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# Potential of new business models for grid integrated water electrolysis

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ABSTRACT

Grid integrated water electrolysers have the potential of coupling electric power systems subjected to high shares of renewable energy sources with sectors of hydrogen demand, thus contributing to European decarbonization goals in future. We therefore investigate the business potential of future electrolyser applications in cross-commodity arbitrage trading by applying a complex power market simulation method for future scenarios and different European countries. Based on this, we evaluate the potential of additional provision of grid services towards grid operators in order to increase the electrolyser utilization ratio. For this, we use a method that identifies measures of transmission grid operators in order to ensure secure grid operation. In this context, uncertain hydrogen prices and different sectors of hydrogen demand are addressed through sensitivities of different hydrogen sales prices. The analysis shows a high dependency of business model efficiency on the hydrogen price. While cross-commodity arbitrage trading can achieve profitability for the transportation sector, applications for the industry sector and natural gas system are less efficient. The results however indicate that for these less efficient applications grid service provision can be an option of increasing the electrolyser utilization ratio thus increasing its profitability.

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## 1. Introduction

In the *Paris Agreement* of 2015, the United Nations emphasized their efforts in pursuing the goal of limiting the increase in the global average temperature to below 2 °C above pre-industrial levels by reducing greenhouse gas (GHG) emissions [1]. The European 2020 climate and energy package sets a target for 2020 of 20% cuts in GHG emissions compared to 1990 within the European Union [2] while the target for 2050 is set to a GHG emission reduction of 80–95% [3]. In order to achieve these ambitious goals, new and sustainable technologies need to be integrated and applied within various sectors. One of these new technologies are flexible water electrolysers applied to power systems subjected to high shares of renewable energy sources (RES) [4]. Using hydrogen renewably generated by electrolyser can reduce GHG emissions in sectors including transportation [5], heating [6], the natural gas system [7,8] and chemical industry [9].

Future applications of water electrolysis and consequently its potential to GHG emission reduction is highly dependent on electrolyser cost-competitiveness [10]. It is therefore crucial to examine new electrolyser business models as well as potential markets and countries that are best suited for these applications. While traditional electrolyser business models are mainly directed towards supplying a specific hydrogen demand of industrial customers [10], new business models for application within RES dominated power systems need to be adjusted to the fluctuating character of RES feed-in. Consequently, these business models require highly flexible electrolysers with dynamic operation capability [11]. New technological advances in electrolyser design indicate, that modern electrolysers can fulfill these requirements [12]. The obvious new business model for electrolysers relies on cross-commodity arbitrage trading between the electricity market and markets for hydrogen during times with low prices for electricity [13]. Business models directed towards electric energy storage consider electrolyser arbitrage trading using temporal spot market spreads at the electricity markets [14]. Situations of low electricity spot market prices and high temporal electricity spot market price spreads increasingly occur due to the rising feed-in of RES units [15]. Other new business models are directed towards provision of system and grid services to grid operators [10]. These ancillary services are needed in order to ensure a stable and secure operation of power systems subjected to high shares of RES [16].

This contribution therefore presents new findings in terms of the potential of new business models for grid integrated water

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electrolysers gained within the Horizon 2020 project *ELYntegration*. Being a collaboration of different European research institutions and technology companies, the project aims at designing and engineering a cost-competitive alkaline water electrolyser of multi-megawatt size that can be used under highly dynamic power supplies [12]. In the following we investigate the economic efficiency of electrolyser business models directed towards different sectors with hydrogen demand and different European countries. Other studies already indicate that provision of control reserve can increase efficiency compared to cross-commodity arbitrage trading. This includes provision of tertiary control reserve [13], secondary control reserve based on historic data [17] and automatic and manual frequency restoration reserve for future scenarios [18]. Apart from these system services, electrolysers are also able to provide grid services. Within this contribution we therefore identify the potential of applying electrolyser load flexibility in order to use RES feed-in that would otherwise be curtailed due to congestions within the power grid.

## 2. Methods

### 2.1. Grid integrated electrolyser operation schemes

In the following, we investigate two different business models for electrolyser power system applications. The operation can be optimized based on the electricity price in order to generate maximum revenues due to cross-commodity arbitrage trading or based on grid service provision in order to counteract grid congestions induced by RES feed-in.

Because the electricity price is more volatile than the hydrogen or natural gas prices, the dispatch of an electrolyser should be optimized against the electricity price in case of cross-commodity arbitrage trading. If the electrolyser is flexible enough in terms of shut down and ramp up times to allow for a spot market price driven dispatch, it benefits from low electricity prices and shuts down when electricity prices are high. Fig. 1 illustrates this strategy exemplarily based on historic spot market prices for Germany. The electrolyser runs at full load as soon as the spread between electricity spot market and hydrogen sales prices is high enough to cover electrolyser conversion losses, i.e. electrolyser operation generates positive contribution margins in situations when the electricity price is lower than a specific threshold. Hence, the shaded area between the curves for the electricity price and threshold in Fig. 1 accounts for the total contribution margin of the business model that can be used in order to cover the fixed costs of the electrolyser.

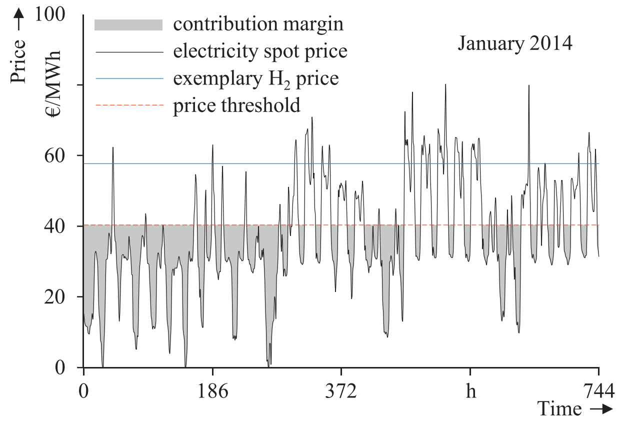

**Fig. 1.** Exemplary electrolyser dispatch based on the historic electricity spot market prices for Germany in January 2014 [19].

