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Impacts of EU Regulation on Green Hydrogen Production and Storage Capacity Design and Operation

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Abstract: In European Union green hydrogen production is regulated to guarantee that transition to green energy will really have positive effect on the mitigation of the climate change, and that the integration of hydrogen economy to existing energy system will be as smooth as possible. However, these regulations complicate the optimal design and operation of the hydrogen production. Requirement about one-hour temporal correlation between contracted variable renewable electricity production and green hydrogen production forces to invest in overcapacity of electrolyzers and high-capacity hydrogen storages to buffer variable hydrogen production to smooth supply flow to hydrogen end use processes. This paper explains these issues with a demonstrative example how different design parameters result to the operation performance of the hydrogen production process.

Keywords: Green hydrogen, regulation, Power-to-X, Energy storages

1. INTRODUCTION

The United Nations Climate Change Conference (COP28) held in the United Arab Emirates in 2023 signed an agreement that signals the "beginning of the end" of the fossil fuel era. [UN, 2023] This means the end of the use of fossil energy. One of the most promising approaches to meet this target is hydrogen. The so-called hydrogen economy, or preferable Power-to-X (PtX) economy, would enable flexibility in the energy system when approaching emission-free electricity production and help in decarbonization of sectors, such as heavy transportation, aviation, shipping, and some industries such as steel manufacturing. (Aalto et al. 2021), (Dahiry et Al. 2022)

In order to solve the climate warming problem, hydrogen and its derivatives used for replacing fossil energy must be carbon free. Hydrogen can be produced in many different ways including more, less or none of fossil carbon. Producing hydrogen by gasifying fossil fuels like coal or lignite results so called black hydrogen. Hydrogen produced from natural gas (methane, CH_4) is grey, and if this conversion process is extended by carbon capture and sequestration (CCS) system, the hydrogen is classified as blue. Hydrogen produced by electrolysis powered by nuclear power originated electricity is pink, and if electrolyzer is supplied by renewable electricity, produced hydrogen is green. (World Economic Forum 2021)

The basic rule for producing green hydrogen is that it must be produced by splitting water in electrolysis process powered by renewable electricity. But this is not the only requirement. European Commission has enacted regulations, Delegated Acts on Renewable Hydrogen, (European Commission 2023) defining more detailed, how green hydrogen should be produced. These regulations affect many ways both in the design of green hydrogen plants and how these plants should be operated.

In this paper we demonstrate how this EU regulation affects the electrolyzer plant design, operation of the plant, and need for buffering storages between hydrogen production and end use. Chapter 2 briefly introduces the regulation about producing renewable fuels of non-biological origin (RFNBO). Chapter 3 discusses how these regulations affect the design of electrolyzer plant and buffer storage capacities and operation strategy of the process. Chapter 4 shows some simulated demonstrations about this issue, and in Chapter 5 there is a discussion about how this regulation effects on hydrogen plant design. Chapter 6 concludes the paper.

2. EU REGULATION FOR GREEN HYDROGEN

In European Union (EU), production of green hydrogen is regulated by several rules related with the origin of the electricity used in electrolyzers. The most straightforward case is the direct connection between renewable energy and RFNBO production. In this case RFNBO production does not utilize grid power at all. In addition to this, the connected renewable energy generation plant must not be older than three years.

If grid electricity is used for hydrogen production, there are four grid connected RFNBO producing routes with varying conditions to ensure that the end product is green.

Route 1. To ensure that the used grid electricity is green, it must fulfill the three following principles:

Additionality: The renewable energy generation installation came online not earlier than 36 months before the RFNBO production facility, and the hydrogen production facility does not consume more electricity than contracted via dedicated power purchase agreement (PPA) or self-generated.

Temporal Correlation: RFNBO production takes place during the same hour as contracted renewable energy generation. Temporal correlation can be buffered via storage behind the

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same network point where the hydrogen production facility is located.

