to 5-8 minutes. In the zone of central Europe, some degree of coordination is already implemented through International Grid Control Cooperation (IGCC) [30]. This initiative applies imbalance netting to avoid the simultaneous activation of aFRR in opposite directions among different control areas.

Manual Frequency Restoration Reserve (mFRR), formerly known as tertiary frequency control, is only activated when a severe outage occurs at a large power plant. Because it is rarely used, and due to large minimum size required to apply for the available capacity product [31], mFRR is judged as a low interest service for electrolysers.

Voltage control is mainly performed by injection and absorption of reactive power. Grid codes usually demand voltage regulation capabilities of synchronous generators and power electronics-interfaced renewable energy sources connected to the transmission network. Transformers, FACTS (Flexible AC Transmission Systems), HVDC (High-Voltage Direct Current) links, battery storage and several industrial consumers are also able to support voltage control. The optimal use of the reactive power provided by these sources is defined by the national TSOs on the basis of optimisation programs, past experience and studies. Supplier remuneration relies on national legislation as well. In the Netherlands, these sources must act within 15 minutes when commanded [32]. For generators with installed capacity >5 MW, voltage control is mandatory and contracted [19]. A yearly tender is organised for external reactive power suppliers, where bilateral contracts for a duration of the entire year are arranged. Remuneration is settled on a pay-as-bid rule, and depending on the contract, a yearly fixed fee or an hourly variable fee is agreed [32]. Since electrolysers are DC loads and limited reactive power is consumed by the other equipment, participation in voltage control can be achieved by varying the active power demand. Using the converter to manage reactive power is a more desirable solution, but an oversized converter would be required to operate at rated active power. For both options though, the response can be completed within 1 second.

Congestion of the electrical network can be dealt with in different ways. Investing in grid infrastructure and using available cross-border capacity are strictly internal TSO relieving efforts. On the other hand, power redispatch or Demand Side Response (DSR) depend on external assets. In the Netherlands, enhancement of the grid infrastructure is the current action plan [33]. However, if a congestion issue is identified, a bilateral contract can be drawn with generators or industrial loads [32]. Electrolysers can contribute to the reduction of congestion by modulating their electricity demand. Furthermore, their fast ramping capability could help mitigate the fluctuations of renewable energy sources and lessen energy curtailment [15].

5. IMPACT OF ELECTROLYSERS ON POWER SYSTEM STABILITY

The contingencies listed in Table II have been simulated to study the impact of electrolysers on power system stability. For these simulations, several assumptions regarding FCR provision were made. In line with [23] and [34], a capacity of ±300 MW (i.e. ±1500 MW/Hz) was assigned in the N3 network. In Scenarios 2 and 3 (cf. Table I), the three power plants within the N3 network and the equivalent generator that represents the rest of the Netherlands have an approximate reserve of ±25 MW each, while the equivalent generator that represents part of the German grid has a reserve of ±200 MW. In Scenario 1, the values of the Dutch generators were increased to ±35 MW to keep the total FCR support constant. The electrolysers operate at rated capacity in all three scenarios (i.e. 300 MW in total). For such reason, FCR reserve is not symmetric, as the electrolysers can only reduce their consumption in response to frequency drops. The reserve is set to -25 MW in Scenarios 2 and 3, and to -35 MW in Scenario 1. The FCR reserves of the Dutch generators and the electrolysers are the same, such that the simulations can effectively compare the cases in which the support comes exclusively from synchronous generators with the case in which the support of one of the generators in the Netherlands is substituted by the electrolysers. Thus, the share of FCR reserve provided by electrolysers is 8.5% in the proposed case study (i.e. 25 out of 300 MW).

As an example, Fig. 9 shows the frequency response after disconnection of COBRAcable for Scenario 2 of 2030. As COBRAcable is importing power, the frequency drops as the synchronous generators in the system slow down. The frequency response is influenced by the inertia of the system, the control parameters of the generators (and other frequency reserve suppliers) and the severity of the disturbance. As the graph shows, electrolysers contribute to limit the maximum frequency deviation (i.e. frequency nadir) by reducing their power consumption. The effects are more noticeable for larger installed electrolyser capacities.

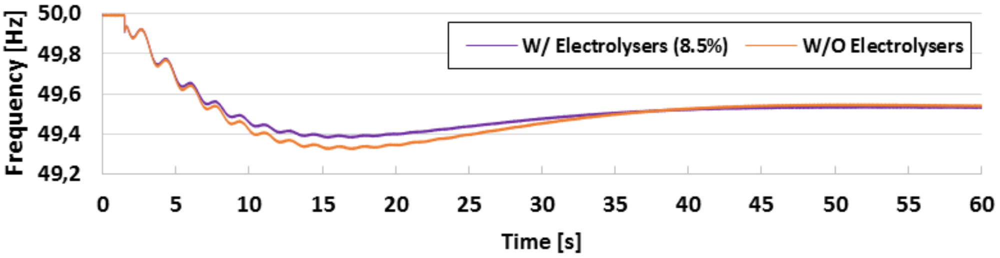


Fig. 9: Frequency response after disconnection of COBRA for 300 MW FCR reserve (Scenario 2).