In case congestions occur within the transmission grid, electrolyser could also be used for provision of grid services. Transmission grid operators resolve congestions by applying remedial network and marked related measures. In case all these measures are exhausted, grid operators currently conduct curtailment of RES units. Instead of curtailing RES feed-in, electrolysers could be used in order to increase the load at the same grid location in critical situations. This decreases the total power feed-in at that location. Thus, grid congestions can be resolved by green hydrogen generation.

According to the German Energy Act, German legislation currently only considers combined head and power plants for provision of grid services in terms of load increase [20]. Consequently, the regulatory framework for potential future reimbursements for such an electrolyser grid service provision is uncertain. It must be taken into account that an additional contribution to congestion elimination by grid service provision can only be achieved by means of effectively additional load. That means, that the flexibility of increasing the power consumption of the electrolyser can only be offered in situations in which the electrolyser is not in operation due to other reasons, e.g. cross-commodity arbitrage trading [21,22].

### 2.2. Hydrogen markets and prices

The revenue of a grid integrated electrolyser originates in the sales of hydrogen to customers. Consequently, the economic efficiency of electrolyser business models is highly dependent on hydrogen prices that customers are willing to pay [23]. Generally, renewably generated hydrogen can be used in different end-user applications thus helping to decarbonize various sectors such as transportation, industry and the natural gas system.

Detailed analyses on future hydrogen prices and maximum permissible hydrogen production costs for different sectors have been conducted in various other studies [10,23–26]. The achievable hydrogen price is not only highly dependent on the type of customer and gas purity levels, but also on hydrogen transport costs in case the location of hydrogen consumption and the location of alternative hydrogen production facilities do not coincide. A realistic price estimation is also challenging due to significant uncertainties for future scenarios like the future price evolution of GHG emission certificate. Additionally, bilateral agreements dominate the merchant hydrogen market leading to a variance in hydrogen prices itself. Based on the literature review, this leads to a broad bandwidth of potential future hydrogen prices for each sector. For the transportation sector, the range of achievable hydrogen prices is 4.0–10.4 €/kg. For large industry customers like refineries, steel manufacturing and ammonia or methanol production facilities the price range is 1.1–4.5 €/kg. Within light industry including glass production and hydrogenation of fat, depending on the country, hydrogen prices of 3.3–9.4 €/kg are achievable [23]. In terms of the natural gas system, the expected hydrogen prices are lowest compared to other sectors and directly coupled to the spot market price for natural gas. In case bio methane injection tariffs also apply for green hydrogen injection, the achievable hydrogen price range might rise to 1.3–2.6 €/kg [23].

In order to account for these uncertainties, we analyze the effect of different hydrogen price scenarios on the utilization ratio and profitability of the electrolyser business models. We choose hydrogen prices that are representative for the relevant sectors.

### 2.3. Overview of simulation method

In order to evaluate future business models for cross-commodity arbitrage trading, it is not only crucial to model appropriate hydrogen prices, but also to identify reliable estimates

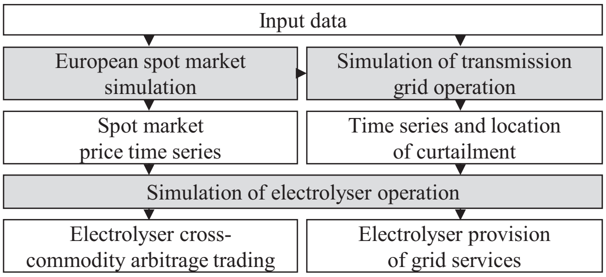

**Fig. 2.** Overview of simulation method.

for electricity price time series for relevant future scenarios. For this, we apply a European spot market simulation, cf. Fig. 2. Based on the spot market price time series and the considered future hydrogen prices, we calculate the electrolyser dispatch due to cross-commodity arbitrage trading. For this, we model a constant hydrogen price for each simulation year neglecting potential price fluctuations that might occur throughout the year. The resulting electrolyser dispatch is input parameter for the evaluation of business models.

The evaluation of electrolyser grid service provision requires an estimation of potential future transmission grid congestions and needs to take into account an estimation of remedial measures applied by grid operators. This includes curtailment of RES feed-in. For this, we apply a model for simulating the transmission grid operation. This simulation uses the market based dispatch of generation units from the spot market simulation as input parameter. These time series for RES curtailment are input for the determination of electrolyser operation due to grid service provision. Table 1 gives an overview of input and relevant output parameters for the models. In the following, we describe the different simulation methods in more detail.

### 2.4. European spot market simulation

Electricity spot market prices are calculated using a fundamental model. This fundamental approach conducts a minimization of the total costs for power generation for an entire year in an hourly resolution for European countries. For solving the optimization problem, we use mixed-integer linear programming solving a proprietary unit commitment model with a commercial optimization solver. The model and its mathematical formulation is described in detail in Refs. [27–29]. Relevant input data is given in Table 1.

Realistic prices are derived from variable production costs, start-up costs and avoided start-up costs. Therefore, detailed technical parameters have to be incorporated. Furthermore, availabilities and reserve provision have to be simulated as well as exchanges of the entire European generation stack. The objective function is set to minimize costs $K$ of power generation $P$ for all market areas $I$, generation units $B$ and time steps $T$:

$$\min \sum_i \sum_b \sum_t K_{b,t}(P_b(t)) \qquad (1)$$
$$\forall\, i \in I, \quad \forall\, b \in B_i, \quad \forall\, t \in T$$

The central constraint is the load coverage, i.e. the generation in each market area $P_b$ combined with imports $P_{Imp}$ and exports $P_{Exp}$ has to cover the load $L$ minus the fixed RES generation $P_{RES}$ in each time step.

$$\sum_b P_b(t) + P_{Imp,i}(t) - P_{Exp,i}(t) = L_i(t) - P_{RES,i}(t) \qquad (2)$$

This problem results in a complex optimization problem with time-linking constraint in the management of storage power units and minimum operating and downtimes of thermal power plants. Thus, a closed-loop formulation of the problem is not feasible in practicable computation times. Therefore, this market simulation method is based on a multi-stage Lagrangian Relaxation and Decomposition approach, cf. Fig. 3.