Geographical Correlation: Renewable energy installation and the electrolyzer are located on the same bidding zone. Or renewable energy is located on an interconnected bidding zone where the day-ahead price is equal or higher than the interconnected bidding zone with RFNBO production. Or renewable energy is on an offshore bidding zone connected to the zone with RFNBO production.

Route 2. The proportion of renewable energy in the electricity market bidding zone, where RFNBO production takes place, exceeded 90 % during previous year. Fulfilling this requirement allows exemptions to temporal and geographical correlation rules. RFNBO production full load hours must be less or equal than 8760 hours multiplied by the proportion [0,1] of the renewable energy.

Route 3. The power grid is sufficiently decarbonized. If emission intensity of the bidding zone grid is below the value of 18 gCO_{2eq}/MJ (65 gCO_{2eq}/kWh), no additional renewable capacity needs to be built. However, renewable energy needs to be contracted via PPA, and temporal and geographical correlations apply.

Route 4. The RFNBO production facility improves grid stability. RFNBO producer can prove with the help of the national transmission system operator (TSO) that during an imbalance settlement period (nation dependent) power-generating installations using renewable energy sources were redispatched downwards, and the electricity consumed for RFNBO production reduced the need for redispatching by a corresponding amount.

There are transition periods for some of these requirements. Perhaps the most important is related with the temporal correlation requirement. The hour-based correlation between renewable electricity production and hydrogen production enter into force in the beginning of 2030. Before that the renewable electricity – hydrogen production balance must be valid in one month time window. This has a big effect on the operation of the hydrogen production system and need of buffering storage capacity between hydrogen production and end use.

3. REGULATORY IMPACTS ON SYSTEM DESING AND OPERATION

The most important rules affecting the design and operation of the electrolyzer plants are the Additionality and the Temporal and Geographical Correlations. Of course, if the electricity grid fulfills the Route 2 requirement about the over 90 % share of renewable electricity in the bidding zone, this would make the design and operation of green hydrogen plants easy and straight forward. Grid electricity could be used for powering electrolyzers as such, and electrolyzer capacity could be designed for very high full load hours. However, fulfilling this 90 % share requirement in near future in most countries is very difficult, because e.g. nuclear generation is not classified as renewable, only low emission.

The Additionality rule is prescribed to accomplish parallel investments both in renewable electricity production and in electrolyzer capacity. Green hydrogen production is not allowed to grab all renewable electricity from the market resulting to increased fossil energy use in other sectors. The Additionality rule states that the renewable electricity production plant supplying green hydrogen production must be no older than three years compared with the electrolyzer plant. Thus, when planning new green hydrogen production capacity, the investor must also take care that there is new renewable electricity production capacity available for supplying the hydrogen plant.

The Temporal Correlation rule states that renewable electricity applied in green hydrogen production must be generated during the same hour as it is used in the electrolyzer plant. In case of using electricity storages, stored electricity to be used later to hydrogen production must be stored behind the same grid point as the electrolysis plant within the same hour as electricity is produced. The temporal correlation rule is prescribed to help to maintain the power balance in the grids. Temporal correlation rule forces the electrolyzer plants consume/store renewable energy at the same time as it is generated in the grid. This will reduce the need of control power to stabilize the grid.

The Geographical Correlation rule states that electricity for producing green hydrogen must not be purchased from a cheaper bidding zone of the electricity market. Regional price differences result from bottlenecks in power transmission capacity. There is no transmission capacity to transfer surplus energy to deficit regions, and energy price in surplus region goes down. This rule is laid down to encourage to invest electricity and hydrogen production plants near each other to prevent increased power transmission needs over long distances. In this planning of optimal locations for electricity and hydrogen production plants the third moving part is the location of the end use of the hydrogen. Possible existence of hydrogen transmission grid has also a big impact on locations of different assets. All these issues must be considered when planning to invest in hydrogen production.