Similar simulations have been performed for all contingencies listed in Table II. A summary of the results is shown in Table III. Tables AIII to AVI in the appendix show the numerical results of these simulations. The results show that the participation of electrolysers improves every situation in which generation or power import is lost. Since the electrolysers are operating at rated power in the considered scenarios, support cannot be provided in the case of a loss of energy export (or demand), which is the case when COBRAcable is disconnected in Scenario 3 of 2030. Because in this simulation, some FCR support by conventional generators is replaced by the electrolysers, which cannot ramp up their consumption further, the total FCR support in the system is reduced, which leads to a worse situation. This probably changes to an improvement if the electrolysers are operating at a smaller capacity. Further simulations are therefore planned to be performed. A combination with fuels cells could be another solution [35]. Table III also shows that the frequency performance for the short-circuit and line-tripping contingencies is not influenced significantly by the electrolysers. This is because in these cases, there is no significant change in the power balance.

Table III: Improvement of the frequency nadir when electrolysers are installed in the system.

Contingency	Year 2030 Scenario 1	Year 2030 Scenario 2	Year 2030 Scenario 3	Year 2040 Scenario 2
Disconnecting COBRAcable	6%	6%	< 0%	6%
Disconnecting NorNed	12%	6%	6%	6%
Disconnecting GEMINI	–	6%	4%	5%
Disconnecting 1 generator at EOS	7%	5%	6%	4%
Disconnecting 2 generators at EOS	–	–	–	3%
Tripping 2 circuits between EOS-VVL	–	0%	0%	0%
3-phase short circuit at VVL	0%	0%	0%	0%

The improvement in % is calculated by: $\left(f_{with.electrolyser} - f_{without.electrolyser}\right) / \left(50 - f_{without.electrolyser}\right)$.

In a second example, a 3-phase short-circuit fault with a duration of 100 ms is studied for Scenario 2 of year 2030. Fig. 10 shows the voltage response. In this case, the electrolysers operate at rated power and, thus, no extra converter capacity is available for voltage control. If operating below rated power, it is possible to influence the voltage response, either directly by reactive power control or indirectly by active power control. Nevertheless, the measured voltage response complies with the grid code requirements in every scenario (i.e. 0.70 pu 50 ms, and 0.85 pu 1.25 seconds after clearing the fault). Further simulations with electrolysers operating at a capacity smaller than rated are planned to be performed.

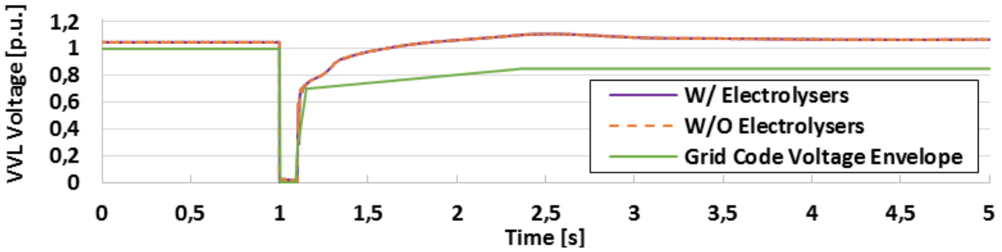


Fig. 10: Voltage response due a 3-phase short circuit in VVL (Scenario 2).

Although electrolysers can contribute to network congestion by varying their power consumption, in the studied network the electrolysers do not have a significant impact on network congestion. The maximum loading percentage of any transmission line in all of the proposed scenarios does not surpass the 45%. The grid infrastructure around the N3 area is very robust and therefore, critical congestion issues are not initially foreseen.

6. CONCLUSIONS AND FUTURE WORK

This paper discussed the impact of electrolysers on the stability of power systems and the ability of electrolysers to support power system stability by participating in ancillary services. The study concentrates on the installation of a 1-MW electrolyser and the potential installation of a 300-MW electrolyser in the northern part of the Netherlands. The simulations for this study are performed in real time on the Real-Time Digital Simulator (RTDS). As electrical models of large electrolyser do not currently exist, an electrolyser model was created in RSCAD specifically for this study. Also, the northern part of the Dutch transmission system has been modelled, including NorNed, COBRAcable, GEMINI wind farm and several conventional generators.

To investigate the possibilities of ancillary services provision by electrolysers, a detailed review of the current regulations of the ancillary services market has been performed. This review shows that electrolysers hold promising potential for frequency support, especially in the short term by Frequency Containment Reserve (FCR). Electrolysers could also participate in automatic Frequency Restoration Reserve (aFRR), but participation in manual Frequency Restoration Reserve (mFRR) is probably less suitable because of the long-term and large capacity requirements. Voltage support could also be provided by electrolysers, but this may require oversizing of the converter in order to provide voltage support during operation at rated capacity. Electrolysers could support congestion management by varying their consumption as well.

In several simulations, the impact of electrolysers on the stability of the power system was studied. These initial simulations show that electrolysers can improve the frequency response, measured as an improved frequency nadir, after various contingencies and disturbances. Because of their fast ramping capabilities, electrolysers can be more effective in providing FCR than conventional generators. The contribution to voltage support was limited in the simulations, which is caused by the fact that the electrolysers were operating at rated power in the considered scenarios. Network congestion was not an issue in the considered system as the transmission lines were all loaded less than half their capacity.