An approach using linear programming (LP) techniques is used for the first step of the optimization computing an initial solution for the exchanges between market areas. With fixed exchanges, an integer decision determines the optimal power output $P$ and start-up decisions $e$ in a second step. The optimization is solved by iteratively relaxing the load coverage $\mu$, the reserve provision constraints $\lambda$ and the Lagrangian function $L$:

$$\max_P \min_{\lambda,\mu} L(P, e, t, \lambda, \mu) \qquad (3)$$

The minimization problem is formulated as a dual Lagrangian function $D$. Due to the Lagrangian Relaxation the dual function can be decomposed separating it into thermal subproblems $\tilde{D}_{th}$ and hydraulic subproblems $\tilde{D}_{hy}$. Those problems are solved separately.

**Table 1**
Overview of simulation input and output data.

| Input data | Relevant output data |
|---|---|
| *European spot market simulation* | |
| • Generation units in all coupled market areas | • Hourly spot market price time series |
| • Dispatch constraints for generation units (gradients, minimum operation and down times) | |
| • Technical parameters and limited availabilities per unit due to power plant outages | • Dispatch and location for each generation unit |
| • Time series per market area (demand, RES, combined heat and power) | |
| • Exchange capacities between market areas | |
| • Primary energy and emission certificate prices | |
| • Reserve demand | |
| *Simulation of transmission grid operation* | |
| • Dispatch and location for each generation unit | • Time series and location of curtailment |
| • Time series and location of demand and RES | |
| • Transmission grid topology | |
| • Operating limits of transmission grid | |
| • Network related remedial measures including relevant constraints | |
| *Simulation of electrolyser operation* | |
| • Hourly spot market price time series | • Dispatch of electrolyser |
| • Time series and location of curtailment | • Costs of electricity demand |
| • Electrolyser key performance indicators (KPI) | • Hydrogen production |
| | • Revenues from hydrogen sales |

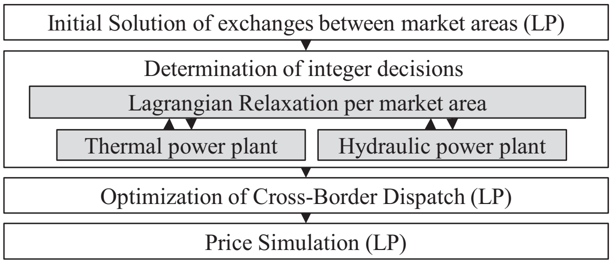

**Fig. 3.** Overview of fundamental day-ahead spot market simulation approach.

Dynamic programming solves the thermal subproblem. A network flow method solves the hydraulic subproblem. A detailed description of the optimization problem can be found in Ref. [27].

$$D(\lambda,\mu) = \tilde{D}_{th}(\lambda,\mu) + \tilde{D}_{hy}(\lambda,\mu) \tag{4}$$

Integer decisions such as thermal unit commitment are adopted from the second stage to the third stage, because results may fail to comply with technical constraint due to the relaxations. Remaining continuous optimization problems are solved in a closed-loop approach in the third stage in order to assure the compliance with time and system coupling constraints. This step is used to calculate the power exchange between market areas considering technical constraints. Main results are cost-minimal power plant dispatch in Europe and cross-border power exchanges.

For the simulation of electricity prices, an additional linear approach is used. The dual variables of the load coverage constraints represent the bidding price of the last cost-optimal power plant in operation. This provides the market clearing price of the spot market. In this context, the bid of a power plant is represented by the objective value in each hour. Additional positive and negative mark-ups for start-up and avoided start-ups are considered using the system costs for the respective hour. In hours with system costs below variable production costs, it is an opportunity for the plant to bid below its variable costs in order to avoid the costs of an additional start-up. Those avoided start-up costs are deducted from the variable costs. The resulting spot market price time series are input for the calculation of electrolyser dispatch for cross-commodity arbitrage trading taking into account the hydrogen price estimates.

### 2.5. End-user price of electricity

For the evaluation of potential business models, it is not sufficient to solely investigate the spot market price of electricity. End-user prices for electricity that apply for electrolyser operators can be significantly higher than the wholesale price due to payments for supply, use of system charges and taxes and levies. In order to account for the cost of supply considering electricity market access costs and aggregator fees, we assume a price component of 30.0 €/MWh based on the average difference between costs of energy and supply for large industrial consumers and mean wholesale market prices based on [12]. Exemptions for grid integrated electrolysers from use of system charges, specific taxes and levies are possible under specific circumstances or are discussed for future applications [12]. While value added taxes are considered within the simulations, we therefore assume exemptions for grid integrated electrolysers from other taxes, levies and use of system charges.

In terms of GHG emission of hydrogen production pathways, various studies indicate a high dependency of the global warming potential of electrolyser operation on the type of electricity supply [30]. Only electrolyser applications using solely RES feed-in are able to significantly reduce GHG emission compared to conventional hydrogen production pathways [31]. In order to classify hydrogen generated by electrolyser as green hydrogen, it must therefore be ensured that the electric energy consumed is generated by RES feed-in. This can be achieved by guarantees of origin (GoO). These certificates assure that the electric energy purchased has been produced from RES and can be traded within Europe. Within this study, we consider a GoO price of 0.4 €/MWh [23].

### 2.6. Simulation of transmission grid operation

For evaluating business opportunities of electrolyser providing grid services, estimations on future grid congestions and appropriate remedial measures by grid operators are necessary. This includes the curtailment of RES and the operation of electrolysers in order to avoid this curtailment.

