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Bachelor's thesis

Model-based scenario analysis of the German hydrogen production in a decarbonized energy system

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Abstract

The world is facing climate issues and is searching for possibilities to avoid further deterioration. Saving emissions of greenhouse gases and therefore abandon fossil fuels seems to be a promising path in recent years. Since hydrogen is widely regarded as an alternative to fossil fuel carriers, this thesis examines a possible hydrogen supply chain for Germany in the year 2040 by the use of a mathematical model. This optimization model is implemented in the programming language Julia to calculate several scenarios. The focus will be on various characteristics of this supply chain like the installed technology mix for hydrogen production, dimensions of production and storage facilities and hydrogen trade between domestic regions. Also, an examination of the optimal production plan and different dynamics over one year and shorter timespans will be done due to an hourly resolution (8760 timesteps) in this example year.

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1 Introduction

Mankind of today faces many issues, some as a worldwide community, some only regionally. Two of the biggest and competing ones are the anthropogenic climate change and energy security for a world-wide rising demand for energy. Often, people who merely contribute to climate change, living in a poor environment with minor emissions, feel the changing condition first, but also wealthy regions like Europe or the US are increasingly affected. Solutions must be found to secure energy demand and lower emissions. One of the major problems for emission-free produced power is the storage, while storing fossil fuels with a high energy density is easily possible. Especially in a large scale, it is difficult to store power because batteries often have low energy densities, are expensive and reliant on seldom earths. Therefore, it is difficult to decarbonize branches like glazing, smelting or heating of buildings. In the transportations sector, problems occur because, high and mobile energy amounts are needed. So, the aim is to establish an energy carrier which fulfils these needs. One possible candidate is hydrogen. Depending on its aggregate phase and pressure, it has a relatively high energy density and can not only compete with fossil fuels but even excel them. Another advantage is that hydrogen is often in form of a gas, so existing infrastructures like pipelines and gas tanks can partly be used with minor investments for a retrofit. In addition, mentioned industries like glazing and smelting often operate on gas supply, so retrofitting such facilities appears possible with an appropriate amount of time. Heavily emitting vehicles such as aircrafts could profit from the high possible energy density of liquified hydrogen and thus abandon kerosine. Cargo ships, also heavily emitting greenhouse gases, don’t need a very high energy density but a lot of energy. Hydrogen might here be an option as well. There are also many attempts by car manufacturers to decarbonize cars by the help of hydrogen.

None of these possible applications has been realized in a remarkable scope because, as with every new technology, some hurdles need to be taken. Besides the challenging characteristics of hydrogen itself, e.g., it is highly explosive and to realize the high energy density, it either must be cooled down to -270°C or compressed to about 700bar, infrastructure and demand must develop in the same pace.

Should there be pilot projects in single factories at first? How can the existing pipeline network be used or retrofitted and how fast will demand grow? How can hydrogen be produced with least possible emissions, should it be produced centralized and then be distributed or stored and what capacities will it need to satisfy a potential demand in 2040 and is there a use case as a new Power-to-X technology? This thesis will deal with the last-mentioned question and will set up a model for a possible hydrogen supply chain for Germany in the year 2040.

1.1 Literature review

Regarding the complexity that comes with introducing a new energy carrier and its infrastructure, it appears inevitable to construct a mathematical model to understand and assess various aspects of this challenge. Due to the importance of future energy supply and thus economic and social stability, such a model must fulfil high standards in terms of relevant purpose-definition, accuracy, precision and, based on that, closeness to reality while maintaining a reasonable level of computability. In recent publications, several approaches have been developed to find a bearable compromise between the foresaid partly conflicting objectives.

In any reviewed article from the past two decades, the model or at least the case study on which the underlying model was applied was limited to a specific country or region of a country. Not necessarily using a quantitative approach but rather conducting different analyses, most studies reviewed are noticeable focused on similar regions: A lot of articles developed a model for the UK or at least applied their model in a case study in the UK: Almansoori, A. & Shah, N. (2009), Moreno-Benito, M., Agnolucci, P. & Papageorgiou, L. G. (2017), De-Léon Almaraz, S., Azzaro-Pantel, C., Montastruc, L., Pibouleau, L. & Baez Senties, O. (2012, 2013), who all followed different but quantitative approaches. Dodds, P. E. & Demoullin, S. (2013) analyse a possible conversion of the UK gas network and Balta-Ozkan, N. & Baldwin, E. (2013) embed hydrogen in the UK MARKAL Energy System model. Other frequently analysed regions are Korea, see Kim, J., Lee, Y. & Moon, I. (2008), Won, W., Kwon, H., Han, J.-H. & Kim, J. (2017) using a GIS (Geographical Information System)-based approach, particular regions from the US, see Johnson, N. & Ogden, J. (2012) or Johnson, N., Yang, C., Ogden, J. (2008) and Germany, e.g., Baufumé, S. et. al. (2013) and Ball, M., Wietschel, M. & Rentz, O. (2007), both using a GIS approach. Other regions appear in the literature as well but not as frequent as those above mentioned do.

In the light of preferably producing hydrogen with renewable energy sources (RES) and distributing it, the use of a model with GIS-information or a standalone GIS-approach allows for a further increase of efficiency. Wind and solar data in terms of RES as well as information about the geography when planning new pipeline routes can be taken into consideration. A special focus has been put on that by Levene, J. I., Mann, M., Margolis, R. M. & Milbrandt, A. (2007).

Setting up an HSC requires to decide about the scope of the supply chain. While it is possible to focus on the production part and neglect transportation and consumption aspects, De-Léon Almaraz, S., Azzaro-Pantel, C., Montastruc, L., Pibouleau, L. & Baez Senties, O. (2013) include production, storage and transport. Going one step further, Almansoori, A. & Shah, N. (2009) involve fuelling stations as well. This decision makes an important step closer to reality and away from the model world but incorporating a higher level of detail, will require a higher computational effort as well. (Baufumé, et al., 2013) This leads to the decision of how to divide the region that is scrutinized. One option is to separate the region into squares as Almansoori, A. & Shah, N. (2009) do or use “real” regions based on existing political states, see Kim, J., Lee, Y., & Moon, I. (2008). An important aspect for the explanatory power of the model is how the distribution network is modelled. Not only the level of detail of this distribution network plays an important role, e.g., a local network with many single fuelling stations or only connections between different regions, but also the mode of transport. The currently relevant modes in reality are railway tank cars, (different forms of) trucks and pipelines, each of them connected with specific investment and operating costs, capacities and scalabilities. In literature, different combinations of modes can be found, like Kim, J., Lee, Y., & Moon, I. (2008) use tank trucks, tube trailers and pipelines, Almansoori, A. & Shah, N. (2009) use a similar mix of trucks, railway tank cars and pipelines and Nunes, P., Oliveira, F., Hamacher, S. & Almansoori, A. (2015) limited their model to trucks and trains. Another possibility is to neglect distribution complexity at all and assume a centralized supply and demand like the OR-Inf-Term-Paper by Günzel, P., Mader, H., Schelten, M. & Guth, H. (2022) on which this thesis is based.

Besides these reality simplifying assumptions, models from the literature can also be differentiated by technical aspects that again determine the explanatory power, closeness to reality and especially computability. Most of the works reviewed use MILP (Mixed-Integer-Linear-Problems), like Moreno-Benito, M., Agnolucci, P., & Papageorgiou, L. G. (2017), De-León Almaraz, S., Azzaro-Pantel, C., Montastruc, L., Pibouleau, L. & Baez Senties, O. (2013) or Almansoori, A. & Shah, N. (2009). These MILPs have some drawbacks like the impossibility of solving nonlinear effects, they need to consider all time periods at once and are prone to the risk of high-dimensionality of the problem. (Urbanucci, L. (2018)) Including integer variables increases the modelling power, resulting in more complexity, see Larossa, J., Oliveras, A. & Rodríguez-Carbonell, E. (2021). All the models reviewed have a cost minimisation as objective function in common, see for example Moreno-Benito, M., Agnolucci, P. & Papageorgiou, L. G. (2017), De-León Almaraz, S., Azzaro-Pantel, C., Montastruc, L., Pibouleau, L. & Baez Senties, O. (2013), Almansoori, A. & Shah, N. (2009). These objective functions look quite different but the purpose to build and/or operate an HSC in the most cost-efficient way stays the same. In De-León Almaraz, S., Azzaro-Pantel, C., Montastruc, L., Pibouleau, L. & Baez Senties, O. (2013), the authors consider a multi-objective problem. This means that the costs minimisation is only one objective beside at least one other objective function (in this case two: Global warming potential, Total risk). This paper describes a mono-objective solution (costs only) and follows a lexicographic approach, what means that the objective functions are prioritized, and the problem is first solved for the one that is ranked highest. If there are several possible solutions or even a solution-field, the next highest objective is optimised in this field.

The research question always determines the time frame for which the model is developed. If the model has the aim to solve dispatch problems as main purpose, the resolution will be very high while the time frame will be small compared to the timeframe which is used to analyse a possible introduction of a HSC, which is in fact the use-case with most research about. Often these models examine several years, like in Almansoori, A. & Shah, N. (2009) who use a timeframe of 34 years and conduct several analyses for 5 different periods in these 34 years. Yang, C. & Ogden, J. M. (2013) worked with a model to analyse the development of the hydrogen infrastructure in 8 regions in California until 2050.