Type of the electricity purchase agreement has also an important role in green hydrogen business. In all cases, where electricity is transmitted via national power grid, there must be a PPA between a supplier and a consumer. PPA is also the Renewable Energy Guarantee of Origin (REGO) needed to certify the origin of the used electricity. In case of variable renewable energy production there are different types of PPAs. For general use, e.g. powering of datacenters, PPAs are made for annual bases. In case of green hydrogen production and because of the requirement of temporal correlation, this is not feasible. The electrolyzer operator expects to get the agreed power for every hour to be able to run the production, but variable energy producer cannot guarantee steady power supply. In this case it must be agreed if the agreement is Baseload type or Pay-as-Produced type. This defines the responsibility of the cost of unsupplied energy. In Pay-as-Produced agreement, the electrolyzer operator has the responsibility to purchase extra energy needed to run the process, but the price for the agreed energy is cheap. In case of Baseload type PPA, the supplier has guaranteed an hourly supply of energy, and the unsupplied energy is purchased and paid by the power producer. Energy price in this kind of

Baseload agreement is higher compared with Pay-as-Produced type agreements.

In this kind of situation of variable renewable power supply it is possible that the hydrogen producer produces only a certain amount of green hydrogen fixed with the consumed amount of green electricity, and the rest of the produced hydrogen is not certified green. This is feasible if there is a customer for a non-green hydrogen.

3.1. Capacity dimensioning

Requirements of the use of variable renewable energy (VRE) and the hourly temporal correlation between power production and consumption affects the dimensioning of the electrolyzer capacity and possible required hydrogen buffer storage capacity. The amount of hydrogen production powered by variable electricity production depends on the statistic characteristics of the variable power production. Nominal power or peak capacity of the renewable power production plant defines the maximum power output from the generation site. In modern on-shore wind power installations on coastal areas of Finland the capacity factor is app. 40 %. This equals with 3500 h of full load hours. With solar PV production the capacity factor in Finland is app. 10% resulting to 876 h of full load hours.

If the electric capacity of the electrolyzer plant is dimensioned equal with the nominal power capacity of the supplying VRE generation site, it can take advantage of all electricity generated on the site. However, the full load hours of the electrolyzer will be low, which means that investment efficiency is low. In this case there will be a lot of invested expensive overcapacity doing nothing most of time of the year.

Reducing the electric capacity of the electrolyzer plant will increase the full load hours and improve the investment efficiency. On the other hand, this reduced capacity electrolyzer plant cannot utilize the peak power outputs from the VRE site and the total amount of produced hydrogen will be reduced. In this case, if the PPA for purchasing electricity is Pay-as-Produced type, the electrolyzer plant operator has to sell the surplus power to the energy market, which is also an extra task, and probably a cost too.

The produced hydrogen may be used as such in industrial applications like green steel manufacturing or hydro cracking processes in chemical industry. The other main use will be raw material for methane, methanol, and ammonia production. Characteristic for most of these end use applications is that they must be operated at steady operation conditions. They provide no flexibility for the system. Methanation processes synthetizing carbon dioxide and hydrogen to methane, CH_4 or methanol, CH_3OH, have some flexibility in their operation, but it is limited. In methanol production this flexibility is achieved by buffering crude methanol between methanation plant and distillation plant used for purification of the product.

This stiffness in the operation of the end use processes results to the need of buffering storages between variable hydrogen production and fixed constant consumption of the end use processes. The size of buffer storages and the amount of constant hydrogen feed to end use processes depends on the electrolyzer capacity related to statistical characteristics of electricity supplying VRE production. High capacity electrolyzer with low full load hours will need bigger storage capacity to be able to produce higher constant flow hydrogen feed.

Thus, the design of the hydrogen production plant to be able to produce constant hydrogen flow is a complex problem. (Gallo 2023) System designer must know the statistic characteristics of supply energy, requirements for the hydrogen flow supplying the end use processes, investment costs of electrolyzers and hydrogen storages, and prices of electricity and hydrogen. The designer must be aware as well the properties and risks of different type of power purchase agreements. If the annual amount and constant supply of produced hydrogen is fixed, the designer has to decide how much VRE capacity is need, what is the needed electrolyzer capacity and how much buffer capacity is needed to smooth the hydrogen outflow. The amount of required VRE capacity depends on the statistics of the VRE production. E.g. in case of hybrid power production using both wind and solar PV generation, the amount of needed VRE capacity will be totally different compared to only wind power production.