For planning appropriate remedial measures, transmission grid operators apply specific operational practices such as the (n-1)-principle [32]. This principle states that voltages at all nodes and currents on all lines have to be kept under operational limits in every relevant contingency situation, e.g. tripping of transmission lines. Additionally, transmission grid operators adopt specific regulatory constraints like the hierarchical activation of the most effective and economically efficient countermeasures [33]. Non-costly network related measures such as transformer tapping have to be applied with highest priority. Market related measures may only be implemented if no more network related measures are available. This includes redispatch of conventional power plants. The curtailment of RES is usually the last measure implemented. In order to not overestimate the potential of grid service provision for electrolysers, these operational practices and regulatory constraints need to be taken into account within the transmission grid simulation.

The simulation model used here applies a fundamental approach based on an optimization problem design [34,35]. This proprietary model was developed within EC FP7 project *Umbrella* [36]. It determines optimized remedial measures for a given grid parametrization. The transmission grid simulation model is based on the hourly dispatch of each power plant and load. These are obtained by the market simulation. By transferring this dispatch onto a model of the European transmission grid, this enables the setup of load flow equations, c. f. equation (5). $\underline{\vec{S}}$ denotes the vector of nodal apparent power, $\underline{\vec{V}}$ the vector of nodal voltages and $\underline{\vec{Y}}$ the admittance matrix of the grid. A solution to this load flow problem is obtained by using Newton-Raphson method.

$$\underline{\vec{S}} = 3 \cdot \mathrm{diag}\left(\underline{\vec{V}}\right) \cdot \underline{Y}^{*} \cdot \underline{\vec{V}}^{*} \tag{5}$$

The determination of optimal remedial measures is done by minimizing the violations of operational constraints including overloading of lines in contingency situations according to the (n-1)-principle. In order to reduce the socio-economic welfare loss generated by redispatch and curtailment, the identification of remedial measures considers both costs and effectiveness to eliminate the overloading. equation (6) gives the general formulation of the security constrained optimal power flow problem. $\vec{x}$ describes the state variables of the load flow equations, $\vec{u}$ the decision variables given by the potential remedial measures and $\vec{y}$ the grid admittances. The minimization of objective function $f$ is subject to equality constraints $\vec{g}$ given by the load flow equations of equation (5) and inequality constraints $\vec{h}$ for the range of decision variables and the operational constraints for line loading and

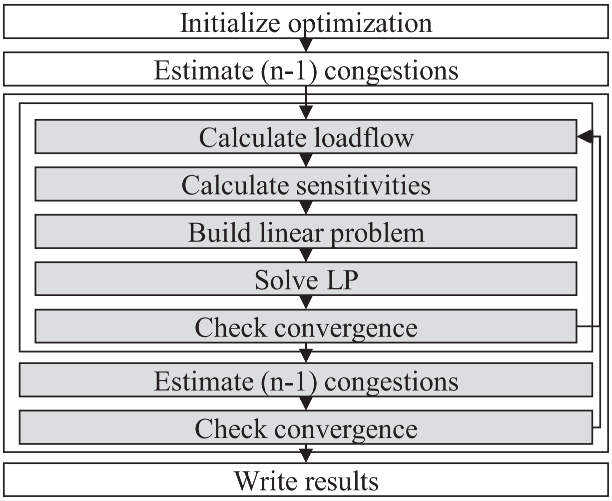

**Fig. 4.** Optimization formulation of transmission grid simulation.

nodal voltages.

$$\begin{aligned} &\min_{\vec{u}} f(\vec{u}) \\ \text{subject to:}\quad &\vec{f}(\vec{x},\vec{u},\vec{y}) = \vec{0} \\ &\vec{h}(\vec{x},\vec{u},\vec{y}) \leq \vec{0} \end{aligned} \tag{6}$$

The problem is solved using a successive linear optimization process as shown in Fig. 4. The optimization formulation starts with an initialization and an estimation of (n-1)-congestions. Based on the solution of the load flow equations, the calculation of sensitivities linearizes the problem. These sensitivities describe the impact of a change of power feed-in at a specific location within the grid on congestions. The model then sets up a linear optimization problem including all degrees of freedom and linear constraints. Thus, equation (6) are simplified to equation (7) with coefficient matrix $\boldsymbol{A}$ and linear constraints $\vec{b}$.

$$\begin{aligned} &\min_{\vec{u}} f(\vec{u}) \\ \text{subject to:}\quad &\boldsymbol{A}\cdot\vec{u} \leq \vec{b} \end{aligned} \tag{7}$$

This linear optimization problem is solved using a simplex algorithm. Since this linearization is a simplification in order to achieve efficient performance, another complex load flow calculation verifies the optimization results. In case of remaining congestions, this procedure is repeated iteratively until all congestions are eliminated. A comprehensive description of the mathematical formulation of the simulation model is given in Ref. [37]. Within this contribution, we considered transformers, reactive power compensation, redispatch of generation units and curtailment of RES feed-in as remedial measures.

In the following, the described model is used in order to identify not only suitable locations within a transmission grid for electrolyser grid service provision but also to estimate the operational hours of the electrolyser within such a scenario. Additionally, we evaluate a business model in which both participation at the spot market for electricity and grid service provision are considered.