Most of the previous works mentioned above assume several sizes like the demand for hydrogen or the supply of resources at specific points and times as given. This creates uncertainty and the literature employs different ways to deal with it. Nunes, P., Oliveira, F., Hamacher, S. & Almansoori, A. (2015) use a method which is called Sample Average Approximation (SAA). This SAA-technique allows to model the future hydrogen demands by a stochastic process. The most common approach is to evaluate the results by computing several scenarios.

Like the above-mentioned decision which transportation modes to apply there is the decision which production methods shall be included. Meeting such decisions leaves the model incomplete and creates uncertainty. On the one hand whether the selected technologies will indeed play the major role in a future HSC and on the other hand if their efficiencies remain as they are today or will improve. Also, it is possible that taxes for CO2-emissions are increased what might lower the attractiveness of the currently most employed technology Steam Methane Reforming (SMR). In the literature, there can be found various technology-mixes for example SMR, Gasification and Electrolysis in Moreno-Benito, M., Agnolucci, P. & Papageorgiou, L. G. (2017), De-León Almaraz, S., Azzaro-Pantel, C., Montastruc, L., Pibouleau, L. & Baez Senties, O. (2013) and Almansoori, A. & Shah, N. (2009). Solely Electrolysis is used by Levene, J. I., Mann, M. K., Margolis, R. M. & Milbrandt, A. (2007), for example. Also scales in production have yet been incorporated, see Agnolucci, P. & McDowall, W. (2013). Nunes, P., Oliveira, F., Hamacher, S. & Almansoori, A. (2015) even managed to introduce different sizes of production facilities.

2 Main Part

2.1 The model

2.1.1 A qualitative approach

The mathematical approach presented in the upcoming pages is an HSC model with prospective regional production of hydrogen, its distribution and regional demand for Germany in the year 2040. The model is a cost-minimization problem that aims to minimize cost not for the single regions but for the whole country as one. Since energy security is and will be vital in future for a highly industrialized and politically important country like Germany, both, hydrogen and power demand are covered by the model in every region and timestep of the year. For this, the model uses a resolution of 8760 timesteps, one for each hour and assumes the regions as the existing 16 states, Germany consists of. In each region, the model can “build” capacities of storage for hydrogen on the one hand and production capacities on the other hand. As there are various ways to produce hydrogen, there is a choice of 4 possible technologies from which the model selects the best suiting for one region and decides which capacities shall be built. Since storage as well as production capacities are linearized due to improved computational time, the model will build capacity itself instead of plants with capacity and it will be able to choose more than one technology for each region but can decide as well that not every region is producing at all. The investment costs to build capacity are assumed to distribute equally over an expected lifetime of 20 years. The technologies are Electrolysis, SMR, Gasification of biomass and Partial Oxidation of Methanol (POM). While SMR and POM are based on fossil fuels and emit CO2, a carbon tax incurs for them. Electrolysis can be executed by the input of power which is meant to be produced by renewable sources only but more expensive, non-renewably produced power can be used as well. The model allows transportation of hydrogen between different regions via pipeline network to overcome regional shortages in hydrogen without being forced to have a filled storage or to build new production capacities. However, transportation costs and minor losses occur. For reasons of simplicity in modelling, every region can directly trade[1] with every other region and not only with its neighbour countries. Therefore, the connections as they are modelled are theoretical and do not have a maximum capacity, regardless of the fact that a hydrogen pipeline network in these dimensions does not yet exist in Germany anyway. In between the regions, a centralized demand and supply is assumed by reasons of decreasing complexity and computational time. A trade for electricity between the regions is implemented besides and independent of the hydrogen trade. Another feature of this model is the reconversion of hydrogen to power. As Germany does not necessarily face the problem of producing enough power from renewable sources it does so in producing it at the desired time. But while storing power itself in large scale is difficult, storing hydrogen as a carrier of that energy and reconverting it whenever needed appears possible. This model allows every region to reconvert previously produced or imported hydrogen and thus to avoid paying for expensive, non-renewably produced power to meet its demand in times of low supply.

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[1] By “trade” is meant to simply transport hydrogen from one region to another. The costs are minimised for whole Germany as one and a region that receives hydrogen from another does not pay anything, what the word “trade” would suggest. The same applies to power- “trade” between the regions.

This model is based on the result of an earlier project (OR-Inf-Term Paper) which used a relatively restricted HSC-model with centralized storage and production facilities for whole Germany. Hence, it did not incorporate transportation complexity between regions. Nevertheless, it employed the 4 production technologies that are used here, as well, and was based on the same data for investment costs, supply and demand etc. To enlarge the model's horizon and thus its explanatory power, it was enlarged by the option for reconversion. To mitigate the negative effect on the computation time that was due to the extended complexity of the model, the former integer including model was transformed to an exclusively linear problem without dissociating too much from reality but assuming that now capacities of storage and production facilities are built, instead of single, countable entities.

2.1.2 A quantitative introduction

The upcoming chapter goes further into detail of the mathematical formulation of the model. 1 unit always equals 1 MJ, here. Sizes used in the model are denoted as follows, beginning with the control variables and given values:

Control variables

- timesteps: The 8760 timesteps/hours in the examined year.
- technologies: The 4 used technologies described above.
- fuels: The inputs for the technologies (power, biomass, natural gas (methane), methanol).
- reg: The 16 regions/states of Germany.

Given values

- x_{fuels}[fuels, timesteps, reg]: The prices for every fuel, dependent on timestep and region.
- input[fuels, technologies]: The input of one fuel (in MJ) that is needed to produce 1 unit (1 MJ) hydrogen. It can occur that one technology uses more than 1 sort of fuel.
- c_{prod}[technologies]: The costs for the production of one unit hydrogen that is technology-specific and covers all costs except costs for used fuels. Due to a lack of sufficient data, this size is only used to include costs for CO2-taxes for SMR and POM.
- $c_{invStorage}$: Investment costs for 1 unit storage capacity.
- $c_{invCostCapacity}$[fuels]: Investment costs for 1 unit production capacity of one technology.
- $c_{externalPowerProd}$[timesteps]: The costs of power that has not been produced renewably.
- TC[reg, reg]: The transportation cost for 1 unit hydrogen from the region of the 1. index to the region of the 2. index.
- reElCosts: The costs for reconversion of 1 unit hydrogen.
- r_{max}[fuels, timesteps]: The maximum available amount of one resource at one timestep.
- PowerProd[timesteps, reg]: The power that is produced renewably in one region in one specific timestep.
- PowerDem[timesteps, reg]: The power demand of one specific region at a timestep without the production of hydrogen.
- storeEff: The hydrogen leakage for 1 hour in %.
- transLoss: The leakage loss of hydrogen per 1 km pipeline.
- transLossPow: The power loss per 1 km transportation.

- hyd_reg_2040[timesteps, reg]: The hydrogen demand for one timestep in one region in 2040.
- compression: The power that is necessary to compress hydrogen to the desired pressure.

Following values are subject to optimization

- prod[technologies, timesteps, reg]: One entry contains how much hydrogen is produced by one technology in one timestep in one region.
- prodCapacity[technologies, reg]: This value indicates how much capacity of one technology is installed in one region.
- useExternalPower[timesteps, reg]: It contains how much power is purchased externally by one region in one timestep. “Externally” means power that was not produced renewably.
- tr[timesteps, reg, reg]: This variable captures the amount of *hydrogen* that was transported in one timestep from the region in the second index to the region in the third index.
- trp[timesteps, reg, reg]: This variable captures the amount of *power* that was transported in one timestep from the region in the second index to the region in the third index.
- rcv[timestep, reg]: The amount of hydrogen that is reconverted to power in one timestep in one region.
- st[timesteps, reg]: The storage level of hydrogen in one timestep in one region.
- capStorage[reg]: The storage capacity that was built in one region and thus the maximum storage content at any timestep for this region.