4. DEMONSTRATIVE EXAMPLE OF DIMENSIONING

This chapter presents a simple demonstrative example how the dimensioning of the electrolyzer capacity is connected to the operational values of the hydrogen production system. The fictive hydrogen production plant has made a PPA with a 200 MW nominal capacity wind power plant. The production profile for the power plant is scaled from a Finnish national wind power data between January 1st – April 30th 2023. Data is available at Fingrid open data system. (Fingrid) The scaled production time series and duration curve are shown in Fig. 1.

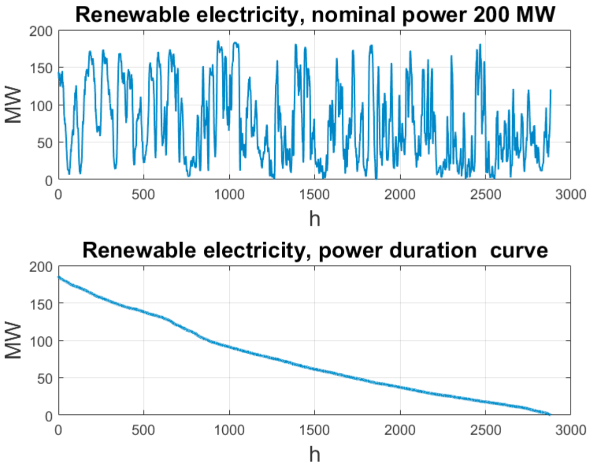


Fig. 1. Wind power production time series and duration curve during. 1.1. – 30.4. 2023. Data is scaled from national wind power production data.

Mean value of the power production is 75 MW and the standard deviation is 51 MW. Production varies between 0 - 186 MW, four months energy production is 215.6 GWh and capacity factor is 0.37. In case of a real individual wind power production site(s), the standard deviation would be higher compared to this value based on national data. National data consists of production values from a wide geographical area smoothing the local variability of the generation data.

4.1. Three different capacity electrolyzers with H_2 storage

In this fictive example there are three different electrolyzer designs based on 4000, 6000, and 7000 hours of full load operation. The electrolyzer electric power capacities are 164 MW, 109.3 MW, and 93.7 MW respectively, and the respective capacity factors are 0.46, 0.68, and 0.80. Electrolyzer efficiency from electricity to hydrogen is assumed to be 67%, which is typical for commercial alkaline electrolyzers. Fig. 2 shows hydrogen production of these three electrolyzers.

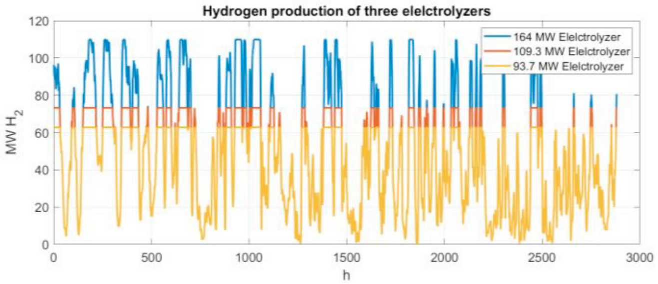


Fig. 2. Hydrogen production of three different capacity electrolyzers.

Variable hydrogen production must be smoothed to constant hydrogen flow for end users. Fig. 3 shows the utilization of buffer storages converting the variable input hydrogen flow to constant supply flow for end users. The constant flows for 93.7 MW_e, 109.3 MW_e and 164 MW_e electrolyzers' production are 39 MW_{H2}, 42 MW_{H2}, and 48 MW_{H2} respectively. States of charge of hydrogen storage for four months operation from Jan. 1st to Apr. 30th 2023 for three electrolyzers are shown in Fig. 3. The main characteristic values of cases are presented in Table 1.