### 2.7. Evaluation method

We evaluate the business models in terms of potential electrolyser full load hours for assessing the electrolyser utilization ratio and in terms of the potential profits to be gained by electrolyser participation at different European spot markets for electricity. For evaluating the profitability, we calculate annual net profits *ANP* for each considered scenario. Based on the identified sales of generated hydrogen, annual revenues *AR* are calculated. The electricity purchase as well as other operational cost components are used in order to identify the expected annual operational costs $AC_{OPEX}$. We calculate equivalent annual costs for capital expenditure $EAC_{CAPEX}$ based on annuities of the investment costs. The annual net profit is determined by:

$$ANP = \sum AR - \sum AC_{OPEX} - \sum EAC_{CAPEX} \tag{8}$$

**Table 2**
Key performance and economic data of electrolyser.

| Electrolyser Data | Unit | 2014 | 2024 | 2034 |
|---|---|---|---|---|
| System lifetime | years | 20 | 20 | 20 |
| $\text{CAPEX}_{\text{electrolyser system}}$ | k€/MW | 990 | 614 | 556 |
| $\text{CAPEX}_{\text{storage units}}$ | €/$\text{kg}_{\text{H2}}$ | 470 | 470 | 470 |
| $\text{CAPEX}_{\text{filling centres}}$ | k€ | 2699 | 2699 | 2699 |
| $\text{CAPEX}_{\text{other investment costs}}$ | % | 37.5 | 37.5 | 37.5 |
| Technical efficiency | $\text{kWh}_{\text{el}}/\text{kg}_{\text{H2}}$ | 53.2 | 51.2 | 49.2 |
| $\text{OPEX}_{\text{electrolyser system}}$ | % | 2.2 | 2.2 | 2.2 |
| $\text{OPEX}_{\text{other costs}}$ | % | 4 | 4 | 4 |

Table 2 presents the assumptions for the economic data we use for calculating the net profits. These assumptions are based on an analysis of electrolyser cost structure [10,23]. This data is applied and extrapolated for an alkaline water electrolyser of 10 MW with an output pressure of 30 bar. The CAPEX includes the investment costs for the electrolyser system, hydrogen storage units and filling centers needed for the physical interface with the hydrogen logistical system. Other investment costs include civil costs and non-equipment costs for engineering, commissioning, start-up and grid interconnection as well as costs for the control system and energy management unit. These are calculated based on a fixed percentage of electrolyser system and storage unit CAPEX. We identify the required size of the storage unit based on consecutive downtimes of the electrolyser. It is assumed that the hydrogen storage unit needs to be dimensioned for ensuring a hydrogen supply at a constant rate per hour. The storage size is therefore dependent on the specific business model and selected scenario.

The electrolyser dispatch and the calculated end-user prices for electricity yield operational costs for electricity purchase and efficiency losses. In addition, maintenance, spare parts and replacement of auxiliary components of the electrolyser system contribute to operational costs. These costs are estimated based on a constant factor expressed as percentage of CAPEX for the electrolyser system. Additional operational costs for the operation of the entire facility are expressed as a percentage of CAPEX for other investment costs. Stack replacement costs and system degradation are not considered. We calculate the annuities of investment costs assuming an interest rate of 8%.

Since the future regulatory framework for grid service provision by electrolysers and corresponding reimbursements is uncertain, we evaluate the potential of grid service provision in terms of full load hours.

### 2.8. Selected power system scenarios

For the evaluation of short, medium and long term business opportunities, we investigate power market scenarios for years 2014, 2024 and 2034. For the spot market simulation for 2014, we use historic data for the generation fleet, exchanges between market areas, primary energy prices and GHG emission certificate prices. The simulation for 2024 is based on scenarios B of the

German grid expansion plan NEP [38] and European Mid-Term Adequacy Forecast [39]. Scenario 2034 is based on NEP and the System Outlook and Adequacy Forecast Vision 3 [40]. The visions also include estimations on future primary energy prices as well as GHG emission certificate prices.

The potential of grid service provision by grid integrated electrolysers is examined exemplarily for Germany. The simulations are undertaken for years 2014 and 2024. The transmission grid model for year 2014 is developed based on publicly available information [41]. For 2024, the transmission grid model is derived from scenario B1 2025 GI of NEP [38], the German offshore grid development plan O-NEP 2025 [42] and from the ENTSO-E network development plan TYNDP 2016 [43] for the ENTSO-E area. The geographic distribution of conventional power plants and RES units is based on [44–47].

## 3. Results and discussion

At first, cross-commodity arbitrage trading is assessed for different countries. Secondly, we investigate the potential of grid service provision by electrolyser in terms of utilization ratio. Finally, we investigate, to what extent provision of grid services in addition to cross-commodity arbitrage trading can increase utilization ratio of the electrolyser.

### 3.1. Cross-commodity arbitrage trading

We investigate cross-commodity arbitrage trade for four different European countries representing different, but characteristic market circumstances. This includes systems with a high share of solar power, wind power, a strong transition of the generation stack and an island position. Spain has high solar irradiance and strongly promotes solar power. Germany has comparably high wind speeds and strongly promotes wind turbines. The Netherlands represent a fast transition from conventional to RES systems with an RES share of 10% in 2014 and 56% in 2034. Portugal has a geographic island position leading to little flexibility and strong dependencies on neighboring countries.

Based on the spot market simulation for the chosen scenarios, we calculate the electrolyser dispatch. Fig. 5 depicts the resulting electrolyser full load hours for different hydrogen prices. Fig. 6 displays the corresponding net profits for a 10 MW alkaline water electrolyser.

For a hydrogen price of 6 €/kg that could be achieved within the transportation sector, the electrolyser runs in base load showing very high numbers of full load hours. Net profits are positive in all countries and increasing for future scenarios. Higher shares of RES induce higher net profits. Differences between the market situations in the different countries are visible. Germany shows the highest net profits in all scenarios as RES share is highest compared to the other countries. In the Netherlands, net profits increase strongly between 2014 and 2024 because of the expected strong increase in wind turbine capacity. In Spain and Portugal, net profits increase in 2024. Profits increase in Spain because of the increasing solar feed-in leading to more hours with low spot market prices at noon when the feed-in may surpass the load. Slightly higher profits in Portugal compared to Spain can be explained by the island position because smoothing effects of volatile feed-in and electricity prices are limited to the market area. Profits increase in 2034 for Portugal but decrease for Spain. This is due to the simultaneity of solar feed-in. Feed-in peaks at noon lead to declines of spot market prices during a few hours a day, but this effect is limited. Higher solar power shares and low electricity prices during a few hours cannot compensate for other effects of rising electricity prices. This effect is not visible in Portugal for two reasons: firstly, a higher share of wind turbines leads to lower electricity prices within more hours per year. Secondly, excess energy cannot be exported well due to the island position of the market, leading to deceasing spot market prices for electricity.