The formulation of the model

Objective function

As mentioned above, this model is a mono-objective model with an objective function that aims to minimize overall costs of the HSC nationwide. It incorporates the costs for:

- The production of hydrogen
- Compressing the produced hydrogen
- Building all storage capacities (paying the depreciation of the built storage)
- Building all production capacities (paying the depreciation of the built capacities)
- External power use
- Transportation of hydrogen between regions
- Reconversion of hydrogen

$$\sum_{timestep}^{timesteps} \sum_{technology}^{technologies} \sum_{fuel}^{fuels} \sum_{r}^{reg} \begin{pmatrix} x_{fuels}[fuel, timestep, r] * input[fuel, technology] + c_{prod}[technology] + \\ x_{fuels}[\text{"Power"}, timestep, r] * compression \end{pmatrix} * \\ * \, prod[technology, timestep, r]$$

$$+ \sum_{r}^{reg} \sum_{technology}^{technologies} prodCapacity[technology, r] * c\_invCostsCap[technology]$$

$$+ \sum_{timestep}^{timesteps} \sum_{r}^{reg} c_{externalPowerProd}[timestep] * use_{externalPower}[timestep, r]$$

$$+ \sum_{timestep}^{timesteps} \sum_{r}^{reg} \sum_{re}^{reg} TC[r, re] * tr[t, r, re]$$

$$+ \sum_{timestep}^{timesteps} \sum_{r}^{reg} rcv[timestep, r] * reElCosts$$

Restrictions

Production maximum. The amount that can be produced by one technology in one timestep and region is smaller or equal the maximum capacity of this technology installed in this region.

$$prod[i, t, r] \leq prodCapacity[i, r] \ \forall \ t \ in \ timesteps, i \ in \ technologies, r \ in \ reg$$

Resource limit. The production in every region and at any timestep is limited to the available amount of resources.

$$\sum_{i}^{technologies} \sum_{r}^{reg} input[j, i] * prod[i, t, r] \leq r_{max} \ \forall \ t \ in \ timesteps, j \ in \ fuels$$

Power maximum. The available power in one timestep in one region (LHS) must exceed or equal the amount of power needed for hydrogen production and compression (RHS).

$$\begin{aligned} PowerProd[t, r] - PowerDem[t, r] + useExternalPower[t, r] + rcv[t, r] * reElEff \\ + \sum_{re}^{reg} trp[t, re, r] * (1 - transLossPow * TD[r, re]) \\ \geq \sum_{i}^{technologies} input[\text{"Power"}, i] * prod[i, t, r] \\ + \sum_{i}^{technologies} prod[i, t, r] * compression \ \forall \ t \ in \ timesteps, r \ in \ reg + \sum_{re}^{reg} trp[t, r, re] \end{aligned}$$

Storage Balance. The storage balance of every region in one timestep must be equal to what has been in the storage in the previous period + production and imports – exports, demand and reconversion. This restriction makes sure that the hydrogen demand is satisfied in every situation.

$$\begin{aligned} st[t, r] = st[t-1, r] * storeEff \\ + \left(\sum_{i}^{technologies} prod[i, t, r] - hyd_{reg2040}[t, r] - \sum_{re}^{reg} tr[t, r, re] + \sum_{re}^{reg} tr[t, re, r] \right. \\ \left. * (1 - TD[re, r] * transLoss) - rcv[t, r] \right) * storingEff \ \forall \ t \ in \ timesteps, r \ in \ reg \end{aligned}$$

Storage at the beginning. The storage is assumed to be partly filled in period 1 with 10% of the built capacity in each region, so that the hydrogen demand is fulfilled in the first period without building later unused production capacities.

$$st[1, r] = 0.1 * capStorage[r]$$

Storage in the last period. Regarding period 1, the storage must have the same fill level.

$$st[8760, r] = 0.1 * capStorage[r]$$

Storage capacity. The storage cannot contain more hydrogen than its actual capacity.

$$st[t, r] \leq \mathrm{capStorage[r]} \ \forall \ t \ in \ timesteps, r \ in \ reg$$

2.1.3 Database

This following abstract introduces the data used in the model and therefore refers to the “Given values” section in the previous chapter. The first section covers the data provided by the academic chair.

PowerProd[timesteps,reg]. This set includes the renewably produced (PV, wind onshore, wind offshore) amount of power in each region at any timestep. It is derived from an overall installed capacity of each source in each region, multiplied with the respective timeseries data that give insight on how much of the installed capacity is usable in this timestep. Due to the fact that the year of matter is 2040, it is realistic to calculate with a significant higher amount of power production because more capacity will be installed, and higher efficiency can be achieved. Hence, the values from today are generally multiplied by factor 2 for the scenario analyses.

PowerDem[timesteps,reg]. The for one year aggregated power demand for each region is given and multiplied by the power demand timeseries that gives insight which fraction of the overall demand for one year is needed in each timestep in this region.

hyd_reg_2040. The prospective nationwide demand for hydrogen in different years, including 2040, is given by the academic chair. To distribute this demand on the single regions, the share of every region’s demand for power of the nationwide power demand is taken and multiplied by the given nationwide hydrogen demand. As above, to get an hourly demand, the power demand timeseries is used again. Assuming the same demand curve for hydrogen and power is questionable but not per sé wrong or unplausible.

The following table with data regarding the production efficiencies and costs is taken from the previous seminar paper (Guenzel, Mader, Schelten, & Guth, 2022) from which this model originated. As described above, several changes were made to the model, especially the linearization, therefore the table was adapted at some points. The previous work already mentioned that it is very time-consuming to research such data and that reliable or homogeneous sources are rare. Therefore, some accuracy unfortunately gets lost.

Table 1: Production data for 4 technologies

	Electrolysis	**Steam Reforming Methane (SMR)**	**Gasification (biomass)**	**Partial Oxidation (POM)**
Technology costs for 1 MJ H2 (c_{prod}[technology])	Neglected (=0)	0.0016 USD (carbon tax)	Neglected (=0)	0.00275 USD (carbon tax)
Resource use for 1 MJ H2 (input[fuel, technologies])	1.5 MJ (power)	0.0041 MJ (power) + 1.266 MJ (gas)	3.6 MJ (biomass)	1.33 MJ (methanol)
Output H2 per hour	240,000 MJ	300,000 MJ	5,000 MJ	100,000 MJ
Investment costs ($c_{invCostCapacity}$)	150 Mio. USD /240,000MJ = 625 USD/MJ	241 Mio. USD (without carbon capture) = 803 USD/MJ, 831 Mio. USD (with carbon capture, not used in the model)	3 Mio. USD = 600 USD/MJ	100 Mio. USD = 1,000 USD/MJ

The remaining values have been researched as well or are assumptions. They will be used in the base scenario and modified in the following scenarios to capture at least some uncertainty that comes with assumptions about future costs, availabilities and efficiencies.

c_external_power_prod[timesteps]. The costs to produce power non-renewably are assumed to be 4 times the price of renewably produced power. Since this is a pure assumption and shall rather be a deterrent of using such power than a real option in normal cases, this size is not region specific.

r_{max}. Except for power, r_{max} is assumed to be infinite.

storeEff. Assumed to be 1 (=100%), meaning that hydrogen does not leak from the storages in significant amounts. (Hao, et al., 2020) Even though this article deals with automotive storages, there is no indicator that significant higher numbers will arise with industrial tanks.

reElCosts. Assumed to be 0 due to a lack of reliable information. Nevertheless, hydrogen must first be produced and that is where costs incur.

transLoss. 2.63*E-6 km^{-1} = (60,000,000m^3/24,200,000,000m^3)/940km. (Xie, Xingzhi, & Mai, 2019) Even though these data are for natural gas and hydrogen is lighter than natural gas and slightly more prone to dissipation, this number will be used because it was not possible to find comparable data for hydrogen.

transLossPow. 8.13*E-5 km^{-1} = (1.3%/100 mi). (AEP, 2022) This approximate share of power that gets lost every transported kilometre.

x_{fuels}.

- Price for biomass: 0.023 USD/MJ (Carmen, 2022)
- Price for natural gas: 0.024 USD/MJ (Focus, 2022)
- Price for methanol: 0.025 USD/MJ (Statista, statista.com, 2022)
- Price for power: 0.0226 USD/MJ (EON, 2022)

compression. 0.12 MJ Power per 1 MJ produced hydrogen (Paschotta, 2022)

TC. The transportation costs from one region to another for one unit hydrogen calculate as follows: 1.65*E-6 USD/(MJ*1km) = 0.5 USD/(1,000ft^3*1,000km) (Brito & Sheshinski, 1997) (value of a gas pipeline, assumed to be similar to the value for hydrogen pipelines).This is multiplied by the distance between two regions to retrieve the cost matrix of 1 unit (1MJ) hydrogen for each distance. The distances between regions are an unprecise measure because there is no pipeline network for hydrogen yet. It shall rather give an intuition if it is very far or rather neighbouring regions. The distances were taken between the approximate centres of two regions.

2.2 Scenario Analyses

Considering the year 2040 and doing calculation or optimizations for this year makes it necessary to make assumptions and doing so, the model involves uncertainty. There are several approaches how to deal with it, the most common method is the use of different scenarios in which for example a political, social, environmental, or economic development in a specific direction is supposed and data are adapted to this new situation. In this work, there will be a Base Scenario with conditions as we face today (except power supply, see previous section), a political scenario that covers the justified threat of very high prices for natural gas, an economic scenario that includes a significant higher demand for hydrogen and an environmentally driven scenario that examines what would happen if there was a “bad” year in terms of renewable energy production, i.e., a very cloudy year with less wind than normal.

