elyntegration

Grid Integrated Multi Megawatt High Pressure Alkaline Electrolysers for Energy Applications

Assessment of market potential

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1 EXECUTIVE SUMMARY

This study presents the results of task 6.1 of the ELYntegration project. The main objective of this task is the assessment of the market potential for future electrolyser applications with a close and dynamic interaction with the electric power grid and with the power markets taking into account high shares of renewable energy sources. Within this assessment, relevant target sectors for hydrogen demand are addressed and major risks and drivers for the market potential of electrolyser business models are identified. Based on these identified risks and drivers, a sensitivity analysis is conducted in order to quantify the impact of these influencing factors on the profitability of electrolyser operation.

1.1 Target Sectors for Hydrogen Demand

Grid-integrated electrolysers participating in electricity markets that are subjected to high shares of renewable energies have the potential of helping European goals of decarbonisation by production of sustainable and renewably generated hydrogen for various sectors of hydrogen demand. Figure 1 shows the potential key markets for future green hydrogen demand.

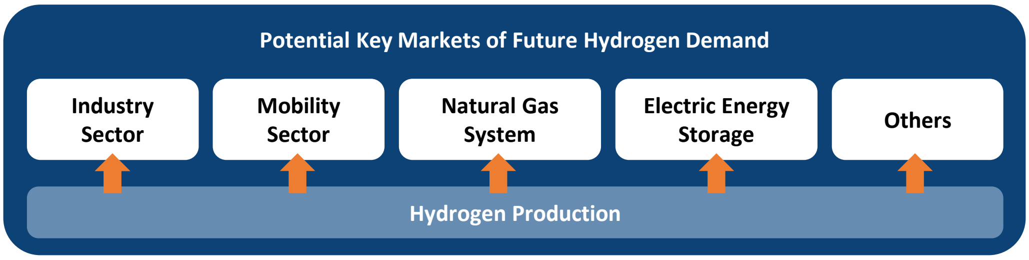

Figure 1: Potential key markets of future hydrogen demand

Industry Sector

The analysis on the hydrogen demand within the industry sector shows that **especially ammonia and methanol production as well as crude refineries show a large demand in hydrogen and can therefore be considered as major target industrial sectors for use of green hydrogen** based on electrolysis.

Within the European Union, ammonia and methanol production facilities and crude refineries are mainly located Germany, Poland, the Netherlands, Italy and France. Consequently, within these countries electrolysers might find it easier to find customers in terms of supplying industrial customers with green hydrogen.

In terms of suitable electrolyser locations within these countries for industry customers, electrolyser should be installed within the vicinity of the customer in order to avoid significant additional costs for hydrogen transport. In this case, grid service provision by the electrolyser might not be a business opportunity as flexibility provision towards grid operators is required at specific locations within the power grid. However, business models that are directed towards cross-commodity arbitrage trading and provision of control reserve are independent on the specific location within country.

Mobility sector

The second major future target sector for hydrogen demand is the mobility sector in terms of the development of fuel cell electric vehicles. So far, hydrogen mobility has not yet seen its breakthrough due to higher investment costs of these vehicles as well as the lack of a substantial hydrogen refuelling infrastructure. Within Europe however, there are multiple initiatives for the promotion of hydrogen mobility and a significant increase of hydrogen mobility is expected in future. Since the estimated future hydrogen prices are significantly higher compared to other target sectors, the **mobility sector shows the most promising market potential in the medium term**.

Natural Gas System

Currently, the electrolyser applications in the natural gas system are negligible and both in the short and in the medium term corresponding business models are not expected to be profitable. On the other hand, **long term opportunities are given due to the large storage capacity for renewable power feed-in** from photovoltaic and wind power plants.

Taking into account the decarbonisation goals of the European Union, it can be envisaged that green hydrogen can achieve higher feed-in tariffs than the spot market price of natural gas thus increasing electrolyser profitability.

1.2 Drivers and Risks

Within this study main drivers and risks were identified that impact the market potential of electrolyser business models. Besides the development of the hydrogen market and potential future hydrogen prices itself, these drivers and risks include

- the end-user price of electricity,
- the development of the power generation system in Europe,
- the price of emission certificates,
- policies towards energy storage systems,
- the development of flexibility provision by alternative new technologies for electrolyser business models directed towards provision of control reserve and
- the design of future flexibility markets.

1.3 Sensitivity Analyses

In order to assess consequences of main market influences on electrolyser business model profitability, sensitivity analyses are conducted within this study. These analyses are based on the methods and calculations presented in deliverable 2.3 of the ELYntegration project [1].

End-user prices for electricity

In a first sensitivity analysis, the impact of different end-user prices for electricity on the profitability of electrolyser business models is evaluated in terms of cross-commodity arbitrage trading. These end-user prices include taxes, levies and grid fees.

Within these calculations, it is assumed that the hydrogen is sold to the hydrogen mobility sector at 6 €/kg. The results indicate, that profitable electrolyser operation can be achieved for all considered countries and future scenarios in case exemptions from taxes, levies and grid fees are considered. In case only exemptions from grid fees are considered, profitable operation can only be achieved for future scenarios for Spain and the Netherlands while electrolyser operation is unprofitable in Germany and Portugal. In case of exemption are considered only for taxes and levies and in case no exemptions are considered, the electrolyser operation is unprofitable for all considered countries and future scenarios.

Consequently, it can be concluded, that exemptions from additional end-user price elements for electricity are crucial for a profitable electrolyser operation in cross-commodity arbitrage trading.

Hydrogen prices

The second sensitivity analysis conducted within this study is directed towards the impact of different hydrogen prices on the profitability of electrolyser cross-commodity arbitrage trading. Figure 2 shows the corresponding electrolyser net margins for all considered countries and a hydrogen price of 5 €/kg and 7 €/kg. The results show that the sales prices for hydrogen have an essential impact on business models. Net margins and thus business models show to be very sensitive towards changes in hydrogen prices. Therefore, opportunities of hydrogen sales have to be analysed very closely when developing business cases for specific locations.

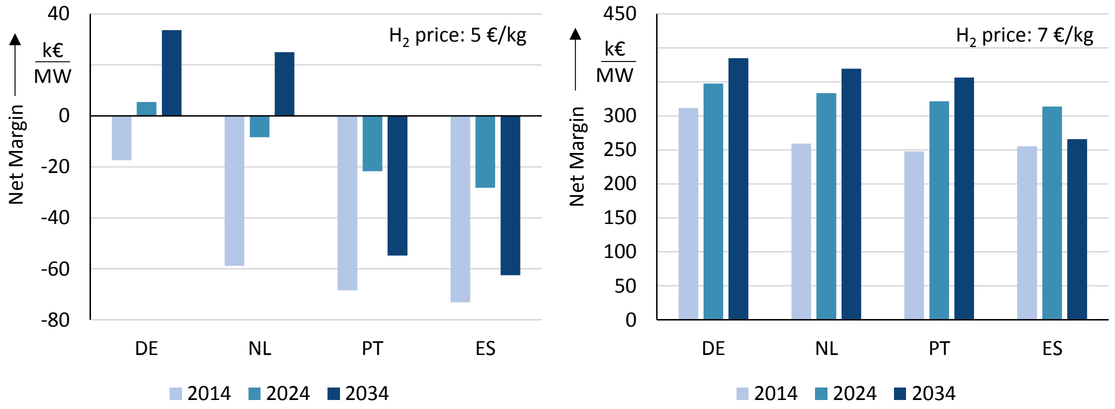

Figure 2: Electrolyser net margins for 2024 considering different hydrogen prices

Share of RES within Generation System

Within the sensitivity analyses, the impact of a different share of renewable energy sources within the European generation system on the profitability of electrolyser business models was investigated. Figure 3 shows the results of the spot market simulation for a generation system of 20 % less RES compared to the base case simulation and 20 % more RES compared to the base case simulation. The results indicate that the composition of the future generation fleet has a significant impact on potential net margins for electrolyser market potential as well. While for a lower RES share the electrolyser net margins are significantly reduced compared to the base case scenario for all considered countries, higher shares of RES lead to a slight increase of electrolyser net margins.

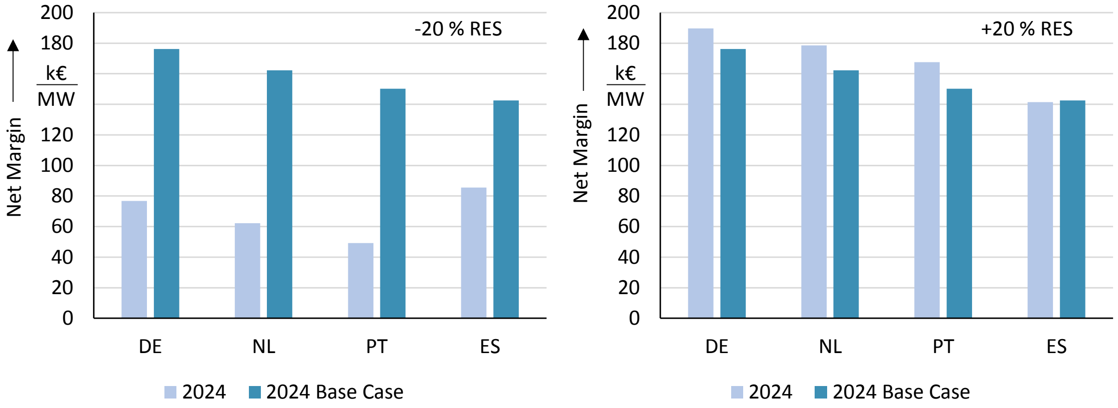

Figure 3: Electrolyser net margins for 2024 for a scenario with 20 % more RES production and with 20 % less RES production compared to the base case

Transmission grid expansion

In terms of grid service provision, the sensitivity analysis on a Germany transmission grid model showed, that not only the location of an electrolyser within the transmission grid has a large impact on potential operational hours based on a future flexibility market for grid services but also the future topology of the transmission grid. Especially in case of a delayed transmission grid expansion e.g. due to prolonged approval procedures of new transmission lines, higher amounts of RES curtailment can be expected thus resulting in higher electrolyser full load hours in case of grid service provision.

1.4 Key findings

- The most attractive target sector for hydrogen demand is the mobility sector since within this sector the expected future hydrogen prices are highest.
- Within the industry sector, especially ammonia and methanol production facilities and crude refineries are promising for electrolyser applications due to their large amounts of hydrogen demand and the potential of reducing greenhouse gas emissions by use of green hydrogen.
- The market potential of electrolyser is especially high in case the generated hydrogen is sold to hydrogen customers in the mobility sector.
- Countries that not only show low spot market prices for electricity but also low additional end-user charges for electricity show promising market potential for future electrolyser applications are especially promising for future electrolyser business models.
- Countries for which future scenarios are dominated by RES are especially promising for future electrolyser business models.
- Countries for which high amounts of RES curtailment is expected in future have a market potential in terms of grid service provision by electrolyser.

2 OBJECTIVES

The research and innovation project „Grid Integrated Multi Megawatt High Pressure Alkaline Electrolysers for Energy Applications“ (ELYntegration) is focused on the design and engineering of a robust, flexible, efficient and cost-competitive single stack multi megawatt high pressure alkaline water electrolyser (hereafter referred to as electrolyser). Besides the design and demonstration of an industrial prototype of a 250 kW electrolyser taking into account all technical improvements for stack, membrane, electrode and balance of plant design gained throughout this project, one main goal of ELYntegration is the investigation and assessment of future grid integration and future energy applications for electrolysers.

This deliverable presents the results of task 6.1 of the ELYntegration project. The main objective of this task is the assessment of the market potential for future electrolyser applications with a close and dynamic interaction with the electric power grid and with the power markets.

The market potential of these electrolyser applications is highly dependent on the specific business model and the corresponding key markets. On the product side of the electrolyser, these key markets include the hydrogen and natural gas market. On the electricity side of the electrolyser, the relevant markets are the spot market for electric energy, the control reserve markets of the power system and potential future flexibility markets for grid services. Specific business models directed towards these different markets and corresponding operational strategies for electrolyser unit commitment are presented in detail in deliverable 2.3 of the ELYntegration project [1]. While deliverable 2.3 focuses on the analysis, development and evaluation of these specific business models, this deliverable targets a more general assessment of market potential identifying target sectors, business climate as well as potential risks and drivers that impact a wider implementation of electrolyser applications for these business models. Consequently, throughout this report, results of deliverable 2.3 are taken into account and referenced.