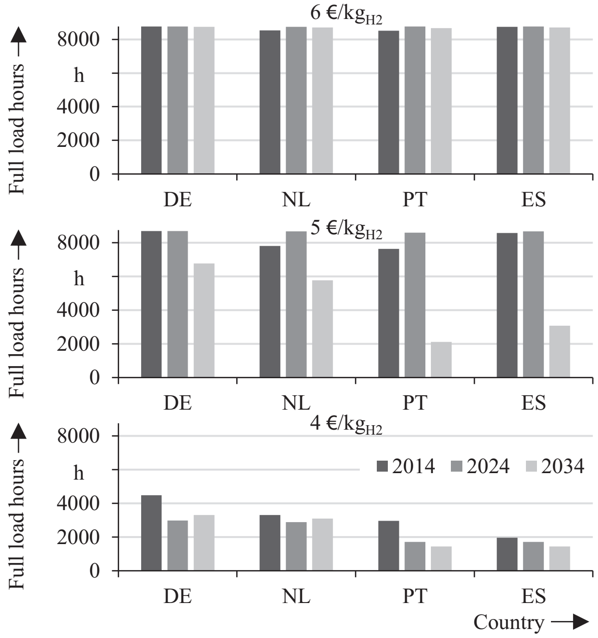

**Fig. 5.** Electrolyser full load hours for cross-commodity arbitrage trading for different hydrogen prices.

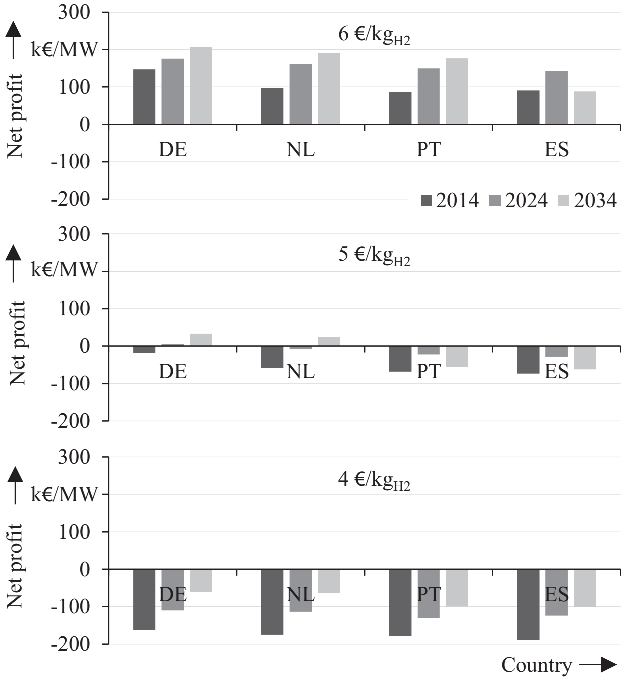

**Fig. 6.** Annual electrolyser net profits for cross-commodity arbitrage trading for different hydrogen prices.

For all considered countries, the operational expenses are higher than annual investment expenses. The highest costs are those for procurement of electricity and for supply and trade. This underlines the importance of low electricity prices for a profitable electrolyser operation and a careful selection of profitable power markets. The exemption from use of system charges and levies is crucial for economically efficient operation.

For decreasing hydrogen prices, full load hours and consequently net profits decrease for all considered countries. For a hydrogen price of 5 €/kg, electrolyser full load hours are still close to full utilization ratio for 2014 and 2024. For 2034, full load hours decline due to the increasing spread in the spot market price for electricity. In terms of net profits, it can be observed that the increasing share of RES leads to an increased profitability of electrolyser operation for future scenarios in Germany and the Netherlands. However, even though full load hours are still high, the decreased revenue due to the lower hydrogen price significantly reduces net profits. For most scenarios net profits are even negative.

For a hydrogen price of 4 €/kg being representative for the industry sector, electrolyser full load hours decline significantly. The electrolyser no longer runs in base load and is in operation between 1500 h and 4500 h per year. In hours of operation, the electrolyser generates positive contribution margins. These are however not sufficient to cover the annuity of investment costs. The decline in hydrogen sales revenues results in negative net profits in all scenarios and times steps and thus leads to unprofitable electrolyser operation.

### *3.2. Provision of grid services within the transmission system*

Since for a decreasing hydrogen price, the utilization ratio of the electrolyser drops for cross-commodity arbitrage trading, a second source of revenues could be the provision of transmission grid services. The spare capacity in situations that are unprofitable for cross-commodity arbitrage trading may be used for that service. We investigate the full load hours that can be expected for corresponding business models exemplarily for Germany.