2.2.1 Base Scenario

This first scenario is considered to give an introduction what kind of data the model delivers and to give an idea what an optimal solution would look like with today prices, efficiencies, and unlimited availability of resources (except power). This scenario is the starting point for further scrutiny with minor and major changes to some assumptions as aforementioned. The initial CO2-tax is assumed to be 30 USD/ton. Following data were used:

Table 2: Overview about data for Input sizes

Sizes	**Values Base Scenario**
PowerProd	see "base_PowerProd"-table in the appendix
PowerDem	see “PowerDem”-table in the appendix
hyd_reg_2040	see "base_HydDem"-table in the appendix
technology inputs, investment costs, efficiencies, taxation	see table in the "Data"-section
c_external_power_prod	see "Data"-section
r_{max}	see "Data"-section
storeEff	see "Data"-section
transLoss	see "Data"-section
x_{fuels}	see "Data"-section
compression	see "Data"-section
TC	see "Data"-section

Running the model returns very detailed data, like the storage filling of every region at each timestep or the exports/imports at one timestep from every region to any other. The table below gives a summary about aggregated exports and imports of regions, their installed capacities of storage and production facilities (per hour) for each technology that is used by at least one region. Note that in the columns “Import TWh” and “Export TWh”, the values shown are a kind of balance for one region’s trade with all other regions. In addition, if there is e.g., a “0.00” in the import column, it does not mean that this region does not import anything at all, but it says that it is a net exporter. This inaccuracy is taken for reasons of clarity and comprehensibility. (All data in TWh).

Table 3: Results Base scenario

Region	Import TWh	Export TWh	Storage Cap. TWh	Electrolysis Cap. TWh	SMR Cap. TWh
Brandenburg	0.00	0.00113	0.00012	0.00002	0.00001
Berlin	0.00018	0.00	0.00010	0.00002	0.00001
Baden-Württemberg	0.07700	0.00	0.00592	0.00010	0.00022
Bavaria	0.00	0.01218	0.01493	0.00015	0.00058
Bremen	0.00134	0.00	0.00007	0.00001	0.00000
Hesse	0.00	0.00459	0.00040	0.00004	0.00003
Hamburg	0.00	0.00062	0.00006	0.00001	0.00001
Mecklenburg-Vorpommern	0.00	0.00756	0.00004	0.00001	0.00002
Lower Saxony	0.00	0.06105	0.00031	0.00006	0.00012
North Rhine-Westphalia	0.00780	0.00	0.00129	0.00015	0.00006
Rhineland-Palatinate	0.00	0.00247	0.00051	0.00004	0.00003
Schleswig-Holstein	0.00	0.00934	0.00007	0.00002	0.00002
Saarland	0.01714	0.00	0.00038	0.00003	0.00001
Saxony	0.00	0.00021	0.00020	0.00003	0.00001
Saxony-Anhalt	0.00	0.00311	0.00015	0.00002	0.00002
Thuringia	0.00	0.00119	0.00010	0.00002	0.00001
Sum	**0.10345**	**0.10345**	**0.02466**	**0.00073**	**0.00117**

It can be observed that every region has own production and storage facilities, so no region relies completely on imports from other regions. Nevertheless, in this base scenario, we can find 5 regions whose import-/export balance is negative, so they import more than they export to other regions. There is no clear pattern which characteristic of a region makes it an importer or an exporter. Two countries with high energy demand (power and therefore hydrogen) and high population, namely Baden-Württemberg and North Rhine-Westphalia as well as 2 city-regions and Saarland (with rather low energy demand) are the importers while the rest has a positive balance. However, a pattern can be seen regarding the installed storage capacity. Nearly all regions have a rather small storage installed (<0.00051 TWh) while the three regions with the highest energy demand (Baden-Württemberg, Bavaria, North Rhine-Westphalia) have significant higher capacities. A similar situation can be observed for production capacities.

These findings are visualised in the graph below.

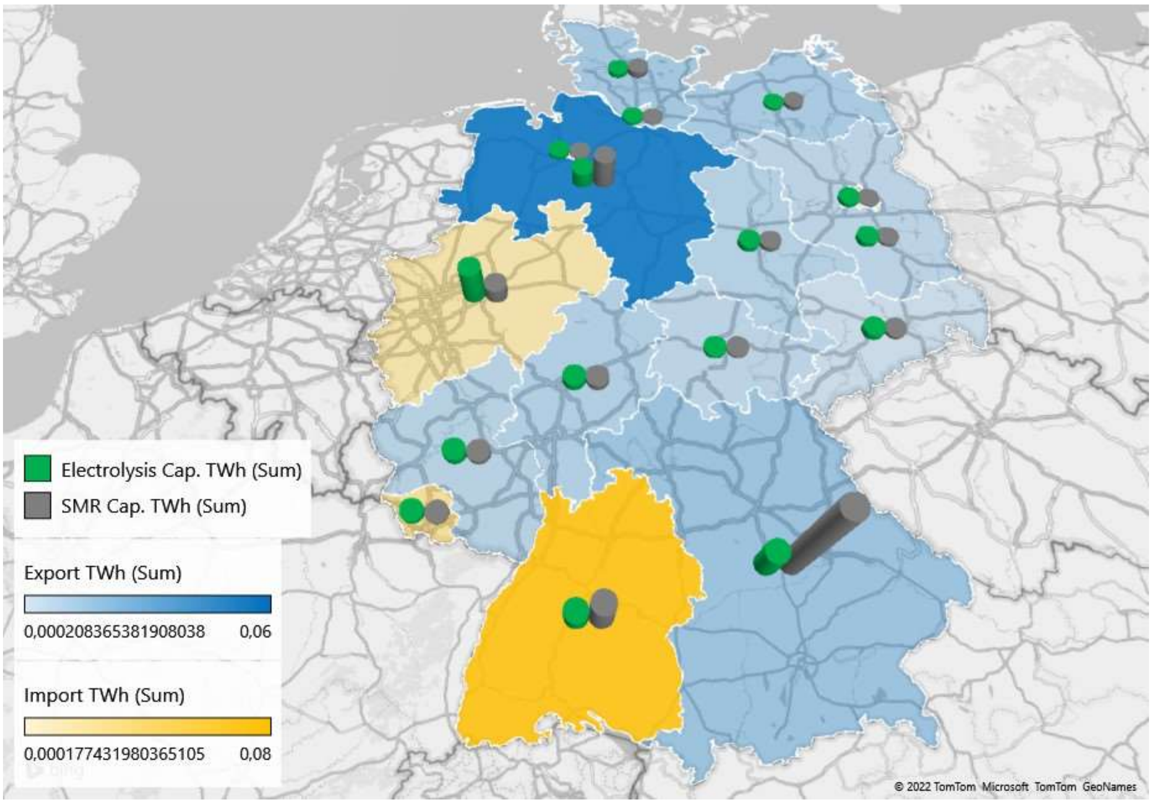

Figure 1: Geographic visualisation Base scenario

This map of Germany points out the production capacities and trading balances for hydrogen. The pillars represent the capacities for each production technology: Electrolysis in green and SMR in grey. The regions are coloured orange if they are importers of hydrogen and blue if they are exporters. The more intense a region is coloured, the more dominant is its import- or export balance. As mentioned above, the three regions with a high demand in energy have the biggest storage and production capacities. Also, while not belonging to these three regions, Lower Saxony has similar capacities for production but can export a lot since its own energy demand is small. Over all regions, it is different if there is more SMR or Electrolysis capacity installed but the clear dominance of SMR in Bavaria explains the difference in overall installed capacity between the two employed technologies, see the sum in *Table 3: Results Base scenario*.

In contrast to this finding, most hydrogen is produced by Electrolysis. Data show that the production with SMR does not take place as constant as with Electrolysis, but in peaks when there is not enough power (see explanations below and *Figure 3: Production plan Base scenario hours 400 to 600 (complete)*). This makes about 20% of overall production. The aggregated production plan can be seen in *Figure 2: Production plan Base scenario* below, where the grey fractions of a bar represent the production of hydrogen by the use of SMR while the green fractions do so for Electrolysis. Each fraction belongs to one region and one region has 2 fractions per month, one for each technology (See *Figure 9: Assignment of bar fractions to regions* in the appendix for an assignment of regions and fractions. This order of regions will remain the same throughout this work for comparability between scenarios.) The only outlier that can be seen is the peak use of External Energy in October. This is due to a very low power production in this month, see *Figure 10: Dimensions for hydrogen and power production, Base model* in the appendix. Therefore, the use of Electrolysis in this month is the lowest overall. From this month on, power production seems to meet power demand. The use of External Energy diminishes and so does reconversion. Overall, monthly production mostly varies between 0.5 TWh and 0.7 TWh and is always higher than the actual demand for hydrogen. In most months, 20% to 30% of the produced hydrogen is reconverted what could explain the "overproduction" and is an indicator for the use of hydrogen as a Power-to-X technology. As the storage filling[2] is not noteworthy throughout the year, this use must be limited to short periods in between the months. In December, SMR is not used anymore because reconversion is too low. However, this seems to explain abandoning SMR in December, it is possible that producing much less hydrogen than in any other month, especially in the last month, might be a signal that the model is slightly flawed, here.