2.1 Target Sectors for Hydrogen Demand

The objective of the first part of this study is directed towards identifying the market potential in terms of expected hydrogen demand. An analysis of different target sector for hydrogen demand is presented. Special focus is given to

- chemical industry,
- crude refinery industry,
- mobility sector,
- natural gas sector and
- other potential target sectors.

Based on this analysis of the presence and future development of end-users of hydrogen, the business climate for electrolyser applications is evaluated. The final goal of this part is to identify attractive hydrogen demand sectors as well as countries within Europe with a high net demand for hydrogen taking into account other hydrogen production pathways within these countries. In terms of the hydrogen side of the electrolyser business models, these countries would be suited for electrolyser applications.

2.2 Potential Drivers and Risks

The second part of the deliverable is directed towards potential drivers and risks. The objective of this part of the study focuses on the identification of major influencing factors that are expected to have a significant impact on the future market potential for grid integrated water electrolyser. This includes uncertainties and risks perceived by potential investors in electrolyser technology with regards towards short and medium and long term opportunities within the relevant markets. Potential drivers that might improve business climate for electrolyser applications are addressed. These factors include

- future scenarios on the development of the European power generation system with impact on spot market and control reserve markets,
- the price of CO_2 emission certificates influencing both prices for hydrogen and electricity,
- policies towards energy storage systems as potential drivers for electrolyser units,
- end-user prices for electricity and potential future exemptions from taxes or other surcharges to be faced by electrolyser units,
- potential future competitors within control reserve markets that might lower revenues from control reserve markets in corresponding business models and
- uncertainties related to the design of future flexibility markets for electrolyser applications within grid services.

This discussion is closely related to the assessment of potential business models in deliverable 2.3 of the ELYntegration project [1] as it determines factors that influence the revenues to be expected by each business model. Based on this assessment, influencing factors are selected in order to run a sensitivity analysis on the simulations presented in deliverable 2.3.

2.3 Sensitivity Analysis

Based on the identified major risks and drivers for electrolyser application, a sensitivity analysis is conduced. The objective of this task is the quantification of the influence of these factors on the contribution margin to be expected by the business models. This is done by simulations based on scenarios presented in deliverable 2.3 with changes in the simulation environment according to the identified influencing factors. This sensitivity analysis includes the assessment of

- the impact of end-user prices for electricity,
- the influence of different hydrogen prices seen by the electrolyser,
- the effect of a different composition of the future European generation system in terms of different RES shares and
- the impact of a delayed transmission grid expansion process on the operational hours of an electrolyser providing grid services.

3 DESCRIPTION OF WORK

3.1 Target Sectors for Hydrogen Demand

Grid-integrated electrolysers participating in electricity markets that are subjected to high shares of renewable energies have the potential of helping European goals of decarbonisation by production of sustainable and renewably generated hydrogen. This “green” hydrogen can be used in various end-user applications.

In the following, target sectors for green hydrogen and the corresponding business climate for electrolysers are investigated. The analysis focuses on current and future developments in terms of sectors having hydrogen demand (see Figure 4) thus presenting potential future customers for both electrolyser hydrogen and electrolyser itself. This chapter also aims at comparing the evolution of hydrogen demand between different countries in Europe in order to assess which countries might show largest business potential for electrolysers.

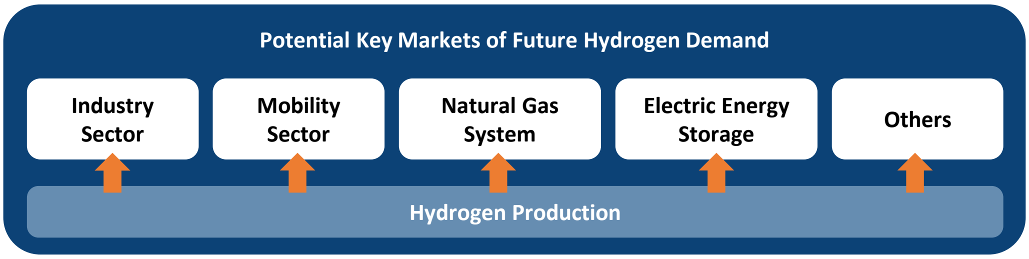

Figure 4: Potential key markets of future hydrogen demand [1]

In 2010, the global hydrogen demand was estimated at 43 Mt, while the European hydrogen demand accounted for around 16 % of the global hydrogen demand (6.9 Mt/year). Studies state that this demand will rise by a yearly rate of around 1 % and will reach around 50 Mt in 2025 [2]. While currently most of the hydrogen is generated via steam methane reforming and is therefore subjected to considerable greenhouse gas emissions, the application of green electrolyser hydrogen can lead to significant reductions in greenhouse gas emissions.

The industry sector accounts for more than 90 % of the hydrogen demand within Europe (6.2 Mt/year) [2]. Currently, other sectors like mobility, the natural gas system and electric energy storage as well as other applications such as heating show a significantly lower amount of hydrogen demand compared to the industry sector. However, in the future, especially the mobility sector in terms of fuel cell electric vehicles (FCEV) show large promise in use of green hydrogen in order to aid European decarbonisation goals.

3.1.1 Industry Sector

While deliverable 2.3 of the ELYntegration project presents a detailed discussion on hydrogen prices to be expected within the industry sector [1], in the following, an evaluation of current and future hydrogen demand and potential customers is given.

Within the industry sector, 63 % of hydrogen demand originates in the chemical industry, around 31 % in the crude refinery industry and 6 % in the metal processing industry. Less than

1 % of hydrogen consumption is used in liquefied form e.g. for rocket and automotive fuels (see Figure 5) [3]. Consequently, by far the largest customers of hydrogen are large companies of the chemical industry. In combination with the refinery processes, these sectors account for 94 % of the total industry hydrogen demand.

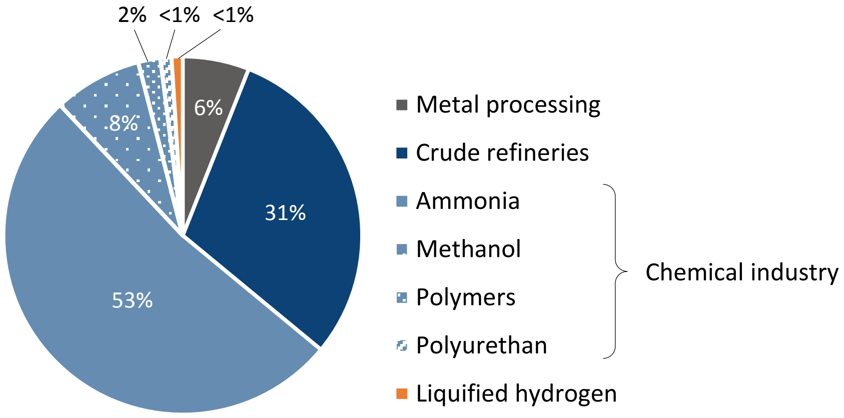

Figure 5: Global share of hydrogen consumption within industry sector [3]

Ammonia production

Within the chemical industry, ammonia production based on the Haber-Bosch process accounts for more than half of the total industry hydrogen demand (around 3.3 Mt/year within Europe). Since most of the global ammonia production is used as fertilizers for the agricultural sector, the hydrogen demand of the chemical industry is mainly driven by the fertilizer industry. Main European producers of ammonia are companies such as Yara having large facilities in Sluiskil, Netherlands (1,900 kt) and Brunsbüttel, Germany (800 kt). Typical ammonia production plants usually require 57,500 to 115,000 tons of hydrogen per year [2]. Considering an electrolyser with a capacity of 10 MW, an electric energy demand of 52 MWh/t_{H2} and 100 % availability, this would require 34 to 68 electrolysers for covering the entire hydrogen demand of one ammonia production plant.

While the global ammonia production is dominated by China covering 32 % of the total global production in 2012, the share for European ammonia production capacities of around 15 % spread out over 17 countries and 42 plants [4]. As shown in Figure 6, the largest capacities for ammonia production within Europe can be found in Germany, Poland and the Netherlands. Over the past 20 years, the European ammonia production has stayed relatively constant, though its market share of the global ammonia production decreased. In 2014/2015, the net import of ammonia for EU-28 accounted for around 13 % of its total ammonia demand [5].

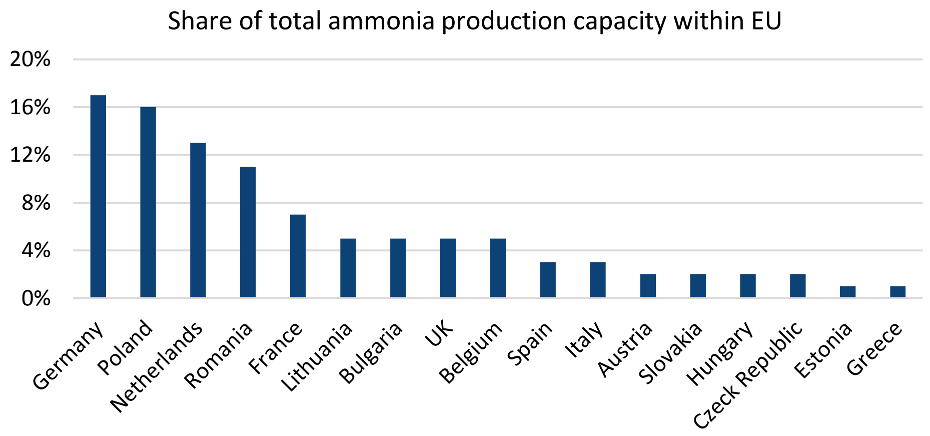

Figure 6: Share of total ammonia production capacity within EU countries in 2012 (total capacity 20,613 k tonnes) [4]

Within Europe, ammonia production mainly relies on natural gas as a feedstock due to availability issues, low costs and its high hydrogen content compared to alternatives such as coal and crude oil [4] [5]. Within the first step of ammonia production, steam methane reforming (SMR) is used for the generation of hydrogen. In this case, natural gas is the key cost factor of ammonia production accounting for approximately 70-85 % of the total production costs [4]. Currently, the use of other alternatives for hydrogen production such as water electrolysis are negligible. In order to reduce greenhouse gas emission of the hydrogen production process, water electrolysis is a viable alternative for aiding European decarbonisation goals [5].

Crude refining

The second largest sector of hydrogen demand is the crude refining industry accounting for 31 % of the industry consumption (around 1.9 Mt/year in Europe). Here, hydrogen is used for example during the production of gasoline, kerosene, diesel and other fuels out of crude oil. Refinery processes with a high demand of hydrogen include hydro treating, hydrocracking and desulphurisation. Main European companies of crude refining include international oil companies such as Total S.A., Shell, ExxonMobil and BP.

The EU share of the global crude processing capacity in 2008 accounted for around 18 % [6]. European countries with the largest crude processing capacities are Germany, Italy, France and the United Kingdom (see Figure 7). The largest refineries within Europe are located in Rotterdam (Netherlands), Antwerp (Belgium) and Normandy (France). Typical refinery plants operate with hydrogen production capacities in the range of approximately 7,200 to 108,800 tons of hydrogen per year [2]. Considering an electrolyser with a capacity of 10 MW, an electric energy demand of 52 MWh/t_{H2} and 100 % availability, this would require 4 to 64 electrolysers for covering the entire hydrogen demand of one refinery plant.

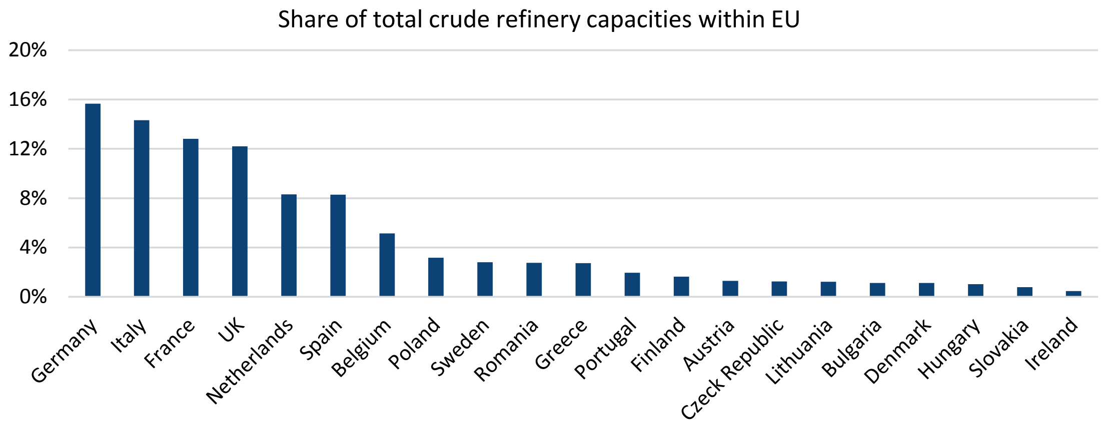

Figure 7: Share of total crude refinery capacities within EU countries (total 777.8 Gt/year) [6]

As discussed in deliverable 2.3 of the ELYntegration project [1], large shares of the hydrogen demand within refinery processes can be covered by hydrogen being generated as a by-product on site as part of other refinery processes e.g. the reforming of naphtha into high-octane products. However, the amount of by-product hydrogen usually only covers a portion of the total hydrogen demand of refineries. For example, the net hydrogen demand of refineries within France accounts for approximately 50 % (161.3 kt/year) and within Germany for approximately 32 % (144.4 kt/year) [7]. Considering an electrolyser with a capacity of 10 MW, an electric energy demand of 52 MWh/t_{H2} and 100 % availability, this would require 96 electrolysers in France and 86 electrolysers in Germany for covering the entire net hydrogen demand.