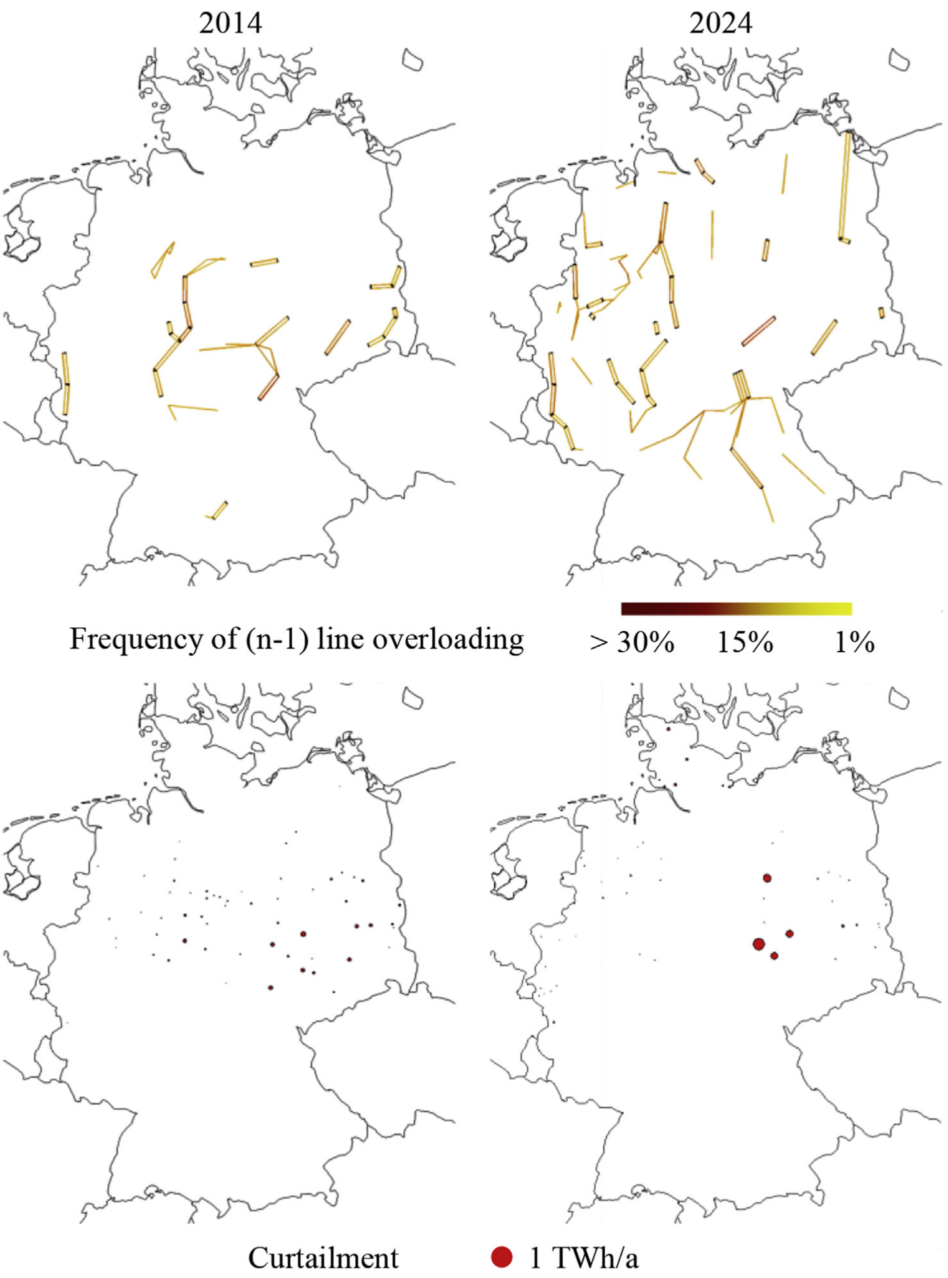

**Fig. 7.** Frequency of (n-1) line overloading and amount and location of RES curtailment for transmission grid simulation for 2014 and 2024.

Fig. 7 depicts the results of the transmission grid simulation for 2014 and 2024 in terms of frequency of (n-1) line overloading before remedial measures by the transmission grid operator and the resulting RES curtailment that is needed in order to remove all (n-1) congestions. Power transfers from wind power feed-in in northern Germany to load centers in southern Germany result in congestions on power lines leading from north to south in situations with exceptionally high power transfers. Compared to 2014, the total number of overloaded lines increases for 2024 while the frequency and height of line overloading decreases. This is due to the expected grid expansion from 2014 to 2024 that does not entirely keep up with the expected increase in wind power capacity in northern Germany by 2024 and the nuclear power phase-out by 2022.

The necessary curtailment is mainly located north of the identified congestions and mainly affects onshore wind power plants in eastern Germany. The total amount of simulated redispatch of conventional power plants is 6.2 TWh while simulated curtailment accounts for 0.5 TWh. A comparison with historic redispatch and curtailment volumes of 2014 for transmission grid operators, i.e. 5.2 TWh respectively 0.9 TWh [48], shows that the applied fundamental approach of transmission grid simulation does not model the reality in an exact way. Among other factors, this is due to the neglecting of topological measures and the assumption of perfect foresight. However, since historic and simulated values only differ slightly, this comparison shows that the approach is a reasonable method for modeling RES curtailment. While the total redispatch decreases to 2.4 TWh by 2024, the total RES curtailment increases to 0.9 TWh.

Based on the results of RES curtailment, we identify the potential of grid service provision by electrolysers. In order to effectively absorb RES feed-in that would otherwise be subjected to curtailment, the electrolyser needs to be located within the vicinity of RES units that are frequently curtailed. Uncertainties due to the future allocation of RES units and the fundamental characteristic of the applied approach impede an exact identification of locations that are best suited for grid service provision by electrolysers. However, the approach enables to identify regions within the transmission grid that are most likely to be suitable. Consequently, for electrolyser business models based on transmission grid services, suitable locations for electrolyser placement are expected to be within eastern Germany.

Fig. 8 shows the corresponding full load hours for the ten locations that are best suited for grid service provision. All of these locations are located within eastern Germany. The results highlight the significant dependency of electrolyser full load hours on the specific grid location. While in 2014 the full load hours for the best suited location are estimated at 447 h, the full load hours rapidly decrease for other locations. Compared to 2014, the potential electrolyser full load hours increase for 2024 up to 729 h.

Due to expected delays in the realization of grid expansion projects in Germany, we investigate the impact of a delayed grid expansion on electrolyser full load hours by 2024. For this we assume that out of the four planned HVDC transmission links from northern to southern Germany only the westernmost one from Osterath to Philippsburg is realized. This corresponds to a decrease in total transfer capacity from north to south by 6 GW [38]. The delayed grid expansion leads to a significant increase of congestions. The total volume of RES curtailment increases to 9.8 TWh. Six locations are identified, for which the electrolyser shows more than 2000 full load hours. These are located within eastern Germany and in Schleswig-Holstein, the northernmost state of Germany. The best suited location shows 2721 full load hours.