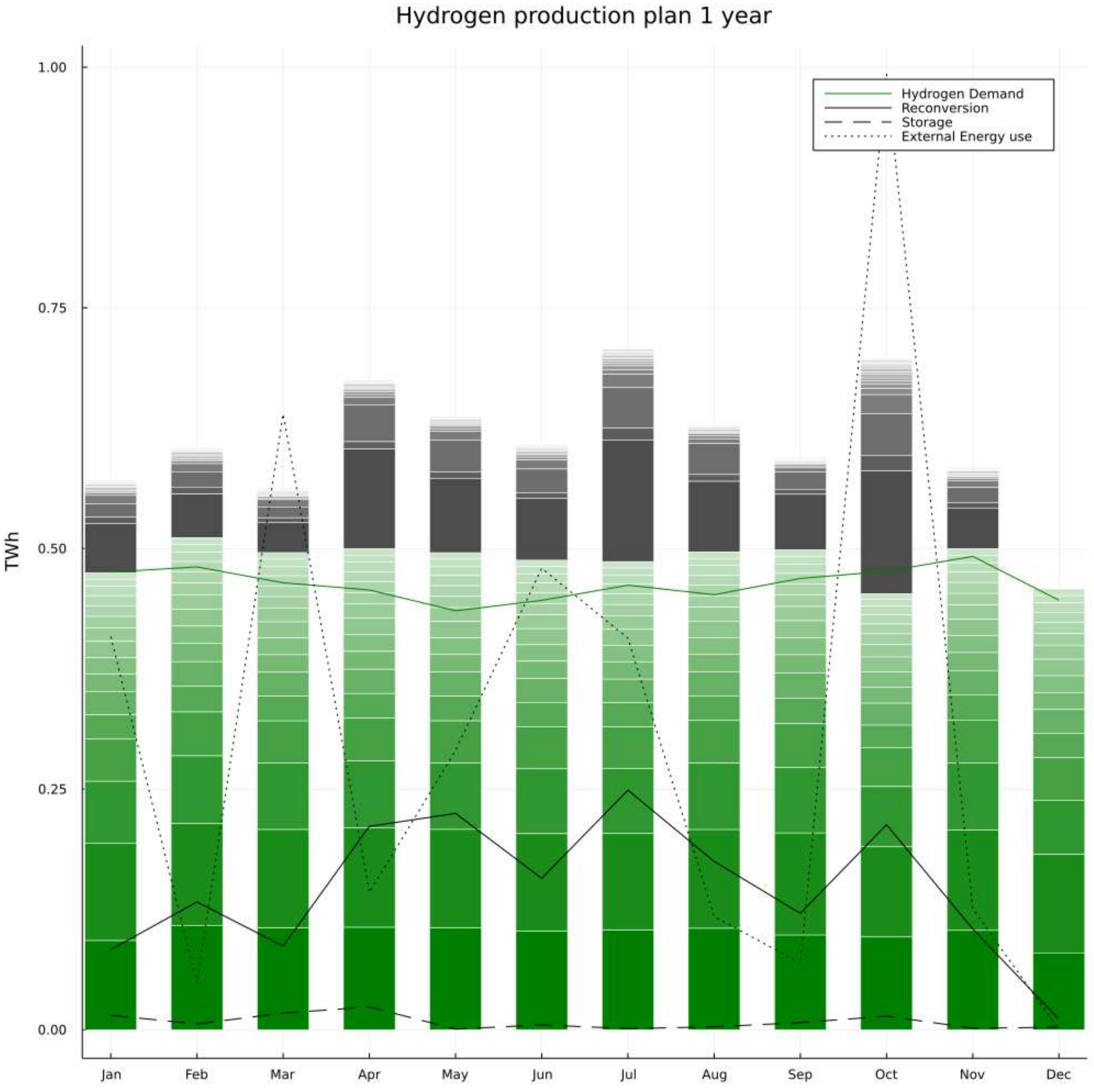

Figure 2: Production plan Base scenario

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[2] The storage line shows the sum of the storage fillings of all regions in the last hour of each month.

Since the model is running on an hourly basis, the monthly analysis looks very smooth but does not reveal all information. For this work, the focus lays on this macro perspective of the model, so the aggregated production plan for one year and the installed capacities. However, to show how the model works and what data it delivers on a lower level, the following abstract will briefly show an excerpt of the production plan for 200 hours in January (hours 400 to 600) that is representative for many other situations. Note that it shows a breakdown on every hour but is still aggregated over all regions.

The first thing to notice is that there is production by at least one technology in almost every hour while Electrolysis is used on a very constant basis in most cases (even though the available power may differ over time, the installed capacity does not seem to exhaust this limit, so the production by Electrolysis can be constant) and SMR is added only at some timeframes, see *Figure 11: Production plan Base scenario hours 400 to 600 (Demand and Production)* in the appendix for a better overview about production than in *Figure 3: Production plan Base scenario hours 400 to 600 (complete)*. In these situations, reconversion (black line) takes place, so intuitively more hydrogen needs to be available. This availability is reached by producing more hydrogen (by SMR) and using the storage (red line). Following intuition, reconversion should be conducted in peaks when there is a higher external need in power than power is produced. Logically, there should not be any power intense Electrolysis at these times and exactly that can be observed. Before this power-scarce time, the storage is continuously filled up by Electrolysis, and as soon as SMR starts working, it is an indicator that the power is scarce now, and the storage is being emptied while reconversion starts. In some situations, the described measures are not sufficient, and the model starts using expensive external power (blue line). This usually happens only when storage is low, see *Figure 3: Production plan Base scenario hours 400 to 600 (complete)*. In this context, it can be concluded that hydrogen helps decarbonising the energy system since it avoids non-renewable external energy. After these intense times, the storage is steadily filled up with green Electrolysis hydrogen, again.

The aggregated production plan above showed that the use of storage and its reconversion is not conducted on large scale over months, but the low-level plan showed that there is indeed a use of this strategy in short terms.

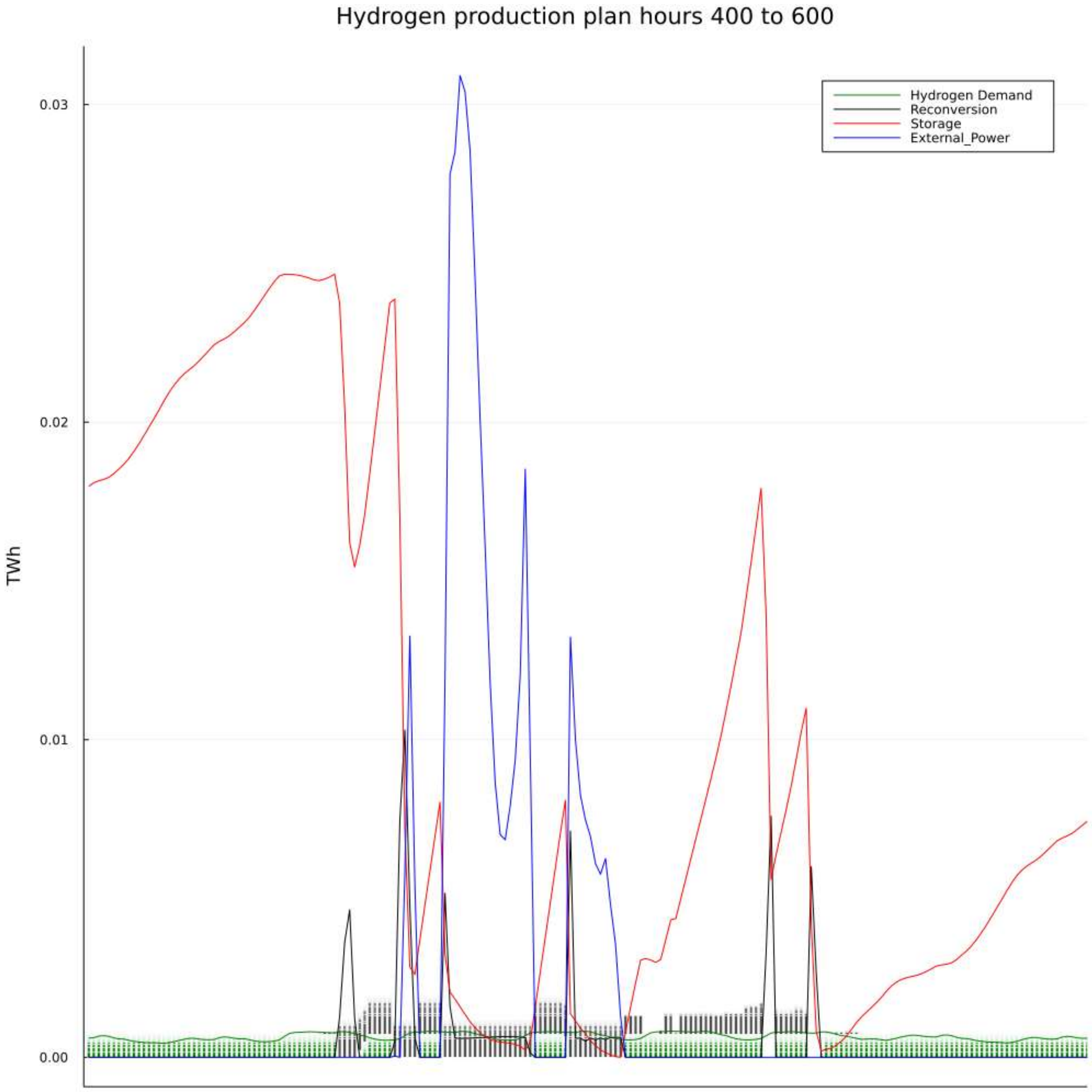

Figure 3: Production plan Base scenario hours 400 to 600 (complete)