Since hydrogen is mainly used for hydrogenation processes during cracking of heavier crudes resulting in an increased hydrogen content and thus lighter products, the demand of hydrogen in the refining industry is expected to increase. This is due to the increasing demand for lighter crude products such as diesel, naphtha and kerosene on the one hand and the increasing exploitation of heavier crudes (e.g. tar and oil sands) on the other hand. Therefore, it is expected that the hydrogen demand within the refinery industry will increase reaching double of hydrogen demand of 2005 in year 2030 [8].

In the past, the hydrogen demand was mainly covered by hydrogen generation based on catalytic reformation of naphtha. Currently, net hydrogen demand is mainly filled with hydrogen production from SMR [7]. However, it is expected that the hydrogen demand at refineries will be increasingly covered by purchase of merchant hydrogen from gas suppliers. This trend can also be seen within the United States [9]. Since refineries show a growing proportion of CO_2 emissions originating in the increasing demand of hydrogen, in future, the application of electrolysis is also viable in order to reduce greenhouse gas emissions as long as production costs are competitive [8] [10].

Methanol

Around 8 % of the total global industry hydrogen demand originates in the production of methanol (around 496 kt/year in Europe) [2] at currently more than 90 methanol plants with a global production capacity of more than 110 Mtons of methanol per year [11]. Within Europe, main methanol production facilities are located within the Netherlands and Germany. The characteristic amount of hydrogen demand of a methanol plant is around 15,000 to 80,000 tons of hydrogen per year. Considering an electrolyser with a capacity of 10 MW, an electric energy demand of 52 MWh/t_{H2} and 100 % availability, this would require 9 to 50 electrolysers for covering the entire hydrogen demand of one methanol production plant.

The conventional feedstock in methanol processing is natural gas that is used in order to produce a mixture of CO, CO_2 and hydrogen (synthesis gas) via steam methane reforming. This synthetic gas is then used for methanol production. Consequently, green methanol pathways using green hydrogen based on water electrolysis can significantly reduce greenhouse gas emissions. Currently, projects at demonstration level and pilot plants exist that are directed towards the production of green methanol or the synthesis of chemicals (power-to-liquids) from CO_2 capture and electrolytic hydrogen [12] [13] [14] [15].

Metal processing

The hydrogen demand for metal processing within steel industry accounts for a share of 6 % of the total global industry hydrogen demand (around 372 kt/year in Europe). Currently, main hydrogen demand arises in processes for the reduction of iron ore as well as in uses of forming and blanketing gas [3]. The typical hydrogen consumption of a metal processing plant is around 36 to 720 tons per year [2]. Considering an electrolyser with a capacity of 10 MW, an electric energy demand of 52 MWh/t_{H2} and 100 % availability, the hydrogen production of one single electrolyser would cover the demand of 2.5 to 50 metal processing plants. As explained within deliverable 2.3 of the ELYntegration project [1], by-product hydrogen within steel industry is currently mainly used for contributing to the heat demand on site resulting in an increased overall energy efficiency of the operation. Generally, the generated hydrogen could also be used for other purposes. However, due to low hydrogen purities of by-product hydrogen, many industry purposes would require extensive purification [8].

Other industry sectors

The hydrogen demand of other industry sectors including chemical industries such as the production of polymers (nylon) and polyurethanes (resins) as well as other applications as rocket or automotive fuel and within the semiconductor industry accounts for only a fraction of the total industry demand of hydrogen. Typical plant capacities for these sectors can be found within [2]. Smaller amounts of hydrogen demand can also be found in the food industry where the hydrogenation process is used for oil and fat. Within this process, unsaturated fat is saturated, which requires hydrogen. This process is typically used for the development of margarine and similar hardened fats for human consumption. Currently, this industry represents only a small fraction of the total hydrogen consumption [2] and is not expected to increase in size within near future because the process also develops trans fats, whose effects on health have been discovered to be harmful. Concluding, the hydrogen business market for electrolysers is much smaller within these industry sectors. However, viable electrolyser applications may especially arise within sectors that depend on a high purity level of hydrogen such as the semiconductor industry.

By-product hydrogen from chlorine production

When identifying countries with large hydrogen net demand, it also needs to be considered, that several industry processes generate hydrogen as a by-product. It needs to be taken into account that within some of these industrial processes, large amounts of by-product hydrogen that are not used on site and are therefore sold as merchant hydrogen to large gas companies or other industrial customers thus reducing the total hydrogen net demand of specific countries. This especially holds true for hydrogen generated within chlorine production processes. For example, by-product hydrogen from chlorine production accounted for around 9 % of total German hydrogen production within 2015 [16]. Within the merchant hydrogen market, electrolyser hydrogen would then need to compete with this by-product hydrogen. Figure 8 shows that within Europe by far the largest amount of chlorine is produced in Germany. Therefore, especially in Germany a significant by-product hydrogen amount based on chlorine production can be expected.

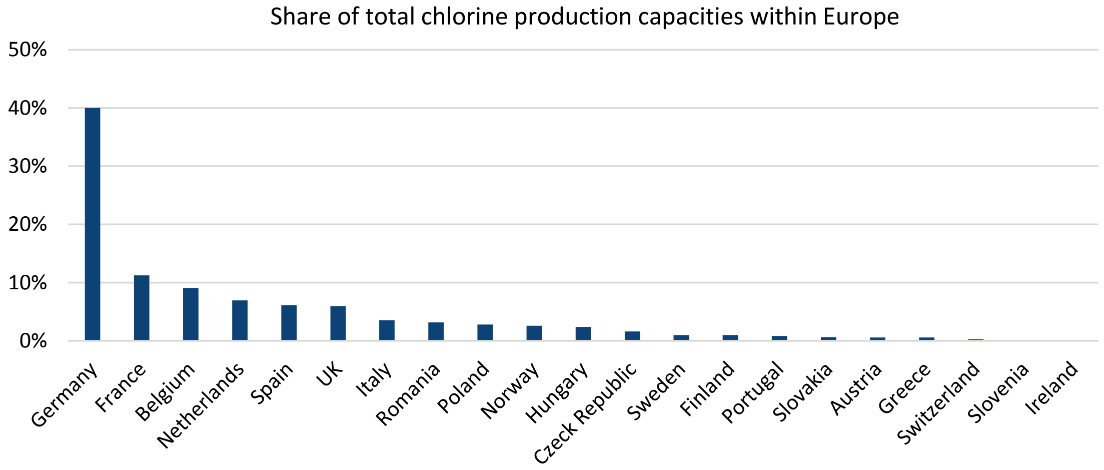

Figure 8: Share of total chlorine production capacities based on chlor-alkali methods within Europe (total capacity 12,174 kt/year) [17]

Conclusion on industry sector

The analysis on the hydrogen demand within the industry sector shows that especially ammonia and methanol production as well as crude refineries show a large demand in hydrogen and can therefore be considered as major target industrial sectors for use of green hydrogen based on electrolysis.

Within the European Union, ammonia and methanol production facilities and crude refineries are mainly located Germany, Poland, the Netherlands, Italy and France. Consequently, within these countries electrolysers might find it easier to find customers in terms of supplying industrial customers with green hydrogen. Especially for Germany however, it can be expected, that due to large amounts of by-product hydrogen generation from chlorine production facilities the total net hydrogen demand might be slightly reduced.

In terms of identifying suitable locations within these countries, water electrolysers should be installed within the vicinity of the industrial customer especially in case of facilities with a large hydrogen demand such as ammonia or methanol production units in order to avoid significant additional costs for hydrogen transport. It needs to be considered, that in this case, specific business models in terms of grid service provision might not be available as here flexibility provision towards grid operators is required as specific locations within the power grid. However, business models that are directed towards cross-commodity arbitrage trading and provision of control reserve are independent on the specific location within country.

3.1.2 Mobility Sector

In the following, an assessment of the future hydrogen demand within mobility sector shall be given. A detailed analysis in terms of hydrogen prices to be expected within the mobility sector can be found in deliverable 2.3 of the ELYntegration project [1].

While estimations for current and future hydrogen demand by industry customers can be made rather easily, estimations for future hydrogen demand within the mobility sector are quite difficult since hydrogen mobility currently remains within a status of demonstration projects. The development of hydrogen demand for mobility sector based on fuel cell electric vehicles (FCEV) is mainly dependent on four factors:

- Driving characteristics (range and time for refuelling)
- Investment costs of the vehicle
- Infrastructure on hydrogen refuelling stations (HRS)
- Fuel costs

Even though driving characteristics of FCEV are already comparable to combustion engine vehicles (CEV), investment costs for FCEV are currently significantly higher than for CEV [8]. Additionally, the number of FCEV remains low, since the current infrastructure on HRS is limited to only a few stations within several cities leading to a suboptimal user-friendliness of FCEV. Here, the problem is intrinsic, since for large infrastructure projects the major obstacle is a low number of FCEV customers. As a consequence, there has not been a breakthrough of FCEV within Europe so far and current hydrogen mobility projects remain dependent on subsidies. Hence, the hydrogen demand within the mobility sector is currently negligible.

On the other hand, many studies indicate that the mobility sector might be the key sector that can generate substantial growth and demand for green hydrogen [2] thus representing one of the main target sectors for hydrogen generated by electrolyser applications. In 2009, the EU agreed on reducing CO_2 emissions by at least 80 % until 2050. This would require a decarbonisation of the road transport by 95 % [18]. Besides using other alternatives to CEV like battery only electric vehicles (BOEV), plug-in hybrid electric vehicles (PHEV) or CEV with fuels based on renewable sources, this could be achieved by use of FCEV.

In future, FCEV may become an important market for Fuel Cell and Hydrogen (FCH) technologies both in terms of European and global scope. Estimations for 2030 reflect a penetration between 7-12 % for the European market [19] while globally the corresponding share varies between 4 % and 25 % [20] [21]. The corresponding estimation of FCEV vehicles for Europe and worldwide for 2030 is shown in Table 1 considering estimation on the total number of all types of passenger vehicles of 313 million in Europe and 1,478 million worldwide for 2030 based on [22].

	Europe		Global	
	Share of FCEV	Amount of FCEV (in million)	Share of FCEV	FCEV (in million)
Lower Bound	7 %	21.91	4 %	59.15
Upper Bound	12 %	37.57	25 %	369.71

Table 1: Estimation of FCEV in Europe and globally in 2030

There have already been initiatives of car manufacturers of developing and commercializing FCEV models. E.g. Toyota has developed the Mirai model with a consumption of 0.92 kg h_2/100km [23], Mercedes has worked on the Mercedes-Benz F-Cell model with a consumption of 0.97 kg h_2/100km [24], Hyundai has worked on its Hyundai ix35 model with a medium consumption of 0.94 kg h_2/100km [25] and Honda has developed its Honda Clarity model with an efficiency of 0.91 kg h_2/100km [26]. Based on the data in Table 1 and considering a decrease of 15 % of the fuel consumption by 2030, the corresponding hydrogen demand of FCEV is shown in Table 2 for the assumption of a medium mileage of 10,000 km per year.

Considering an electrolyser with a capacity of 10 MW, an electric energy demand of 52 MWh/t_{H2} and 100 % availability, this would require 1,037 electrolysers for 7 % FCEV and 1,778 electrolysers for 12 % FCEV in Europe for covering the entire hydrogen demand of the FCEV.