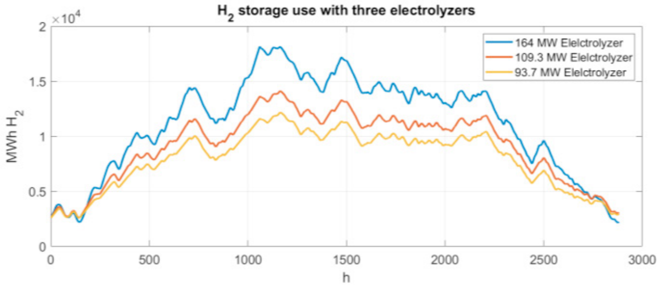


Fig. 3. Hydrogen storage use with three different capacity electrolyzers.

Table 1. Hydrogen production and use of storage capacity.

Eletrolyzer full load hours	Eletrolyzer capacity [MWx]	Storage capacity [GWh]	Continuous load supply [MW]	Constant production [GWh]
7000	93.7 MWe 61 MW_{H2}	12.2	39	112.32
6000	109.3 MWe 71 MW_{H2}	14.1	42	120.96
4000	164 MWe 107 MW_{H2}	18.1	48	138.24

4.2. Electrolyzers with H_2 and battery electricity storages

One option to increase full load hours of the electrolyzer is install battery energy storage (BES) in front of the electrolyzer. Fig. 4 shows the 109.3 MW electrolyzer's power consumption with and without BES, and the state of the charge of the BES. During two first months, wind power production frequently rises above electrolyzer capacity, and BES is charged to support operation during low wind power production periods. However, during two last months, wind power production is most of the time less than electrolyzer capacity, and BES is not charged, and it cannot support the hydrogen production. In this case BES does not affect remarkable the use of hydrogen storage.

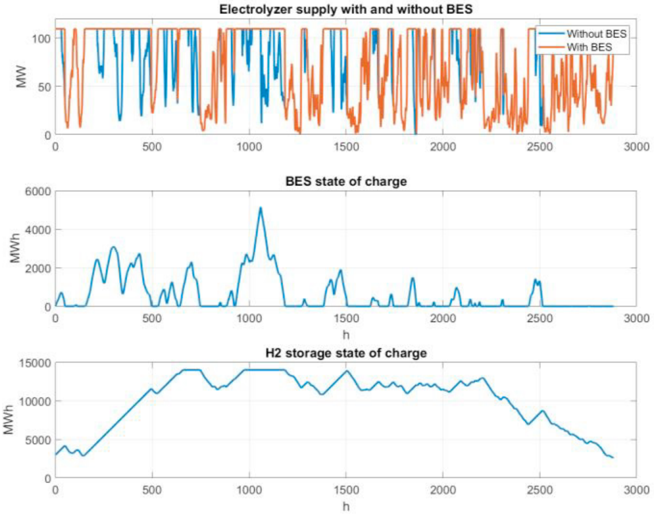


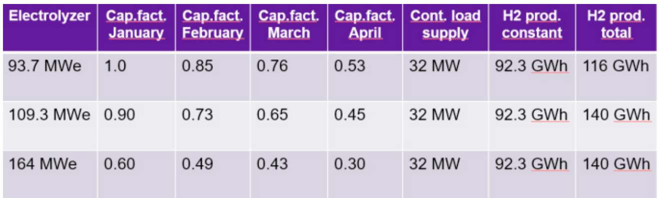
Fig. 4. Electrolyzer plant operation with and without BES, and the state of the charge of the BES and H2 storage.