2.2.2 Scenario "Expensive Gas"

In the base scenario, it could be seen that a mixture of two technologies was used, SMR and Electrolysis. Since gas is a fossil fuel, its use is connected to GHG emissions on which taxes are imposed. It is not yet exactly known how the GHG taxation structure will develop until 2040 but most likely we will experience higher taxes. In addition, the market structure for gas is likely to not be the same in 2040. Right now, we see major, political motivated shifts in supply structures for gas which are connected with a strong increase in prices. LNG terminals are built, and Germany is searching for alternative supply countries to limit its dependence on Russian gas supply via pipelines. It is tough to predict how prices for gas will develop until 2040 but we saw major increases during the last months, and it appears absolutely possible that this development will not be reverted but hold on in the next years. These two factors (taxation and raw prices) create the first scenario. Prices for methane (for SMR) and methanol (for POM) will be multiplied with factor 3 to capture possible developments. Availability of gas will not be limited because it appears unlikely that gas will be empty at all, its availability will probably depend on the willingness to pay higher prices. In the first step, taxes remain the same as in the base scenario but shall be multiplied with 2 in the next step. When supply and prices for power and biomass (for Gasification) remain the same as before, it is to be expected that the production shifts away from SMR (and POM which hasn't been used anyway in the base scenario) towards Electrolysis and/or Gasification.

Table 4: Results scenario "Expensive Gas"

Region	Import TWh	Export TWh	Storage Cap. TWh	Electrolysis Cap. TWh	SMR Cap. TWh
Brandenburg	0.00025	0.00	0.00014	0.00003	0.00
Berlin	0.00126	0.00	0.00010	0.00002	0.00
Baden-Württemberg	0.01525	0.00	0.00333	0.00019	0.00
Bavaria	0.00	0.03444	0.01371	0.00059	0.00
Bremen	0.00187	0.00	0.00008	0.00002	0.00
Hesse	0.00	0.00018	0.00038	0.00005	0.00
Hamburg	0.00102	0.00	0.00006	0.00001	0.00
Mecklenburg-Vorpommern	0.00	0.00077	0.00006	0.00002	0.00
Lower Saxony	0.00	0.00503	0.00038	0.00011	0.00
North Rhine-Westphalia	0.00929	0.00	0.00124	0.00019	0.00
Rhineland-Palatinate	0.00	0.00328	0.00057	0.00005	0.00
Schleswig-Holstein	0.00	0.00045	0.00010	0.00003	0.00
Saarland	0.00613	0.00	0.00042	0.00004	0.00
Saxony	0.00355	0.00	0.00017	0.00003	0.00
Saxony-Anhalt	0.00315	0.00	0.00015	0.00003	0.00
Thuringia	0.00238	0.00	0.00009	0.00002	0.00
Sum	**0.04414**	**0.04414**	**0.02099**	**0.00145**	**0.00**

Table 4: Results scenario "Expensive Gas" confirms the suggestions from above. SMR is completely replaced by Electrolysis, neither POM nor Gasification appear as well. The obvious reason for that is the higher price of fossil fuels. In addition to that, the situation for importing and exporting countries changed. All regions are producing in this scenario themselves but are still importing and exporting, as well. Now, only 7 countries are exporting, instead of 11 from the base case and all the changes made are former exporting countries, turning into importing countries. There is no obvious reason for this finding since power can be transported unlimitedly and without time loss between all regions, the same applies for produced hydrogen. Also, the demand characteristics (power and hydrogen) of importing/exporting countries does not reveal why we see fewer exporters in this scenario. The installed storage capacity remained on a similar level, and for sure, Electrolysis capacity rose while SMR was abandoned to 0 in every region. Noticeable is that an overall lower capacity was installed. From 0.0019 TWh in the base scenario (0.00073 TWh + 0.0017 TWh) the value decreased to 0.00145 TWh. A possible explanation is that the cost advantage of reconverting hydrogen from SMR against directly

using external energy has decreased, so generally a lower amount is reconverted and therefore, less hydrogen is needed. The lower level of reconversion in every month can be seen in *Figure 5: Production plan scenario "Expensive Gas"*.

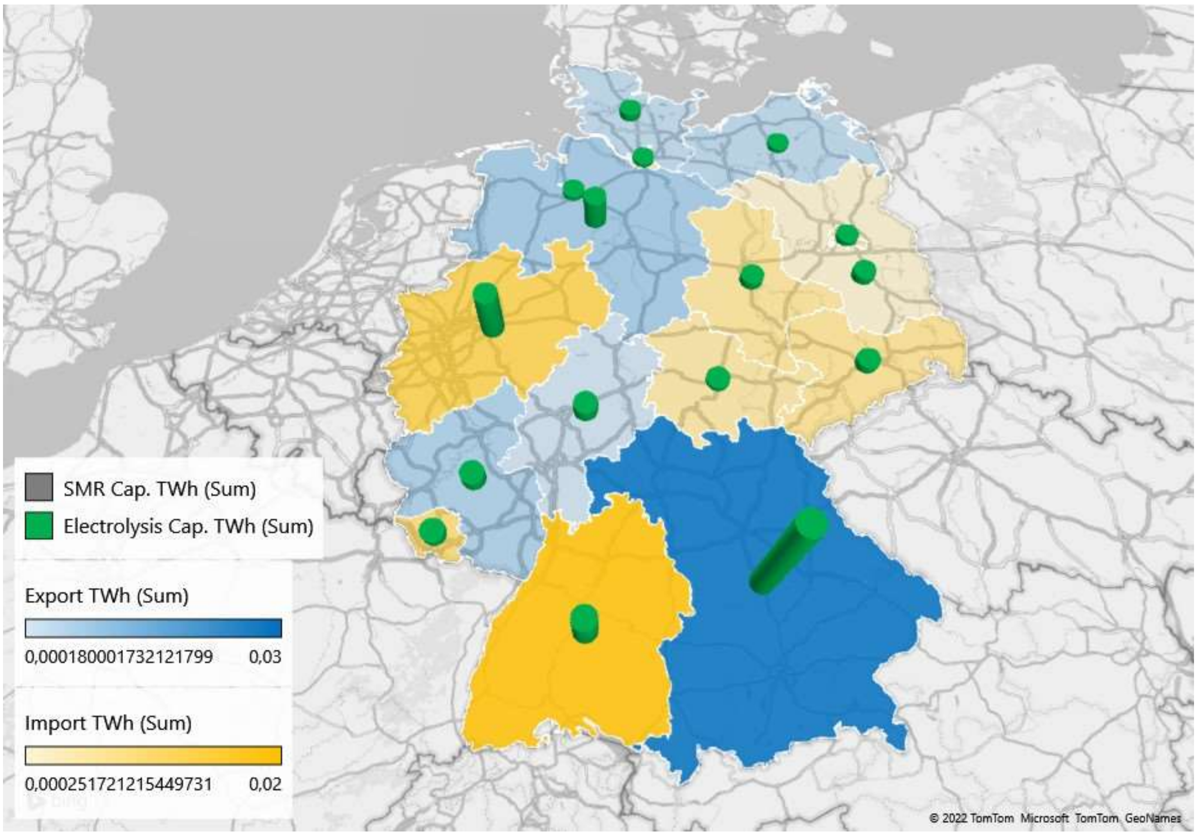

Figure 4: Geographic visualisation Scenario "Expensive Gas"

Figure 4: Geographic visualisation Scenario "Expensive Gas" shows a visualisation of the table above. The SMR capacity in form of grey pillars has been removed and replaced by only Electrolysis capacity in form of green pillars. The biggest importers/exporters are the adjacent regions Baden-Württemberg (BW) and Bavaria and it would make perfectly sense if they were source and destination for each other's hydrogen because of the small distance. Indeed, looking into the data, BW is the biggest customer for Bavarian hydrogen and Bavaria is the biggest source for BW as well. Bavaria has the by far highest production capacities in whole Germany, followed by NRW, BW and Lower Saxony, where even though they have high capacities, only two of them are aggregated exporters due to their high own hydrogen need.