	Europe		Global	
	Share of FCEV	Hydrogen demand (in kt)	Share of FCEV	Hydrogen demand (in kt)
Lower Bound	7 %	1,748	4 %	4,718
Upper Bound	12 %	2,996	25 %	29,490

Table 2: Expected hydrogen mobility demand in Europe and globally in 2030

Other assumptions within different studies lead to a FCEV penetration of passenger cars within the EU of 9-13 % in 2030 [2] which is in line with the assumptions and aforementioned data in this section. At national level, Figure 9 shows the expected hydrogen demand within the mobility sector of the different national directives for hydrogen mobility of France (*H2 Mobilité France*), the UK (*H2Mobility UK*) and Germany (*NOW – National Organization Hydrogen and Fuel Cell Technology*). It can be seen, that especially the initiatives of the UK and Germany expect a large increase of yearly hydrogen demand of up to 216 kt (Germany) [27] respectively 254 kt (UK) in 2030 [28].

Considering an electrolyser with a capacity of 10 MW, an electric energy demand of 52 MWh/t_{H2} and 100 % availability, this would require 129 electrolysers in Germany, 151 electrolysers in the UK and 53 electrolysers in France for covering the entire hydrogen demand of the FCEV.

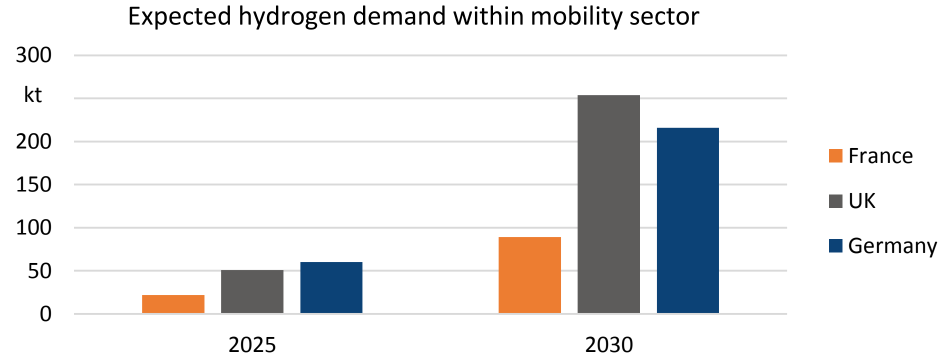

Figure 9: Expected hydrogen demand within mobility sector for France, UK and Germany based on national mobility partnerships [29] [28] [27]

Current discussions mainly focus on passenger cars for hydrogen mobility since here the largest amount of hydrogen demand can be expected. However, there are also projects focussing on other parts of the mobility sector. This includes hydrogen fuelled fleet vehicles, buses and other heavy duty vehicles such as trucks [8]. Other projects investigate the application of hydrogen as a fuel for trains [16]. Additional applications for hydrogen technology might arise within the marine sector, e.g. as primary power for smaller vessels or as baseload power for stationary ships in port or as backup power supplies in case of emergency situations [30] [31]. So far, these projects remain within research and development or demonstration status.

To conclude, it needs to be emphasized that estimations in terms of the future hydrogen demand within the mobility sector show some uncertainty since the future development of corresponding applications is highly dependent on European and national regulations, including incentives for both FCEV and hydrogen refuelling infrastructure. Discussions on incentives include initial funding for FCEV. For example, since 2016 a buyer's premium of 4,000 € is granted for BOEV as well as for specific FCEV in Germany. Other incentives might include funding support for demonstration projects for other hydrogen fuelled vehicles or for expansion of hydrogen infrastructure or tax reductions.

3.1.3 Natural Gas System

In terms of future hydrogen use, some discussions are also directed towards the future role of hydrogen as a long term storage option for renewable power feed-in by photovoltaic and wind power by using the natural gas system. The two methods that can be applied for this purpose are direct blending (understood as direct feed-in of hydrogen into the natural gas system as an admixture) or blending with an additional methanation step in order to convert hydrogen into synthetic methane. However, due to low natural gas prices, high investment costs for electrolysers and high conversion losses, today's amount of hydrogen injected into the natural gas grid is negligible. In general, for both synthetic methane as well as direct feed-in of hydrogen to the natural gas system, the electrolyser gas can be used as a substitute for natural gas und thus be applied within conventional uses of natural gas:

- Building heating systems
- Natural gas fired power plants

- Combined heat and power plants
- Natural gas vehicles (NGV)
- Industrial applications

In terms of blending however, it needs to be considered that the maximum amount of hydrogen within the natural gas system is limited. In literature, studies differ in terms of the maximum permissible amount of hydrogen admixture to the natural gas system. While [2] states, that a hydrogen injection of 1 $\%_{vol}$ up to 15 $\%_{vol}$ would only cause minor technical drawbacks to the natural gas system. According to [32] and [33] an admixture of more than 4-5 % might already be critical. When it comes to end users of natural gas, even this ratio could already cause damages to technology. For example, in case of conventional combustion engines, an admixture of up to 2 $\%_{vol}$ of hydrogen is permitted within the natural gas fuel. However, even at ratios of around 2-5 $\%_{vol}$, large amounts of hydrogen could be stored within the existing natural gas system of more than 0.5 million tons of hydrogen [2]. In case an additional methanation step is used, the produced synthetic methane can be used as an equivalent of natural gas. Therefore, there is no maximum amount of admixture. Because of no volume restricts, the storage capacity within the natural gas system is even larger compared to a direct admixture of hydrogen [33]. However, due to additional conversion losses for the methanation process, the efficiency of the overall process decreases.

Currently, the electrolyser applications in the natural gas system are negligible and both in the short and in the medium run corresponding business models are not expected to be profitable. On the other hand, long term opportunities are given due to the large storage capacity for renewable power feed-in from photovoltaic and wind power plants. Especially in terms of its long discharge times and its large storage capacity, the technical potential of electrolysers is very high compared to other storage alternatives like batteries, compressed air or pumped storage [33]. Taking into account the decarbonisation goals of the European Union, it can be envisaged, that “green” hydrogen can achieve higher feed-in tariffs than the spot market price of natural gas. Analogous to current feed-in tariff schemes of bio methane, green hydrogen injection tariffs could support electrolyser business models directed towards natural gas system in order to aid decarbonisation goals and could lead to more efficient operation also in the short and medium run for electrolyser applications [1] [34].

3.1.4 Other Applications

In addition to industry sector, mobility sector and natural gas system, other applications for hydrogen use are currently in discussion. These applications include

- Co-generation of power and heat within buildings
- Fuel cell fork lifts
- Autonomous power systems for stationary or portable off-grid applications
- Uninterruptible power systems

Being niche applications, hydrogen and fuel cell use within these applications is viable option e.g. in order present alternatives to conventional fuels and to bring down CO_2 emissions. However, even in case of a significant amount of hydrogen applications within these sectors in future, their future hydrogen demand will most likely be small compared to the other end user sectors for hydrogen.

3.2 Potential Drivers and Risks

In the following, potential drivers and risks for the future market potential of electrolysers are discussed. Besides uncertainties in terms of future green hydrogen prices for example within the mobility sector, this includes the end user price of electricity for electrolysers and potential future exemptions from taxes, network costs and other surcharges that might present a significant driver. Additionally, influencing factors on future developments within the relevant key markets of the electrolyser both in terms of hydrogen and electric energy have to be taken into account since uncertainties within future scenarios of these markets have a significant impact on the future profitability of electrolyser energy applications. Consequently, based on the business models developed and evaluated in deliverable 2.3 of the ELYntegration project [1] and summarized in the following, important factors influencing the economic efficiency of electrolyser operation within these different markets are described. Table 3 presents a summary of the relevant markets for each of the considered business models. Hence, uncertainties within the development in these markets also results in uncertainties of the profitability of the relevant business models.

BM 1: Cross-Commodity Arbitrage Trading
BM 2: Provision of frequency containment reserve (FCR)
BM 3: Provision of positive automatic frequency restoration reserve (pos. aFRR)
BM 4: Provision of negative automatic frequency restoration reserve (neg. aFRR)
BM 5: Provision of positive manual frequency restoration reserve (pos. mFRR)
BM 6: Provision of negative manual frequency restoration reserve (neg. mFRR)
BM 7: Optimized electrolyser unit commitment taking into account the spot market for electric energy as well as all control reserve markets
BM 8: Provision of grid services within the congestion relieving process on transmission level
BM 9: Cross-commodity arbitrage trading with additional provision of transmission grid services

Business Model	**Hydrogen Market**	**Spot Market for Electricity**	**Control Reserve Markets (FCR, aFRR, mFRR)**	**Grid Services**
BM 1	X	X		
BM 2 – 6	X	X	X	
BM 7	X	X	X	
BM 8	X			X
BM 9	X	X		X

Table 3: Relevant markets for the different business models of deliverable 2.3

Apart from uncertainties in terms of the development of future hydrogen demand and future hydrogen prices as well as uncertainties in terms of the end user price for electricity, the major influencing factors on the development of these markets are presented in Table 4. These can therefore be interpreted as potential risks and drivers for future electrolyser applications. Even though some of these risks and drivers may mainly influence only one of the relevant markets for the different business models, complex interrelations between the different markets as well as between the different developments of risks and drivers exist. In the following, these risks and drivers are discussed in more detail.

Potential risk or driver	**Hydrogen Market**	**Spot Market for Electricity**	**Control Reserve Markets (FCR, aFRR, mFRR)**	**Grid Services**
Development of power generation system		X	X	X
Price of CO_2 emission certificates	X	X	X	X
Policies towards storage units		X	X	X
Competition within control reserve markets			X	
Design of future flexibility markets for grid services				X

Table 4: Main impact of potential risks and drivers on relevant markets for electrolyser business models

3.2.1 End User Price for Electricity

For electrolyser business model efficiency, the electricity price seen by the electrolyser operator is essential. It is therefore not sufficient to solely investigate the wholesale price determined at the electricity markets since the end user prices can be up to nine times higher due to payments for supply, use of system charges and taxes and levies. These price elements are highly dependent on the national regulatory framework. Consequently, the end user prices within European countries differ significantly. The efficiency of potential business models for electrolysers is therefore not only dependent on the wholesale prices but also on the regulatory framework in each country. A detailed analysis of end user prices for electricity can be found in deliverable 2.1 of the ELYntegration project [35].

In order to analyse the influence of end user prices on business models for electrolysers, potential revenues are assessed in section 3.3.3 when considering end-user prices with no exemptions, with exemptions from network charges and with exemptions from taxes, levies and network charges.

3.2.2 Development of Power Generation System

Another major factor that influences the efficiency of potential future electrolyser applications is the development of the European power generation system because the composition of the generation stack determines electricity prices. Especially the capacity of RES power plants due to its intermittent power feed-in has a significant impact on future prices at the spot market for electricity as well as the different control reserve markets. On the one hand, a large amount of RES leads to an increasing amount of situations with very low spot prices for electricity (e.g. high wind/low load situations) as well as an increasing amount of situations with high spot prices (e.g. low wind/high load situations). On the other hand, the demand for control reserve increases in case of high shares of RES in the generation system. Additionally, especially the allocation of RES in combination with the corresponding grid expansion has an impact on the congestions within the power grid and therefore on the potential of electrolyser applications within a future market for grid services. Consequently, also national policies and roadmaps for RES expansion or the plan for a phase-out of specific conventional power generation technologies such as nuclear power or lignite fired power plants have a large impact on the economic efficiency of future electrolyser applications.

The evaluation of business models in deliverable 2.3 uses best guess scenarios for the development of the power generation system within the market and transmission grid simulations. However, since the composition of future generation system imposes a significant uncertainty within the simulations, in section 3.3.5 a sensitivity analysis for year 2024 is performed that identified the potential risks seen by investors for electrolysers due to different estimates for the future share of RES in the European power system.

3.2.3 Price of Emission Certificates

The development of CO_2 emission certificate prices also has a significant impact on the development of all key markets and therefore impacts the future potential of all considered future business models for electrolyser applications.

Firstly, it is expected that the merchant hydrogen price is strongly influenced by emission certificate prices. Since merchant hydrogen is mainly dominated by hydrogen production via SMR of natural gas, CO_2 equivalent emissions of this production pathway accounting for 11.888 g per kg of hydrogen produced [36] impact the expected hydrogen price. Consequently, rising prices of emission certificates are most likely to result in increasing hydrogen prices thus having a positive effect on the revenues generated by the sales of hydrogen within all business models. Additionally, increasing CO_2 emission certificate prices are expected to impact on willingness to search for alternatives than SMR not only for future hydrogen sectors such as mobility but also and especially for hydrogen demand in the industry sector.