The study will be continued by several next steps. First, the developed electrolyser will be validated against field measurements of the 1-MW pilot electrolyser installed in the northern Netherlands. Also, further simulations will be performed, which can also consider frequency and voltage support by electrolysers operating at capacities smaller than rated. The possibilities for ancillary services provision will be investigated further as well, and for this purpose, new control strategies for electrolysers will be developed.

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APPENDIX

Table AI: Projected regional electricity demand for the years 2030 and 2040.

Region	Load 2018 [MW]	Load 2030 [MW]	Load 2040 [MW]
Groningen-Drenthe	823.95	875.04	893.42
Overijssel	760.25	802.83	819.69
Friesland	372.13	397.44	405.78
Total	**1956.33**	**2075.31**	**2118.89**
Projected growth w.r.t. 2018	**–**	**+6.08%**	**+8.31%**

For 2030, the demand in each region grows a 6.2%, 5.6% and 6.8% respectively. For 2040, the growth for every region has been estimated as a 2.1% with respect the 2030 values.

Table AII: Aggregated system load in the N3 area for the years 2030 and 2040 (in MW).

Voltage Level	Bus	Year 2030 Scenario 1	Year 2030 Scenario 2	Year 2030 Scenario 3	Year 2040 Scenario 2
≤ 110 kV	DZW	144.1	229.1	224.7	239.8
220 kV	VVL	579.3	988.0	829.6	988.7
	MEE	255.6	255.0	247.0	257.2
380 kV	ENS	27.2	1194.2	898.9	1191.7
	ZWL	354.3	869.4	488.7	854.4
	MEE	63.9	1064.9	412.0	1015.3
Total		**1424.4**	**4600.6**	**3100.9**	**4547.1**

For Scenario 2, although the regional demand is higher in 2040 than in 2030, the influence of the PSS/E grid model for 2040 makes the total power exchange to be lower than in 2030.

Table AIII: Summary of the results obtained for the 2030 Scenario 1.

Contingency	Frequency Nadir [Hz]		Improvement	
	W/O Electrolysers	With Electrolysers	[mHz]	[%]
Disconnecting COBRA (300 MW)	49.700	49.718	18	6%
Disconnecting NORNED (700 MW)	49.168	49.267	99	12%
Disconnecting 1 gen. EOS (430 MW)	49.504	49.537	33	7%
3-phase short circuit at VVL	Equal performance in both cases		-	0%

Table AIV: Summary of the results obtained for the 2030 Scenario 2.

Contingency	**Frequency Nadir [Hz]**		**Improvement**	
	W/O Electrolysers	**With Electrolysers**	**[mHz]**	**[%]**
Disconnecting COBRA (700 MW)	49.211	49.255	44	6%
Disconnecting NORNED (700 MW)	49.210	49.255	45	6%
Disconnecting GEMINI (600 MW)	49.318	49.357	39	6%
Disconnecting 1 gen. EOS (800 MW)	49.033	49.086	53	5%
Tripping 2 circuits at EOS-VLL	Equal performance in both cases		-	0%
3-phase short circuit at VVL	Equal performance in both cases		-	0%

Table AV: Summary of the results obtained for the 2030 Scenario 3.

Contingency	**Frequency Nadir [Hz]**		**Improvement**	
	W/O Electrolysers	**With Electrolysers**	**[mHz]**	**[%]**
Disconnecting COBRA (-300 MW)	50.882	51.102	-220	-25%*
Disconnecting NORNED (700 MW)	49.224	49.269	45	6%
Disconnecting GEMINI (450 MW)	49.553	49.569	16	4%
Disconnecting 1 gen. EOS (800 MW)	49.035	49.090	55	6%
Tripping 2 circuits at EOS-VLL	Equal performance in both cases		-	0%
3-phase short circuit at VVL	Equal performance in both cases		-	0%

*As in the simulation, the electrolysers are operating at rated capacity and cannot ramp up their consumption further, while FCR support of some conventional generators is replaced by electrolysers, the total FCR support in the system reduces and the frequency nadir becomes worse in this specific case. Further simulations with electrolysers operating at smaller capacity will be performed later.

Table AVI: Summary of the results obtained for the 2040 Scenario 2.

Contingency	**Frequency Nadir [Hz]**		**Improvement**	
	W/O Electrolysers	**With Electrolysers**	**[mHz]**	**[%]**
Disconnecting COBRA (700 MW)	49.204	49.249	45	6%
Disconnecting NORNED (700 MW)	49.203	49.249	46	6%
Disconnecting GEMINI (600 MW)	49.382	49.414	32	5%
Disconnecting 1 gen. EOS (500 MW)	49.487	49.506	19	4%
Disconnecting 2 gen. EOS (1000 MW)	48.192	48.240	48	3%
Tripping 2 circuits at EOS-VLL	Equal performance in both cases		-	0%
3-phase short circuit at VVL	Equal performance in both cases		-	0%

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