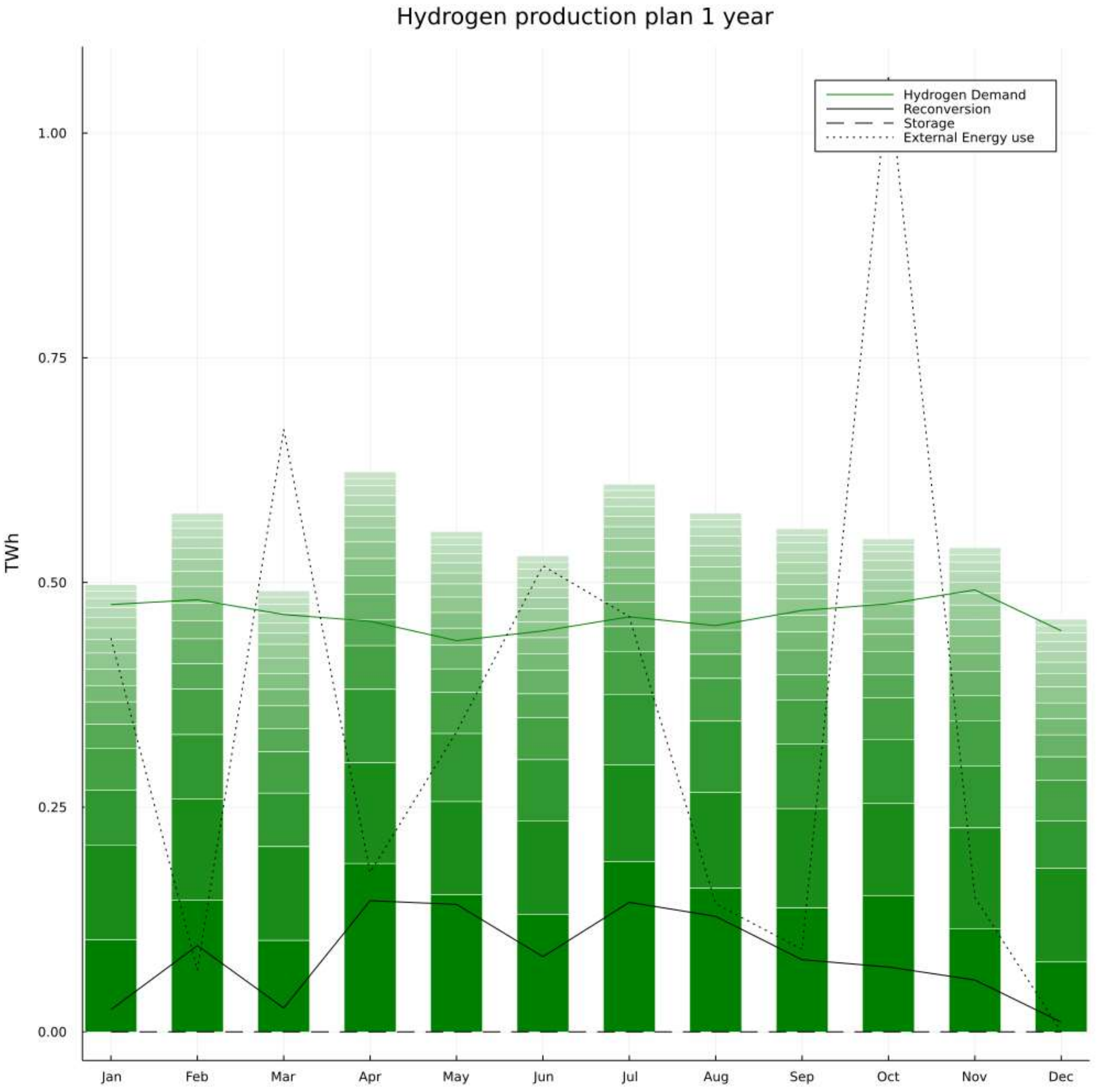

Figure 5: Production plan scenario "Expensive Gas"

The production plan for this scenario shows some of the results already found. It is an Electrolysis-only production plan, the monthly pillars are therefore separated into only 16 blocks for 16 producing regions. Compared to the Base scenario, less reconversion takes place. In December, we see the lowest level of reconversion, like before. The production in all months varies between 0.5 TWh and 0.63 TWh, the whole time above the actual need, because of the reconversion. There are no noteworthy outliers. However, it should be noted that, even though the storage capacity built is comparable between the base and this second scenario, the storage here is again very small at the end of every month. As in the base scenario, the model does not decide to store hydrogen in large scale over months to overcome possible production shortages in later periods.

Since there is no CO2-intense technology used, even with the initial CO2-price, increasing taxes will not lead to a different result, so this step will be forgone for this scenario.

2.2.3 Scenario “Higher Hydrogen Demand”

Until this point, only data from the chair were used to estimate values for hydrogen demand. Because these data originate from a model as well or are at least subject to assumptions, it is necessary to analyse the effect on the production plan and investments in capacity if there was a large change to these data. The estimate that was used until now was 20 PJ hydrogen demand p.a. for the whole country, that equals 5.56 TWh. Since hydrogen is meant to partly replace natural gas by time and we are facing severe political issues regarding natural gas, as mentioned above, these 5.56 TWh appear quite low. This scenario focuses on how an HSC would look like when a significant amount of the current gas demand is replaced by hydrogen in 2040. The nationwide demand for natural gas is about 952 TWh[3] p.a. (Destatis, 2022). From this number, 89 TWh (Statista, 2022) are used for power production, so these will be deducted since hydrogen should be made by renewable power anyway and so it would distract the approach of replacing this part of natural gas consumption. So, 863 TWh are subject for replacement. However, it is tough to estimate which fraction of this amount will indeed be replaced, but 1/8 (approximately 111 TWh [4]) seems to be a realistic amount for this model, especially in the light of having used 5.56 TWh in previous runs and not risking a too large step. Carbon taxes will first remain the same as in the base scenario but will be doubled, afterwards. It can be expected that, obviously, much higher production capacities will be built compared to the base case and the renewably produced power will possibly not be sufficient to meet the demand by an Electrolysis-only production, so a technology mix will probably be applied, as we already saw in the base case.

In fact, we see a combination of the two methods Electrolysis and SMR, where the overall installed SMR capacity is again twice the Electrolysis capacity, every region except Saarland installed more SMR than Electrolysis capacity. It is noteworthy that, even though the overall demand was multiplied by 20, the capacities have increased only by factor 8.5 and 10.4 for Electrolysis and SMR, respectively. Obviously, installed capacity and demand do not necessarily have a linear relationship. Storage and trades do also not have a linear relationship with demand, what is not surprising. Nevertheless, all mentioned values increased, but by far not by factor 20. Again, there is a decentralized production, so all regions produce for themselves but still trade with other regions. As in the base scenario, only 5 regions are net importers, the only change is that Bavaria changed places with Berlin but there is still no clear pattern what characteristics make a region an importer or exporter. However, in *Figure 6: Geographic visualisation scenario "High Hydrogen Demand"* we can see that all northern regions are net exporters, while the whole south and Bremen are importing. Since the model allows for immediate and unlimited power transport and there are no differences in price or availability of natural gas, regional advantages should not play a role, so this appears not to be a systematic pattern but a coincident.

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[3] 904.5 imports + 47.8 domestic production = 952.3 [Bil. kWh]

[4] The model itself runs with MJ and in order to keep it reasonably simple, the initial hydrogen demand (20 PJ) was simply multiplied with 20, so we end up with a precise number of 400 PJ (or 111,11 TWh). In the light of just assuming 1/8 as realistic, this inaccuracy is acceptable.

Table 5: Results scenario "High Hydrogen Demand"

Region	Import TWh	Export TWh	Storage Cap. TWh	Electrolysis Cap. TWh	SMR Cap. TWh
Brandenburg	0.00	0.03358	0.00088	0.00022	0.00038
Berlin	0.00	0.02134	0.00064	0.00015	0.0003
Baden-Württemberg	0.56984	0.00	0.01133	0.00108	0.00124
Bavaria	0.43034	0.00	0.01955	0.00151	0.00153
Bremen	0.00397	0.00	0.00042	0.00013	0.00025
Hesse	0.00	0.15705	0.00233	0.0002	0.00081
Hamburg	0.00	0.01033	0.00029	0.0001	0.0002
Mecklenburg-Vorpommern	0.00	0.07771	0.00024	0.00015	0.00021
Lower Saxony	0.00	0.35706	0.00207	0.00038	0.00147
North Rhine-Westphalia	0.00	0.26748	0.00693	0.00093	0.00302
Rhineland-Palatinate	0.00834	0.00	0.00234	0.00029	0.00067
Schleswig-Holstein	0.00	0.12359	0.00034	0.00026	0.00037
Saarland	0.19155	0.00	0.00208	0.00032	0.0004
Saxony	0.00	0.00593	0.00138	0.00021	0.00048
Saxony-Anhalt	0.00	0.11734	0.00118	0.00014	0.00055
Thuringia	0.00	0.03265	0.00084	0.00011	0.00031
Sum	**1.20405**	**1.20405**	**0.05284**	**0.00618**	**0.01219**