The influence of increasing CO_2 emission certificate prices on spot market prices are not that easily to be assessed. On the one hand, rising certificate prices lead to increasing operational costs of conventional power plants with large amounts of CO_2 emissions such as large lignite fired power plants. As a result, in case the marginal costs of these power plants are price setting at the spot market for electric energy, a direct increase of spot market prices is to be expected. On the other hand, in case the increase in prices for the certificates are high enough, a fuel switch might occur. Currently, primary energy costs for lignite are lower than for coal and natural gas while CO_2 emissions are highest for lignite fired power plants followed by hard coal and natural gas fired power plants. Currently, the resulting marginal costs for lignite are still lower than for coal and for natural gas fired power plants. However, rising certificate prices might reverse this effect. Consequently, in this case marginal costs for coal and natural gas fired power plants would be lower resulting in an increasingly unprofitable operation of lignite fired power plants as their full load hours would decrease. Eventually, this fuel switch would lead to a gradual displacement of those generation capacities that show large amounts of CO_2 emissions significantly increasing future prices at the spot market for electric energy.

Since a large amount of control reserve is covered by conventional power plants, CO_2 emission certificate prices also affect the energy prices on these markets. Hence, the economic efficiency of business models of electrolyser participation in control reserve is affected.

A fuel switch would also lead to impacts on the potential of electrolyser provision of transmission grid services in a possible future flexibility market within the congestion relieving process. The replacement of existing generation capacities of lignite power plants by natural gas fired power plants has an impact on transmission grid congestions and therefore on the necessary curtailment of RES in order to ensure a secure transmission grid operation. Thus, also the full load hours of business model 8 and 9 would be affected by a variation of CO_2 emission certificate prices.

3.2.4 Policies towards Energy Storage

The economic efficiency of electrolysers is influenced by political and regulatory decisions. Generally, regulation sees storage units as end-users. This is lawfully reasoned by arguing that storage unit at first consume electricity, the latter reconversion of stored energy into electricity is a different topic. Policies that promote storage units as end-users in general and thereof electrolysers are exemptions from certain electricity elements for end-users. Current possible exemptions are discussed within section 3.2.1, where the end-user prices for electricity are assessed.

Another possibility of funding is financial support for investments in storage units. The European Union addresses the funding of storage in the “Guidelines on State aid for environmental protection and energy 2014-2020” [37]. If a financial assistance falls in the category of state aid, these guidelines apply. Within the guidelines, it is stated that state aid is to be designed as investment support and no operational support for the unit. Furthermore, the aid is not allowed to cover 100 % of investment costs, because then it would not be compatible with the European domestic market. However, these guidelines do not require for countries to act on storage support policies. This as well applies for the directive on the promotion of the use of energy from renewable sources, which urges the member states to take suitable measures for the support of storage units. It states: “There is a need to support the integration of energy from renewable sources into the transmission and distribution grid and the use of energy storage systems for integrated intermittent production of energy from renewable sources” [38]. However, this is only formulated as a suggestion without establishing the legal requirement for a financial support of storage units, so investment support schemes or further exemptions for storage units cannot be safely foreseen for the future.

The support of storage units may not only benefit electrolysers, but as well bears the risk of higher competition in the markets when more storage units – may it be electrolysers or other storage systems – penetrate the market due to increased financial support. This higher market penetration of storage units would lead to peak shaving effects for electricity prices at the spot market and thus a lower volatility. The “shaved” peaks may be high or low peaks. For the electrolyser, this would lead to fewer hours of low electricity prices and reduced full load hours.

3.2.5 Competition within Control Reserve Markets

The economic efficiency of electrolyser business models that are directed towards participation in control reserve markets is highly dependent on the future development on control reserve markets. This includes on the one hand the required future capacity of control reserve markets for FCR, aFRR and mFRR and on the other hand on the amount of participants within these markets. A risk towards these business models are therefore other technologies that might supply control reserve in future power systems dominated by large shares of RES power. A large competition by other technologies that might show higher maturity or higher cost efficiency than electrolysers could destroy profitability of electrolyser business models.

Therefore, in the following, a short analysis of major competitors on these markets is given. Table 5 shows an overview of potential competitors on the relevant control reserve markets.

Table 5: Potential future competitors on control reserve markets for electrolyser units

Competitor	FCR	pos. aFRR	neg. aFRR	pos. mFRR	neg. mFRR
Battery storage	X	X	X	X	X
RES		X	X	X	X
Power-to-heat		X	X	X	X
Sheddable loads			X		X
Pump storage		X	X	X	X
Flexible loads		X	X	X	X

While battery storage systems are not well suited for long term energy storage, a provision of FCR is already technically feasible and economically suitable due to their highly dynamic performance. First projects for central battery storage systems providing FCR are already in operation in Germany [39]. For smaller battery storage systems participation in FCR is feasible in case of pooling mechanisms. Provision of positive and negative aFRR and mFRR are technologically feasible as well, however due to high investment costs, economic efficiency still needs to be evaluated within these markets [39]. However, due to lower control reserve market prices for frequency restoration reserve, it is to be expected that battery storage systems will at first participate in FCR. For new potential business models for electrolysers, in terms of control reserve markets battery storage systems can be considered as main competitors on future FCR markets.

In terms of frequency restoration reserve, the competition by other technologies is significantly larger. Due to its similar load characteristic and its mature technology as well as in comparison to electrolysers low investment costs, power-to-heat technology can be considered as an important competitor to electrolysers within control reserve markets. Generally, prequalification for both aFRR and mFRR are technically feasible for power-to-heat applications with focus on negative control reserve. Within these control reserve markets operation is already profitable [40]. Other research already shows, that power-to-heat has a large potential for decreasing prices at control reserve markets as well as reducing the amount of must-run capacities of conventional power plants within the power system [41]. Consequently, a future high participation of power-to-heat units in control reserve markets might significantly decrease contribution margins for electrolyser business models that are focused on these markets.

Other potential competitors within aFRR and mFRR are pumped hydro power plants that can participate at both positive and negative automatic and manual frequency restoration reserve markets. The same holds true for RES power plants. Here, a provision of positive FRR is possible [42]. In medium and long term, also a reduction of feed-in of intermittent RES power units as negative control reserve is possible. Generally, flexible biomass power plants such as bio methane fired power plants are also suitable for participation at FRR markets. However, due to regulation these units mostly run in base load operation participating at the spot market for electricity [40]. Large sheddable industrial loads are able to provide both negative aFRR and mFRR. By use of an aggregator for shiftable loads a collective provision of FCR is theoretically possible [43].

It can also be expected that pooling companies, that aggregate smaller power units of different technologies such as biomass and RES power plants, emergency generators, flexible industrial loads and heat pumps, will participate in these control reserve markets. By pooling, participation within all control reserve markets (FCR, aFRR and mFRR) can be achieved [42].

Additionally, the increasing cooperation between the European transmission system operators within the international grid control cooperation (IGCC) significantly impacts future control reserve markets. An increasing cooperation might lead to a reduced amount of required control reserve to be kept available and thus to reduced prices at the control reserve markets within Europe. Consequently, revenues to be gained by electrolyser business models within these markets might face decreasing profitability in case of an increased cooperation within Europe.

3.2.6 Design of Future Flexibility Markets for Grid Services

In terms of business model 8 and 9, which are both directed towards future provision of grid services by electrolysers, the design of corresponding future flexibility markets imposes a high uncertainty to future electrolyser application and especially to potential contribution margins. As already discussed in the analysis of future business models in deliverable 2.3, currently, there is no regulatory framework for those flexibility markets on distribution levels even though potential future designs are discussed. The same holds true for regulation in terms of flexible load in order to absorb curtailment energy of RES that may remove stress on the transmission grid. Since corresponding electricity prices and potential reimbursements are not to foreseeable, profitability of these business models is challenging to evaluate. Additionally, within such flexibility markets, it is to be expected that electrolysers would face competition by other technologies with load flexibility such as power-to-heat applications or battery systems.

Even in case these flexibility markets exist in future, economic efficiency of corresponding electrolyser applications would be dependent on the location of the electrolyser within the distribution or transmission grid. Only locations within regions of excess RES energy would be suited for electrolyser provision of grid services, thus limiting market potential.

It also needs to be taken into account that grid expansion planning is directed towards a congestion free grid (apart from a curtailment of 3 % of the overall RES feed-in in Germany). Consequently, in the long run it is to be expected that potential operational hours of an electrolyser only providing grid services would be rather low resulting in poor economic efficiency. However, in the short to medium run, larger potential full load hours can be expected in case the grid expansion does not hold pace with RES expansion due to delays in installation of new power lines. In order to evaluate corresponding short to medium potential of electrolyser grid service provision on transmission level, section 3.3.6 presents a sensitivity analysis exemplarily for the German transmission system for year 2024 with delayed installations of HVDC links connecting northern to southern Germany.

3.3 Sensitivity Analyses

3.3.1 Methodology

In order to assess consequences of main market influences on electrolyser business model profitability, sensitivity analyses are conducted in the following. In order to provide a viable environment to compare influences, the sensitivity analyses are based on the calculations described and analysed in deliverable 2.3 of the ELYntegration project [1]. Thus, for details about the modelling methodology, deliverable 2.3 is to be considered. In the sensitivities, no changes are conducted to the scenario environments except for the described sensitivities. Sensitivities are addressed in terms of end-user prices for electricity, changes in hydrogen prices, changes in the share of RES within the European generation system and different grid developments influencing the potential of providing grid services by electrolysers.

Electrolysers do not only pay wholesale market prices of for electricity and costs of supply but also need to incorporate taxes, levies and network costs. Therefore, net margins considering end-user prices of electricity are assessed. In order to account for possible changes in the hydrogen market, sensitivities with higher and lower hydrogen prices are conducted. Two other factors influence business models of electrolysers: the composition of the generation fleet when conducting cross-commodity arbitrage and the grid development when considering additional revenues from redispatch participation. Therefore, a sensitivity analysis concerning the generation fleet as well as a sensitivity concerning the grid development are analysed.

3.3.2 Base Scenario

The base scenario for the sensitivity analysis is based on the following assumptions, which are described in detail in deliverable 2.3 of the ELYntegration project [1]. Assumptions in terms of market environment are listed in Table 6. The economic data and other key performance indicators for the electrolyser are listed in Table 7. This data is based on the analysis in [34] and [44]. In terms of calculating and dimensioning of electrolyser system components we apply the same method as described in [1].

Table 6: Key Assumptions for business model evaluation [1]

Key Indicator	**Unit**	**2014**	**2024**	**2034**
Hydrogen Price	€/kg_{H2}	6.0	6.0	6.0
Costs of Supply	€/MWh	30.0	30.0	30.0
Taxes and Levies	€/MWh	exempted	exempted	exempted
Grid Fees	€/MWh	exempted	exempted	exempted
Green Certificates	€/MWh	0.4	0.4	0.4
Electricity Prices	Based on Market Simulations			
Control Reserve Prices				

Table 7: Assumed key performance indicators for the evaluation of business models of a 10 MW alkaline water electrolyser project [1]

Key Performance Indicator	Unit	2014	2024	2034
Power Consumption	kWh_{el}/kg_{H2}	53.2	51.2	49.2
Output Pressure	bar	30	30	30
$CAPEX_{ely}$	k€/MW	990	614	556
$CAPEX_{H2\ storage}$	€/kg	470	470	470
$CAPEX_{filling\ centre}$ 200 kg/h, 30 bar → 200 bar	k€	2699	2699	2699
$CAPEX_{other\ costs}$	$\%(CAPEX_{ely}+CAPEX_{H2\ storage})$	37.5	37.5	37.5
System lifetime	years	20	20	20
$OPEX_{ely}$	$\%CAPEX_{ely}$	2.2	2.2	2.2
$OPEX_{other\ costs}$	$\%CAPEX_{other\ costs}$	4	4	4

Base Case Results

Net margins for all four countries and times horizons resulting from cross-commodity arbitrage trading in the base case are presented in Figure 10. Overall, net margins are rising in future scenarios. Higher RES shares contribute to more hours with low or negative residual load which lead to lower electricity prices in those hours. It is visible that developments differ between countries due to different circumstances, which are strongly influencing potential business models for electrolysers.