Installing BES together with 109.3 MW electrolyzer increased the constant hydrogen supply from 42 MW_{H2} to 46 MW_{H2}, and the full load hours of the installation from 6000 to 6900. The total four months hydrogen production increased from 121 GWh to 140 GWh. Roughly speaking, with BES the 109.3 MW electrolyzer produced same performance as 164 MW electrolyzer without BES, and the need of H_2 storage capacity is smaller compared with 164 MW electrolyzer.

4.3. One-month temporal correlation

There is a transition period in EU regulation for hourly temporal correlation until the end of 2029. During the transition period electricity production and electricity consumption for hydrogen production must be balanced in one calendar month. One month balancing period allows more flexible operation of the electrolyzers and reduce the need of H_2 storage capacity. Grid electricity can be used more freely to compensate fluctuations of the VRE production. With the electricity production characteristics applied in this demonstration, hydrogen production based on monthly energy balance is shown in Table 2. In this consideration there were no H_2 storage capacity installed, but the momentary variability of VRE production was compensated by grid electricity. Monthly capacity factors depend on the monthly wind power production. With the highest production in January, capacity factors are the biggest, and in April, when the wind power production is the lowest, also capacity factors are the smallest. In this study the level of the continuous hydrogen supply was defined by the lowest monthly production. Of course, monthly constant supply level is higher during the months with higher wind power production, but the minimum level for four months period comes from the lowest monthly level. The second remark is that the total four months H_2 production does not increase when increasing the electrolyzer capacity from 109.3 MW to 164 MW. This is because on monthly level already the capacity of 109.3 MW electrolyzer can use all electric energy produced by the wind power plant. In case of 93.7 MW electrolyzer, in January capacity factor is 1, and all VRE production cannot be used, and this reduced the amount of totally produced hydrogen.

Table 2. Production values of three electrolyzers when monthly based temporal correlation is applied.



Electrolyzer	Cap.fact. January	Cap.fact. February	Cap.fact. March	Cap.fact. April	Cont. load supply	H2 prod. constant	H2 prod. total
93.7 MWe	1.0	0.85	0.76	0.53	32 MW	92.3 GWh	116 GWh
109.3 MWe	0.90	0.73	0.65	0.45	32 MW	92.3 GWh	140 GWh
164 MWe	0.60	0.49	0.43	0.30	32 MW	92.3 GWh	140 GWh

5. DISCUSSION

The topic of this study was to demonstrate how multi dimensional problem the design of the green hydrogen production plant is. Main reason for this complexity is EU's requirement for the hour based temporal correlation between VRE production and hydrogen production. From the point of view of the electrical system, this requirement is feasible. It forces the hydrogen production system to follow fluctuations in VRE production and balance on hourly level supply and demand. This is very important when the share of VRE production in power systems increases. It helps to adopt maximal amount of VRE production in the system.

Temporal correlation is a problem especially if the further use of hydrogen requires constant supply levels. At the moment most of the planned end use applications are this type, e.g. using green hydrogen for reduction of iron ore in green steel making, and raw material in chemical industry. Haber-Bosch process for ammonia production must also be operated continuously at constant operation point. Methanation processes like Sabatier and Fisher-Tropsch, synthetizing hydrogen and carbon dioxide/monoxide to methane and methanol have some flexibility in their operation. However, also these processes are operated at high pressures and temperatures, and their frequent starting and stopping is not possible. However, they can be operated at varying load levels with moderate ramping rates, app. 10% /h.

The structure and the dimensioning of the main components of the green hydrogen production plant depends on the statistic characteristics of supplied VRE, characteristics of further use of produced hydrogen and investment costs of different unit processes such as electrolyzers BES and hydrogen storges. According to (Aghosseini et al. 2023) capital investment costs (CAPEX) for BES will be 0.11 M€/MWh in 2030 and it is expected to drop to 0.06 M€/MWh by 2050. CAPEX for tank type hydrogen storages is 0,03 M€/MWh. CAPEX for electrolyzer investment is app. 1 M€/MWe, but it varies a lot depending on the electrolyzer type.