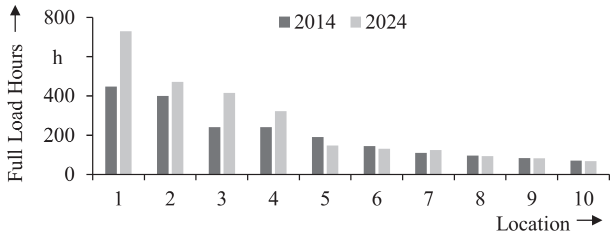

**Fig. 8.** Electrolyser full load hours for different locations within the transmission grid for Germany.

### 3.3. Spot market participation and provision of grid services

In the following we analyze the potential of grid service provision in addition to cross-commodity arbitrage trading in order to increase electrolyser profitability especially for hydrogen price scenarios that lead to non-profitable electrolyser operation. The following electrolyser application scenarios are compared:

1. Cross-commodity arbitrage trading
2. Cross-commodity arbitrage trading with additional provision of grid services
3. Cross-commodity arbitrage trading with additional provision of grid services assuming a delay in grid expansion until 2024 (only westernmost HVDC link in Germany realized)

Fig. 9 shows corresponding full load hours for these electrolyser application scenarios for different hydrogen prices. For hydrogen injection into the natural gas system, we consider hydrogen injection tariffs that equal the natural gas price for the corresponding scenarios, i.e. hydrogen prices of 0.5 €/kg in 2014 and 0.6 €/kg in 2024. For these scenarios, the hydrogen price is too low for cross-commodity arbitrage trading and full load hours are zero. Consequently, in case grid services are offered in addition to spot market participation, the corresponding electrolyser full load hours for application scenario 2 and 3 are solely based on grid service provision: 447 h for 2014, 729 h for 2024 and 2721 h for 2024 with a delayed grid expansion.

For a hydrogen price of 3 €/kg, cross-commodity arbitrage trading leads to full load hours of 741 h in 2014 and 320 h in 2024. In case of additional grid service provision, the utilization ratio can be increased by 50% in 2014 and by 200% in 2024. For the scenario of delayed grid expansion, the utilization ratio is increased up to

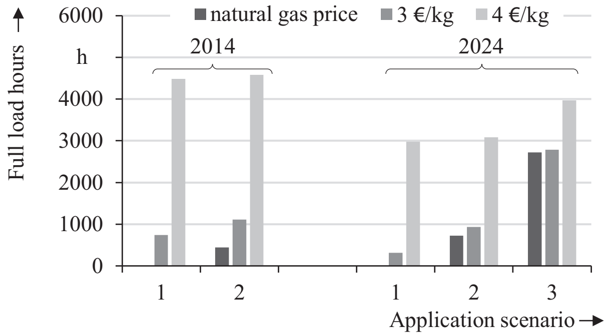

**Fig. 9.** Maximum electrolyser full load hours for Germany: (1) for cross-commodity arbitrage trading, (2) for cross-commodity arbitrage trading and provision of grid services, (3) for cross-commodity arbitrage trading and provision of grid services with delay in grid expansion.

2785 h. For a hydrogen price that is representative for industrial hydrogen applications, i.e. 4 €/kg, the additional provision of grid services leads to an increase of electrolyser utilization ratio by 2.1% in 2014 and 3.4% in 2024. In case of a delayed grid expansion by 2024, the electrolyser utilization ratio increases by 33.1%. In case of higher hydrogen prices like 5 €/kg or 6 €/kg, the electrolyser already operates at almost full utilization ratio due to cross-commodity arbitrage trading at the spot market. Consequently, in this case additional provision of grid services is not possible as the utilization ratio cannot be increased further.

It can be seen that additional provision of grid services is able to increase electrolyser utilization ratio specifically in case the full load hours based on cross-commodity arbitrage trading are low. On the one hand, situations with a high feed-in of RES lead to low prices at the spot market and thus promote cross-commodity arbitrage trading. On the other hand, the high feed-in of RES in these situations also leads to frequent grid congestions resulting in the need for curtailment. Consequently, situations with low electricity prices and situations with need for grid service provision often coincide. As a result, the provision of grid services in addition to spot market participation shows potential of increasing the electrolyser utilization ratio especially in case of low hydrogen prices. Assuming corresponding future remuneration schemes for grid service provision by electrolysers, profitability of business models might therefore be increased specifically in scenarios where cross-commodity arbitrage trading alone leads to unprofitable operation.

## 4. Conclusion

Based on the investigations above, we can conclude that cross-commodity arbitrage trading is especially promising in those countries that show high shares of RES in general and wind power specifically. Due to the rising share of RES as well as decreasing investment costs for electrolysers for future scenarios, it can be expected that business models become more profitable in future applications.

The results also highlight the significant dependency of business model efficiency on the hydrogen price that customers are willing to pay. As hydrogen price estimates for future scenarios are highest within the transportation sector, this sector is most promising in terms of profitable electrolyser operation. However, for profitable operation, exemptions from specific components of end-user prices for electricity are crucial. In case of lower hydrogen prices within the industry sector, electrolyser full load hours and net profits drop and profitable operation cannot be achieved for all scenarios. For applications of hydrogen injection into the natural gas system, electrolyser business models are unprofitable for all considered future scenarios.

In terms of grid service provision by electrolysers in order to avoid curtailment of RES, full load hours are highly dependent on the point of grid connection. For corresponding business model, only those locations are favorable that are within the vicinity of RES units subjected to a significant amount of curtailment. On the one hand, it could be shown that even if the location of grid connection is well suited for grid service provision, full load hours are significantly lower compared to cross-commodity arbitrage trading with the hydrogen transportation sector. On the other hand, the results indicate that provision of grid services in addition to cross-commodity arbitrage trading can increase electrolyser utilization ratio especially in case of low hydrogen prices. Therefore, assuming corresponding future remuneration schemes for grid service provision by electrolysers, profitability of business models might be increased specifically in scenarios where cross-commodity arbitrage trading alone leads to unprofitable operation. This includes both hydrogen supply towards industrial customers as well as hydrogen feed-in into the natural gas system.

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