In Spain and Portugal, net margins increase in 2024. Slightly higher net margins in Portugal compared to Spain may be explained by the island position, because smoothing of volatile feed-in and prices are limited to the market area. In Portugal, net margins are increasing in 2034 as well. In Spain, a country with high shares of PV, an increase in net margins is observed between 2014 and 2024. In 2034, net margins decrease slightly in comparison. This may be explained by the simultaneity of solar feed-in. Generation peaks at noon lead to declines of prices during a few hours a day, but this effect in limited and may be exhausted already in 2024. Higher PV shares and low electricity prices in a few hours cannot compensate other effects of rising electricity prices. In Spain, less lignite is used for cheap electricity generation in the future and imports from France become more expensive because Frances generation system is shifting away from cheap nuclear power generation.

In Germany, where continuously rising shares of RES are expected, net margins increase in 2024 as well as in 2034. The same effect is seen for the Netherlands. High shares of RES, especially wind turbines, influence electricity prices. Those reach zero in many hours because marginal costs of RES electricity production are close to zero. Low electricity prices are an advantage for the electrolyser, leading to a positive prospect for the future. An advantage of wind turbines is that the number of hours where wind feed-in is high not as limited as for PV.

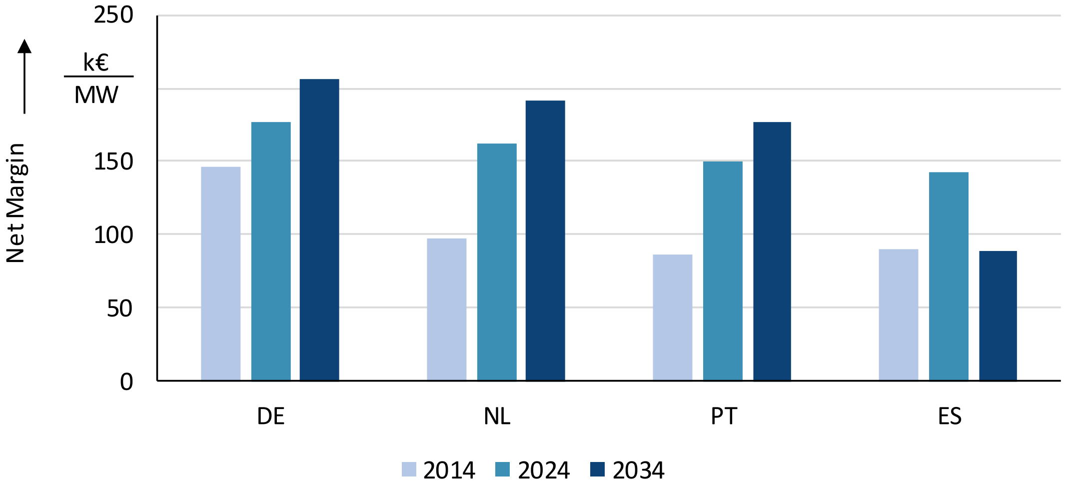

Figure 10: Net margins for 10 MW electrolyser for cross-commodity arbitrage trading

3.3.3 End User Prices of Electricity

A consumer in the electricity market does not only pay the wholesale electricity price and costs of supply, but may also have to pay additional surcharges such as network costs, taxes and levies. Exemptions of those were assumed in the base case. Additional surcharges have a substantial influence on the expenditure of the electrolyser operator and therefore impacts the efficiency of possible business models crucially. The actual price for the consumed electricity depends on different regulations, which determine exemptions from surcharges or the percentage of levies that need to be paid.

In order to assess the effect of exemptions from taxes and levies and network costs, sensitivities are conducted considering the following assumptions:

- Base Scenario: Exemptions from taxes, levies and network costs
- Sensitivity 1: No Exemptions
- Sensitivity 2: Exemptions from taxes and levies
- Sensitivity 3: Exemptions from grid fees

Those taxes, levies and network costs for large industry end-users such as a 10 MW electrolyser are shown in Figure 11 for the different countries. It can be seen that surcharges for network costs, taxes and levies are very high in Germany, followed by Portugal, and lower and Spain and in the Netherlands. This can as well be seen in the net margins generated by electrolysers dispatched in the markets with those different specifications.

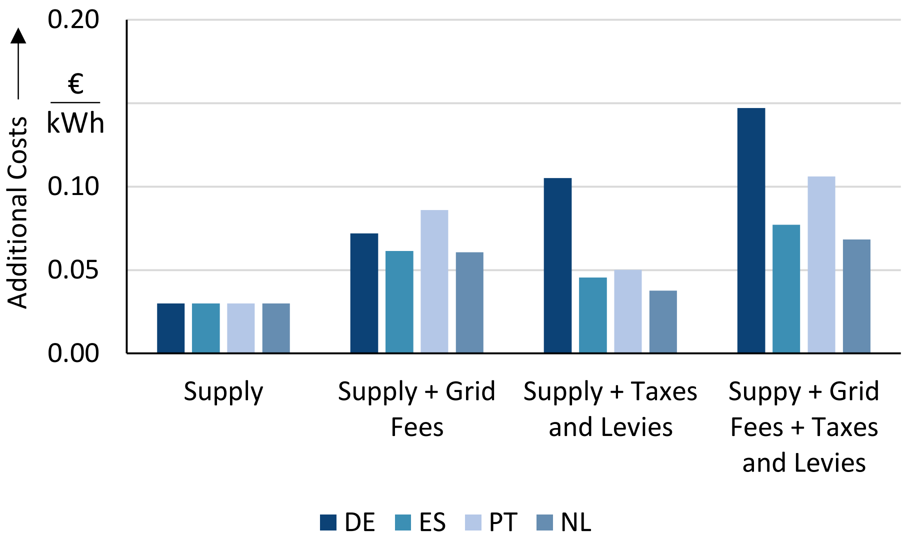

Figure 11: End-user costs for electricity in addition to wholesale market prices [1] [35]

Cross-Commodity Arbitrage Trading considering no exemptions

Potential net margins considering end-user prices for electricity with no exemptions from taxes, levies or network costs are negative. When no exemptions are granted, operation is not profitable in any country or year. Net margins are strongly declining when end-user prices are high and electrolysers cannot be operated profitably when no exemptions from high fees are granted. This shows the high relevance of political decisions towards exemptions. Exemptions are crucial for a profitable operation.

Cross-Commodity Arbitrage Trading considering exemptions from taxes and levies

Net margins considering end-user prices with exemptions from taxes and levies are negative as well. Network costs have to be paid in this sensitivity. With the exemption, results show slight improvements, but net margins are still negative for all analysed countries and time frames. Grid fees are higher than taxes and levies in all countries but Germany, hence the exemptions from grid fees is a crucial part for a profitable operation.

Cross-Commodity Arbitrage Trading considering exemptions from grid fees

Figure 12 shows full load hours considering end-user prices with exemptions from grid fees. Taxes and levies have to be paid in this scenario. With this exemption, full load hours are considerably high in the Netherlands, Portugal and Spain. In Germany, taxes and levies are so high that a profitable operation is not possible. Net margins are still negative in Germany and as well in Portugal. This is because taxes and levies are high in those two countries as shown in Figure 11. In the Netherlands and in Spain, positive net margins may be reached in the future. In Spain, net margins are positive in 2024 when exemptions from grid fees are granted, in the Netherlands, this happens in the year 2034. This difference can be explained by different spot market prices for electricity in the two countries as analysed in section 3.3.2.

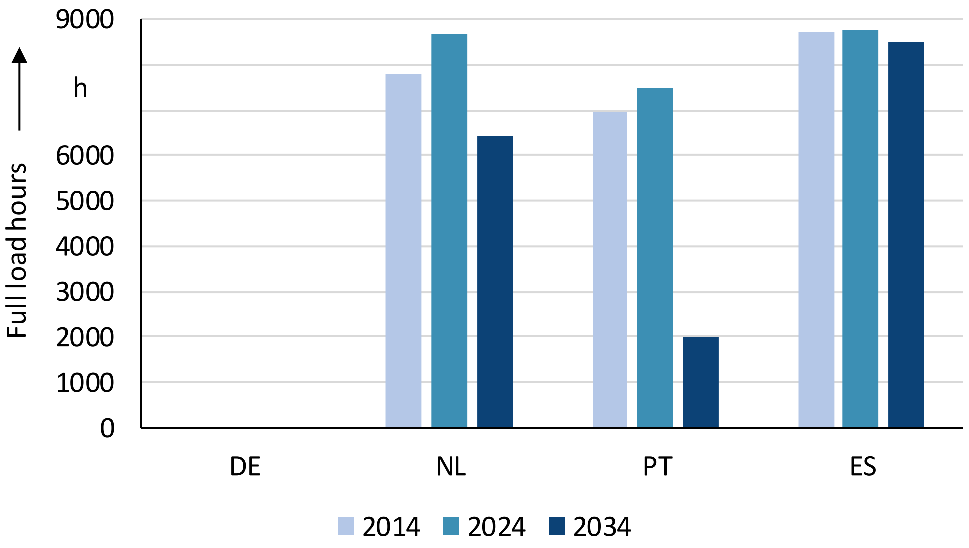

Figure 12: Full load hours considering exemptions from grid fees

This shows in conclusion that not only exemptions are crucial for a possibly profitable operation of electrolysers, but also that different national regulations as well as the set-up of the electricity market can strongly influence margins in current and future scenarios.

3.3.4 Hydrogen Prices

The estimation of a current and future hydrogen price is discussed in section 3.2 as well as in deliverable 2.3 of the ELYntegration project. Based on that analysis, sensitivities of net margins depending on different hydrogen prices are assessed within this section.

The following sensitivities are considered in order to understand effects of changing hydrogen market environments or changing business models with different hydrogen prices.

- Hydrogen prices of 5 €/kg
- Hydrogen prices of 7 €/kg

Cross-Commodity Arbitrage Trading considering hydrogen prices of 5 €/kg

The influence of hydrogen sales prices on the feasibility of the electrolyser can be seen when a lower hydrogen price is considered. The results of the sensitivity are shown in Figure 13. When considering lower hydrogen prices of 5 €/kg, full load hours are still high but net margins decrease significantly compared to the base case. In Spain and in Portugal, net margins are negative in all years. In Germany and the Netherlands, net margins reach positive values in 2034 of around 35 k€/MWa and 25 k€/MWa respectively.

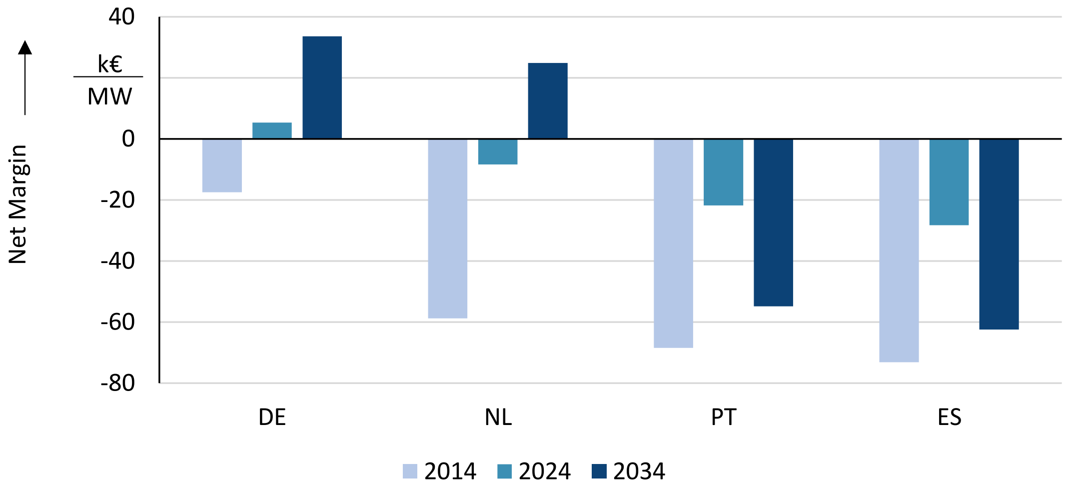

Figure 13: Net margins considering reduced hydrogen prices

Figure 14 shows net margins when hydrogen prices of 7 €/kg are considered. Net margins then are about twice as high as in the base case, where 6 €/kg are assumed to be a realistic price for the production of hydrogen for the mobility sector. It can be seen that this increase of hydrogen prices of 16 % results in net margins that are roughly 100 % higher.