One important question is how different type of electrolyzers bear variable operation condition. This is very important, because the flexibility of the hydrogen economy is planned on the flexible operation of the electrolyzers. Electrolyzers have so far been operated at constant operation environments. There are some preliminary reports that variable operation conditions will reduce electrolyzers' nominal capacity but not so much their efficiency. This topic is under an intense research work. For some type of electrolyzers also big increase in thermal losses during part load operation has been reported. This reduces the hydrogen production efficiency remarkable under part load operation conditions. If this is the case for all electrolyzers, there must be applied some kind of economic dispatching for production planning as is used in production planning of power plants connected in the power grid. [Majanne et. al. 2022]

One important issue in hydrogen manufacturing planning is, what is the value of the green certificate of the produced hydrogen. It is essential that the produced hydrogen must be carbon neutral or very low emission hydrogen. If this is not the case, there is very little sense in this whole hydrogen economy. But if this green certificate is not needed, then it is possible to avoid many problems and use e.g. nuclear energy for hydrogen production. On the environmental point of view this will reduce the use of fossil energy as well and reduce greenhouse gas emissions, and the optimal dimensioning of the production equipment and operation of the system would be much easier.

6. CONCLUSIONS

Regulations guiding the production of green hydrogen have strong effects on the design and operation of hydrogen production plants. The regulation is enacted to guarantee that transition to PtX economy will really have positive impact on climate change and that the integration of the PtX economy with the rest of the power system will be as smooth as possible. However, these regulations make the optimal design and operation of hydrogen production plants very difficult issue. Requirement of hourly based temporal correlation between variable renewable energy production and green hydrogen production leads to poor investment efficiency due to overcapacity and need of high-capacity buffer storages between variable hydrogen production and steady hydrogen supply to most of the end use processes.

To make the PtX economy as feasible as possible, the main property to be developed in future is the flexibility. Electrolyzer technology have to be designed to bear flexible operation and even more important issue is to develop the further processing systems of hydrogen more flexible. Current process technology does not support flexible operation of methanation and ammonia processes, but this is something we need in the transition to green energy.

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REFERENCES

Aalto et al.,2021, Electrification, Accelerating the Energy Transition. Elsevier 2021. ISBN 978-0-12-822143-3. DOI https://doi.org/10.1016/C2019-0-03794-6

Aghosseini A. et al. 2023, Energy system transition pathways to meet the global electricity demand for ambitious climate targets and cost competitiveness. Applied Energy 331 (2023) 120401

Dahiru, A.R., Vuokila, A., Huuhtanen M., Recent development in Power-to-X: Part I - A review on techno-economic analysis, Journal of Energy Storage, Volume 56, Part A, 2022, 105861, ISSN 2352-152X, https://doi.org/10.1016/j.est.2022.105861.

European Commission 2023, Commission sets out rules for renewable hydrogen, https://ec.europa.eu/commission/presscorner/detail/en/IP_23_594, referred 8.2.2024

Fingrid Open Data. https://data.fingrid.fi/en/, referred 8.2.2024

Gallo, M.A., García Clúa, J.G. 2023, “Sizing and analytical optimization of an alkaline water electrolyzer powered by a grid-assisted wind turbine to minimize grid power exchange”, Renewable Energy, ISSN 0960-1481, Vol. 216, 118990, Elsevier, 2023. https://doi.org/10.1016/j.renene.2023.118990

Majanne, Y., Björkqvist, T., Vilkko, M. 2022. Scenarios for future power system development in Finland. IFAC-PapersOnLine, Volume 55, Issue 9, 2022, Pages 6-11. https://doi.org/10.1016/j.ifacol.2022.07.002

United Nations 2023. https://sdg.iisd.org/events/2024-un-climate-change-conference-unfccc-cop-29/, referred 8.2.2024

World Economic Forum, 2021. Energy Transition, Grey, blue, green – why are there so many colours of hydrogen? Jul 27, 2021. https://www.weforum.org/agenda/2021/07/clean-energy-green-hydrogen/ , referred 8.2.2024