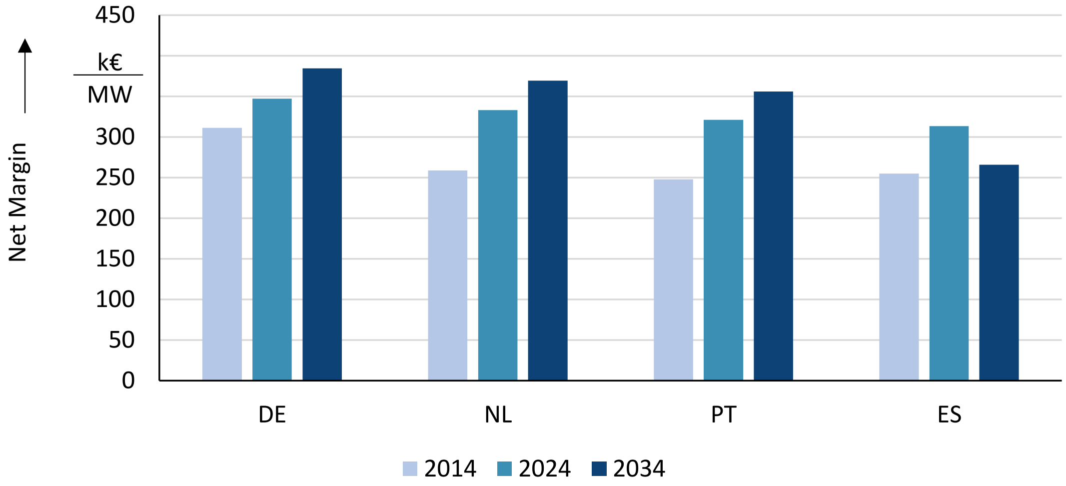

Figure 14: Net margins considering increased hydrogen prices

The sensitivities show that the sales prices for hydrogen have an essential impact on business models. Net margins and thus business models show to be very sensitive towards changes in hydrogen prices. Therefore, opportunities of hydrogen sales have to be analysed very closely when developing business cases for specific locations.

3.3.5 Share of RES within Generation System

In this section, the influence of the composition of the generation fleet on electrolyser profitability for cross-commodity arbitrage trading is analysed. Therefore, two further spot market simulation runs were conducted. For one sensitivity run, the feed-in of wind turbines and PV power systems was reduced to 80 % representing a less “green” scenario and in the other run, increased to 120 % representing a scenario with a stronger transition towards RES. The calculations are based upon the 2024 scenarios described in deliverable 2.3 of the ELYntegration project considering no changes but the amount of RES feed-in [1]. The hydrogen price is set to 6 €/kg.

In a market with a generation fleet with 20 % less production by RES, spot market prices rise compared to the base case simulation. Consequently, this leads to lower full load hours and revenues for electrolysers, shown in Figure 15. Net margins decline between the base case and the sensitivity by over 50 to 60 % in Germany in 2024 and the Netherlands and 30% in Spain and 60 % in Portugal. The decline is very pronounced because hours which are very profitable for electrolysers – hours with very low spot market prices – are a direct result of high RES feed-in. When RES shares are not high enough to cover a majority of the load in certain hours, electricity spot market prices do not go below marginal prices of base load power plants. Then, the lower spread between the electricity spot market price and the hydrogen price leads to lower net margins.

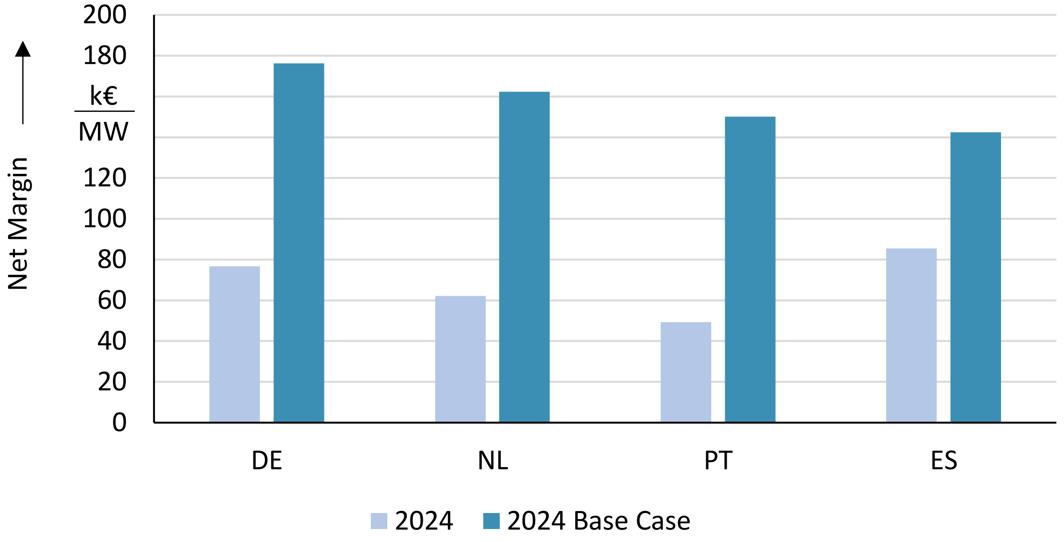

Figure 15: Potential electrolyser net margins in 2024 for a scenario with 20 % less RES production compared to the base case

The opposing development can be seen for a greener scenario with 20 % more RES production. With higher shares of RES, spot market prices of electricity prices decrease especially in hours with high RES production, which increases the spread for cross-commodity arbitrage trading for the electrolyser. The results of the sensitivity are shown in Figure 16. In all considered countries, net margins increase. The sensitivities show that markets with high shares of RES are a chance for electrolysers to enable a profitable operation when electricity prices are low, zero or negative in times of high RES feed-in.

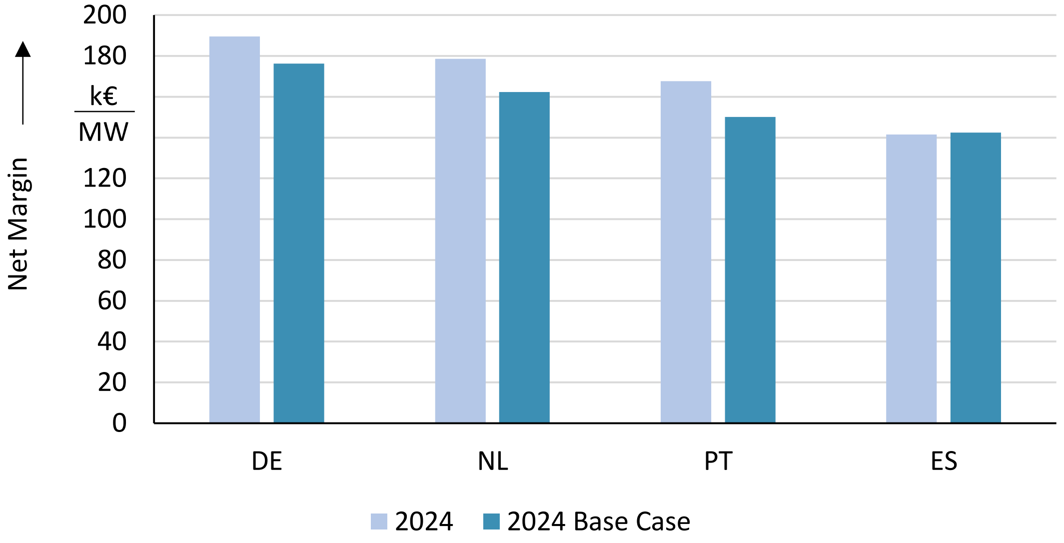

Figure 16: Potential electrolyser net margins in 2024 for a scenario with 20 % more RES production compared to the base case

3.3.6 Transmission Grid Expansion

In deliverable 2.3 of the ELYntegration project [1], the theoretical potential of electrolyser operation for provision of transmission grid services within the congestion relieving process are presented for 2014 and 2024 based on a transmission grid model for Germany derived from scenario B1 2025 GI of the German grid development plan NEP 2025 [45], the German offshore grid development plan O-NEP 2025 [46] and from the ENTSO-E network development plan TYNDP 2016 [47] for the ENTSO-E area. In the following, a sensitivity analysis is provided that identifies the impact of a slowed progress of the transmission grid expansion. For the performed transmission grid simulation, the same methodology as well as the same market and grid model are used as presented in deliverable 2.3.

The German grid development plan for 2024 entails four HVDC transmission lines that connect the wind power generation in northern Germany to the load centers in southern Germany. These HVDC lines are planned with a transfer capacity of 2 GW each. In the following, the corresponding transmission grid model is referred to as reference scenario *4HVDC*. Since the commissioning of the three eastern HVDC transmission links (Brunsbüttel – Großgartach, Wilster – Grafenrheinfeld, Wolmirstedt – Isar) is expected to be finished in 2025, the sensitivity grid scenario for 2024 only includes the western HVDC link from Osterath to Philippsburg (scenario *1HVDC*). The HVDC transmission lines for both scenarios are shown in Figure 17.

In comparison to the reference scenario *4HVDC*, the total transfer capacity from northern Germany to southern Germany in scenario *1HVDC* is reduced by 6 GW. Consequently, during situations of high wind power feed-in and high power transfers, the remaining AC transmission lines face higher stress and more frequent overloading. The corresponding frequencies of overloaded lines before remedial measures taken by transmission grid operators are shown in Figure 20 of the appendix for both reference and sensitivity scenario.

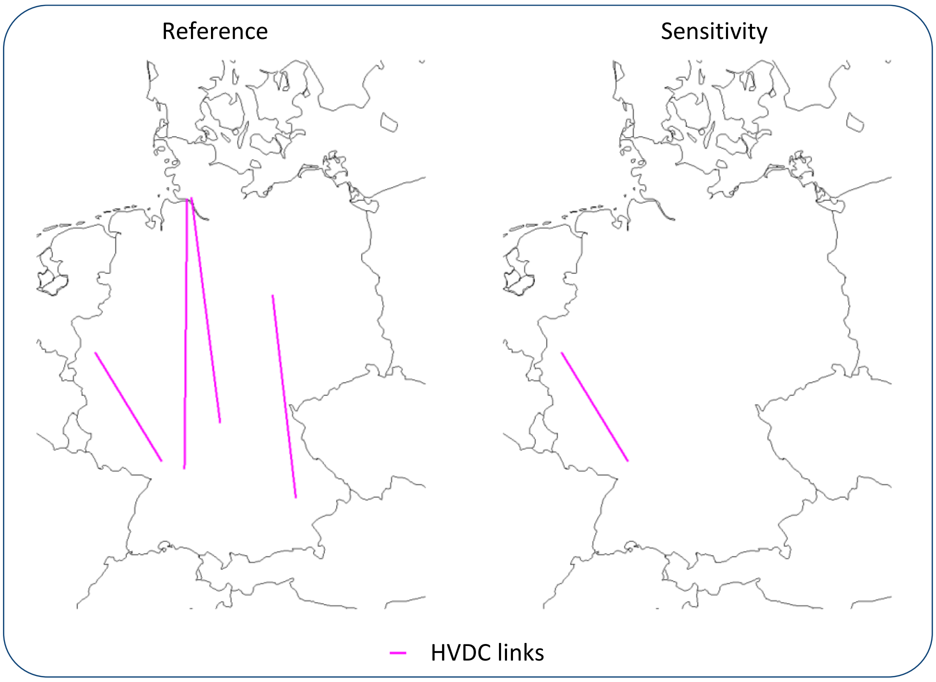

Figure 17: HVDC links for reference scenario *4HVDC* and sensitivity scenario *1HVDC* for transmission grid model 2024

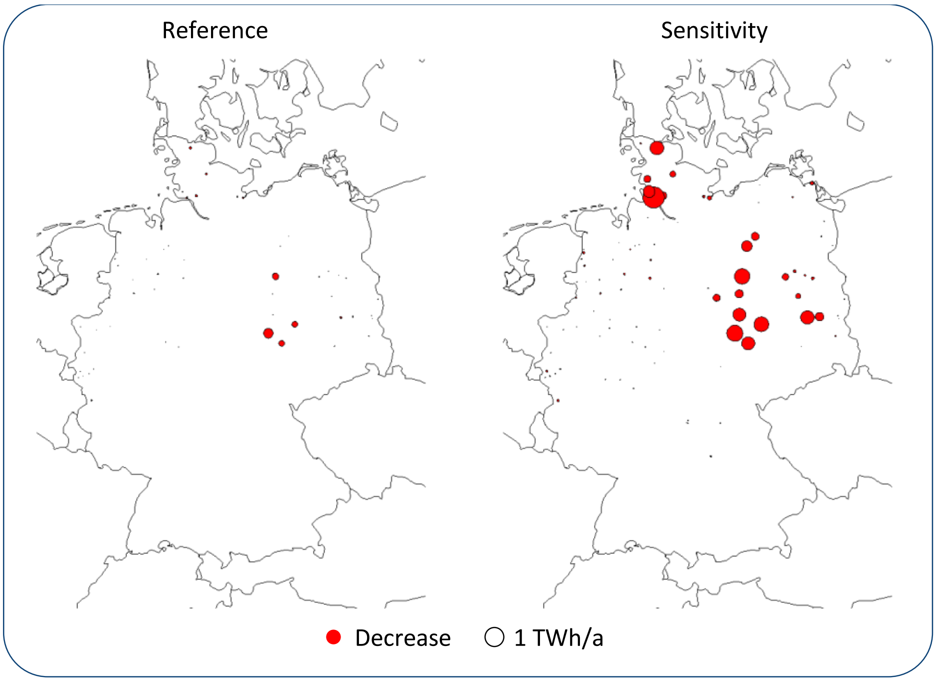

Figure 18: Allocation of yearly RES curtailment for reference scenario *4HVDC* and sensitivity scenario *1HVDC* for 2024

In order to remove these additional congestions for scenario *1HVDC*, the amount of market related remedial measures by the transmission grid operator increases. Consequently, the total yearly redispatch and curtailment volume increases from 3.3 TWh in scenario *4HVDC* to up to 27.96 TWh in scenario *1HVDC*. The sum of the RES curtailment for both on- and offshore wind power plants increases from 0.9 TWh to 9.80 TWh. The allocation of RES curtailment is shown in Figure 18. The allocation of the total yearly redispatch and curtailment volumes is shown in Figure 21 of the appendix. While in scenario *4HVDC* the best suited area for an electrolyser placement within the transmission grid in order to absorb RES curtailment energy is mainly within the German federal state Saxony-Anhalt in the eastern part of the country, scenario *1HVDC* identifies suitable areas not only within Lower-Saxony, but also in other parts of eastern Germany, mainly the federal state Brandenburg as well as at the German coast in federal state Schleswig-Holstein.

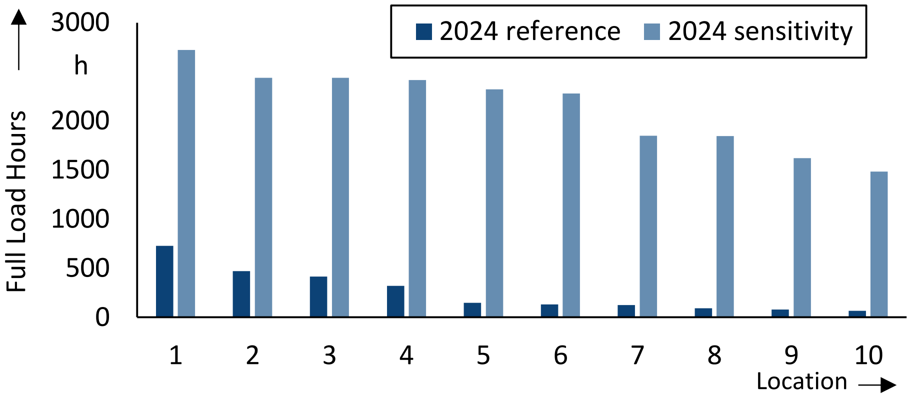

Figure 19: Full load hours for electrolyser providing grid services based on business model 8 for the 10 locations with highest full load hours

The full load hours for the theoretically best suited electrolyser locations based on the fundamental simulation is shown in Figure 19 for both reference and sensitivity scenario. This comparison shows, that due to the modelled slowed grid expansion process, the potential electrolyser full load hours increase significantly for all locations.

It can be concluded that not only the location of an electrolyser within the transmission grid has a large impact on potential operational hours based on a future flexibility market for grid services but also the future topology of the transmission grid. Especially in case of a slowed process of expanding the current transmission grid e.g. due to prolonged approval procedures of new transmission lines to be built, higher amounts of RES curtailment are to be expected which could be used by an electrolyser to achieve higher full load hours. On the other hand, this sensitivity analysis indicates, that in case the frequency of congestions within the transmission grid decreases, also the potential of future electrolyser grid service provision decreases.

It needs to be mentioned, that for a potential future grid service provision by electrolysers, according legislation and a flexibility market would have to be established first since so far no corresponding legislation exists (also see deliverable 2.3 [1]). Consequently, the impact of prolonged transmission grid expansion on potential revenues for electrolysers is highly dependent on the design of future regulation and market design for load flexibility and is therefore not possible to be estimated.

4 CONCLUSIONS

Based on the business models of electrolysers developed and evaluated in deliverable 2.3 of the ELYntegration project, within this study a market potential assessment for these business models was conducted. In terms of the sales of electrolyser hydrogen, most promising target sectors for hydrogen demand were identified. It could be shown, that especially within the European industry sectors large amounts of hydrogen demand occur. Within the industry sector, ammonia production facilities, crude refineries and methanol production facilities show the largest net demand of hydrogen. Consequently, these sectors show the largest potential for electrolyser and green hydrogen applications within the industry sector. The second major promising market for the sales of hydrogen is the mobility sector by using hydrogen as a fuel. So far, hydrogen mobility has not yet seen its breakthrough due to higher investment costs of these vehicles as well as the lack of a substantial hydrogen refuelling infrastructure. Within Europe however, there are multiple initiatives for the promotion of hydrogen mobility and a significant increase of hydrogen mobility is expected in future. Due to lower hydrogen prices, the use of hydrogen within the natural gas system represents lower business potential for electrolyser applications than industry and mobility sector. Consequently, in terms of hydrogen demand, **countries that show large amount of potential industry customers, especially within ammonia production and crude refining industry are most promising**. These include Germany, the Netherlands, France, the UK and Poland. **Countries for which a significant increase of hydrogen mobility is estimated in future, especially show highly promising business potential** not only because of the additional hydrogen demand but also because for these applications the hydrogen price is expected to be significantly higher than for industry applications.

Within this study main drivers and risks were identified that impact the market potential of electrolyser business models. Besides the development of the hydrogen market and potential future hydrogen prices itself, these drivers and risks include

- the end-user price of electricity,
- the development of the power generation system in Europe,
- the price of emission certificates,
- policies towards energy storage systems,
- the development of flexibility provision by alternative new technologies for electrolyser business models directed towards provision of control reserve and
- the design of future flexibility markets.

In order to quantify the impact of the identified main drivers and risks for future electrolyser applications, sensitivity analyses were conducted. It could be shown, that the consideration of end-user prices for electricity for electrolyser business models incorporating taxes, levies and network charges has a significant impact on the net margins of electrolyser business models. It can be concluded, that **especially those countries that not only show low spot market prices for electricity but also show low additional end-user charges for electricity show promising market potential for future electrolyser applications**. Additionally, potential exemptions from end-user charges for electricity favour electrolyser market potential.

The sensitivity analysis also shows that the sales price for hydrogen has an essential impact on the business models for electrolysers. Already a small decrease of hydrogen sales prices results in a significant decrease of net margins. Consequently, **the market potential of electrolyser is especially high in case the generated hydrogen is sold to hydrogen customers in the mobility sector**.

The results of this study indicate that the composition of the future generation fleet has a significant impact on potential net margins for electrolyser market potential as well. With higher shares of RES, spot market prices of electricity decrease resulting in an increase of the spread for cross-commodity arbitrage trading for the electrolyser. Consequently, a reduction of RES production within the European generation system leads to a decline in electrolyser net margins. It can be concluded, that **countries for which future scenarios are dominated by RES have promising market potential for electrolysers**.

In terms of the provision of transmission grid services, the sensitivity analysis shows, that not only the location of an electrolyser within the transmission grid has a large impact on potential full load hours but also the future topology of the transmission grid. For a delayed grid expansion, higher amounts of RES curtailment can be expected leading to higher full load hours for the corresponding electrolyser business model. It can be concluded, that **countries for which high amounts of RES curtailment is expected in future have a high market potential in terms of grid service provision by electrolyser**.

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5 APPENDIX

5.1 Transmission Grid Simulation Results

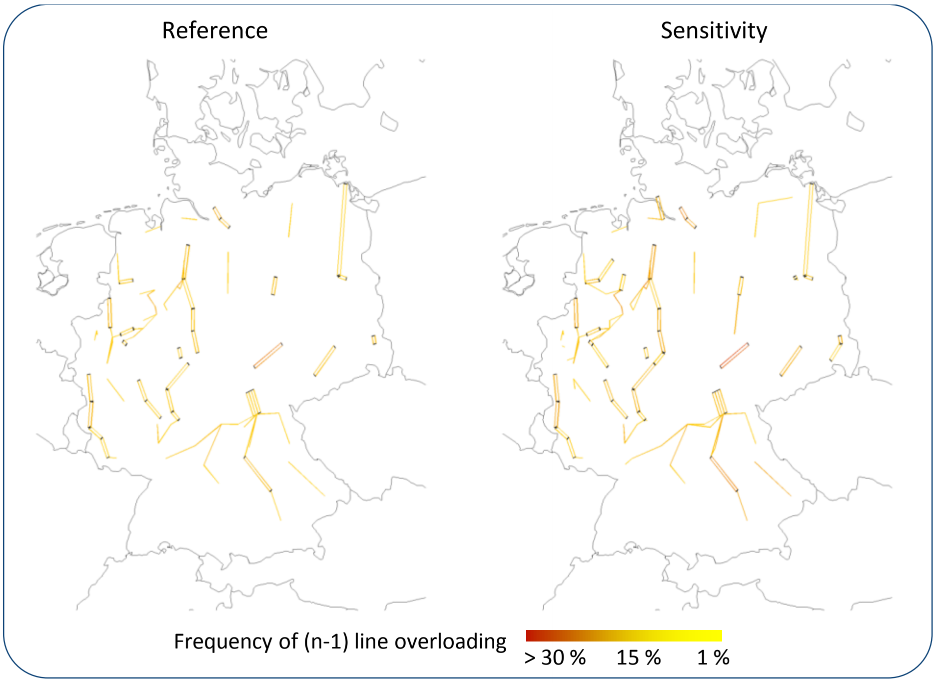

Figure 20: Line overloading for reference scenario *4HVDC* and sensitivity scenario *1HVDC* for 2024

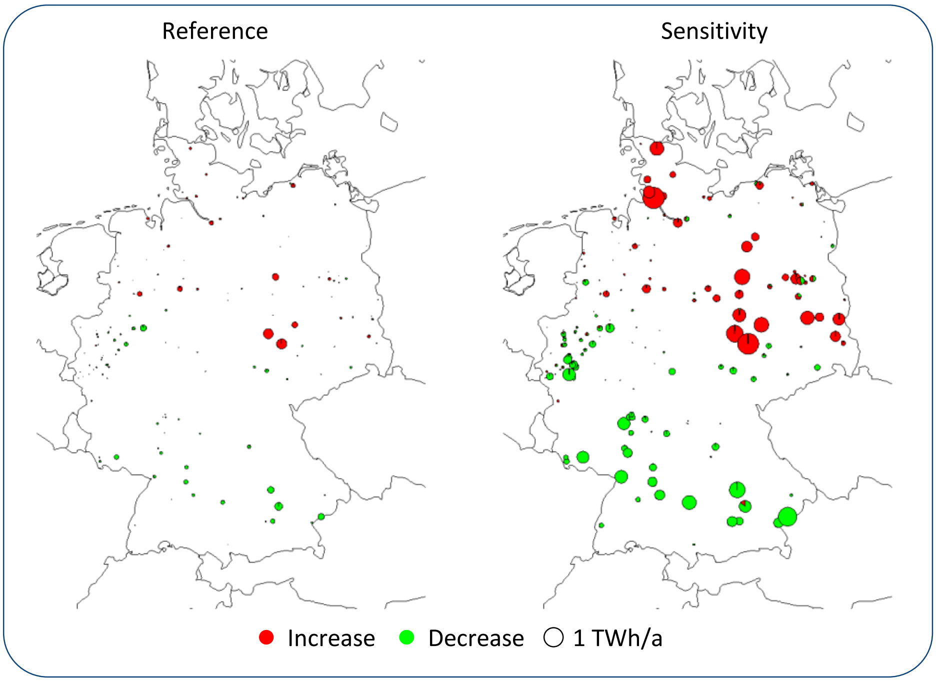

Figure 21: Allocation of yearly redispatch and curtailment for reference scenario *4HVDC* and sensitivity scenario *1HVDC* for 2024