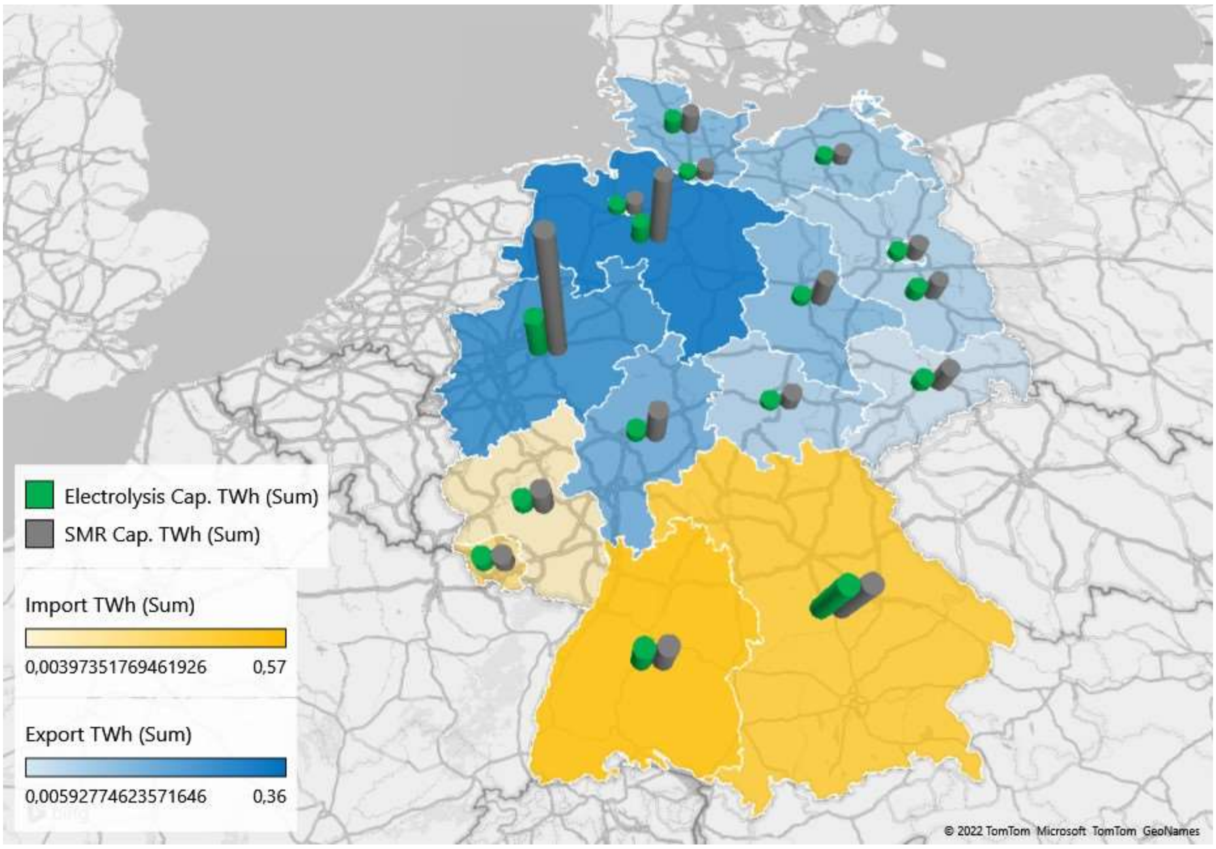

Figure 6: Geographic visualisation scenario "High Hydrogen Demand"

As to be expected, the production shows that about 20 times more hydrogen is produced than in the base scenario, slightly below 10 TWh per month. Again, there are no clear peaks or outliers visible but what can be observed is that the portion of SMR has increased significantly compared to the base case. Most probably, there is not enough renewable power production to meet the regular power demand and the hydrogen production simultaneously, so that SMR is used instead. Reconversion, storage level and external energy use are, as before, of lower importance so that the production is mainly driven by the hydrogen demand.

When putting a higher tax (factor 2.0) on CO2-emissions, the model tries to avoid SMR, see *Figure 12: Production plan scenario "High hydrogen demand" with increased tax on CO2* in the appendix. While Electrolysis capacities are more than doubled, the capacities of SMR are not cut proportionally to the overall production cut. (See *Table 6: Results scenario "High hydrogen demand" with increased tax on CO2*) Most probably, the model keeps these capacities to react to demand peaks.

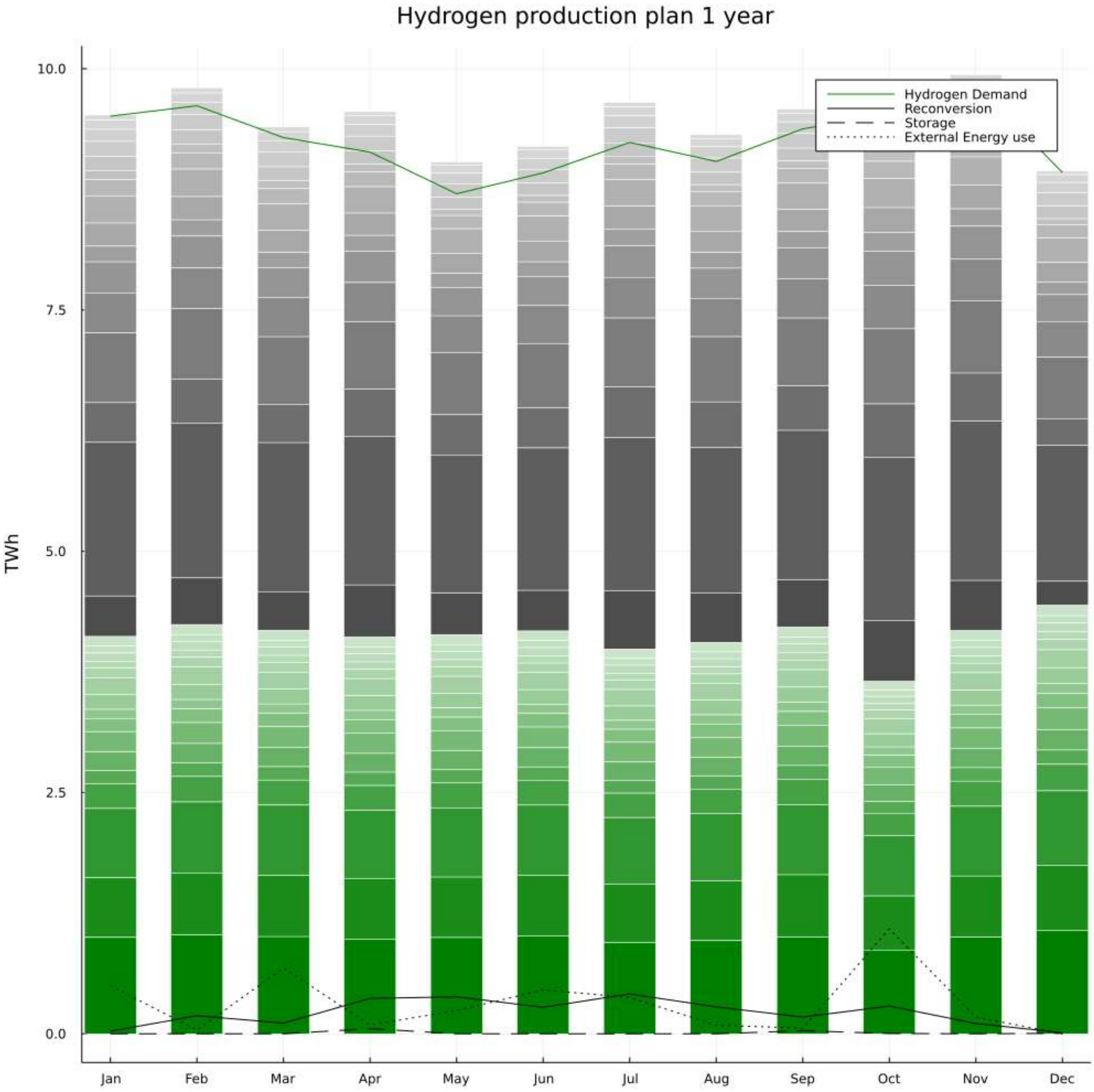

Figure 7: Production plan scenario "High Hydrogen Demand"

2.2.4 Scenario “Low Renewables”

The scenarios before dealt with conditions that were caused by humans: Higher prices for natural gas and higher hydrogen demand. This scenario will deal with a completely exogenous variable, the production of renewable power on which basically all Electrolysis was based previously. It is realistic that, from time to time, a year is below average in terms of wind or solar and this scenario shall help to understand how the optimal production structure of hydrogen will react to such a year. In this case, the whole renewable energy production was multiplied by 0.75. This amount does not mean a complete shutdown, but a significant gap compared to previous runs. The expectation for the outcome is an increased use of SMR and less use of Electrolysis due to less power supply.

Unfortunately, the model falls in this scenario into a deficient scheme that was known from an earlier incomplete version of the model. Due to lower power production and the missing possibility of Power-To-X technologies (besides hydrogen), the model struggles to meet the external power demand in numerous regions and timesteps even though there should be enough power production aggregated over the year. Hydrogen is then used as a Power-to-X technology but not to carry power over long time but to reconvert it quickly. This way, the model can save the cost for building storage and avoids the use of expensive external energy. The problem is that the hydrogen that is reconverted comes to large portion from SMR. So, to meet the power demand, hydrogen is just used as a medium to convert gas to power. Regular external power demand is in another dimension than the regular hydrogen demand of 5.56 TWh p.a. Reconversion takes place in this dimension and it changes the complete behaviour of the model. Hence, a lot data that were examined in previous scenarios are not comparable anymore and this work will only present the resulting production plan. A distinct higher amount than needed (actual hydrogen demand) is produced and the production is mainly driven by reconversion, see *Figure 8: Production plan scenario "Low Renewables"*.

As in scenario “Expensive Gas”, a second run with higher carbon taxes will be forgone because it will not change the problematic behaviour of the model and so it will not create new insights.

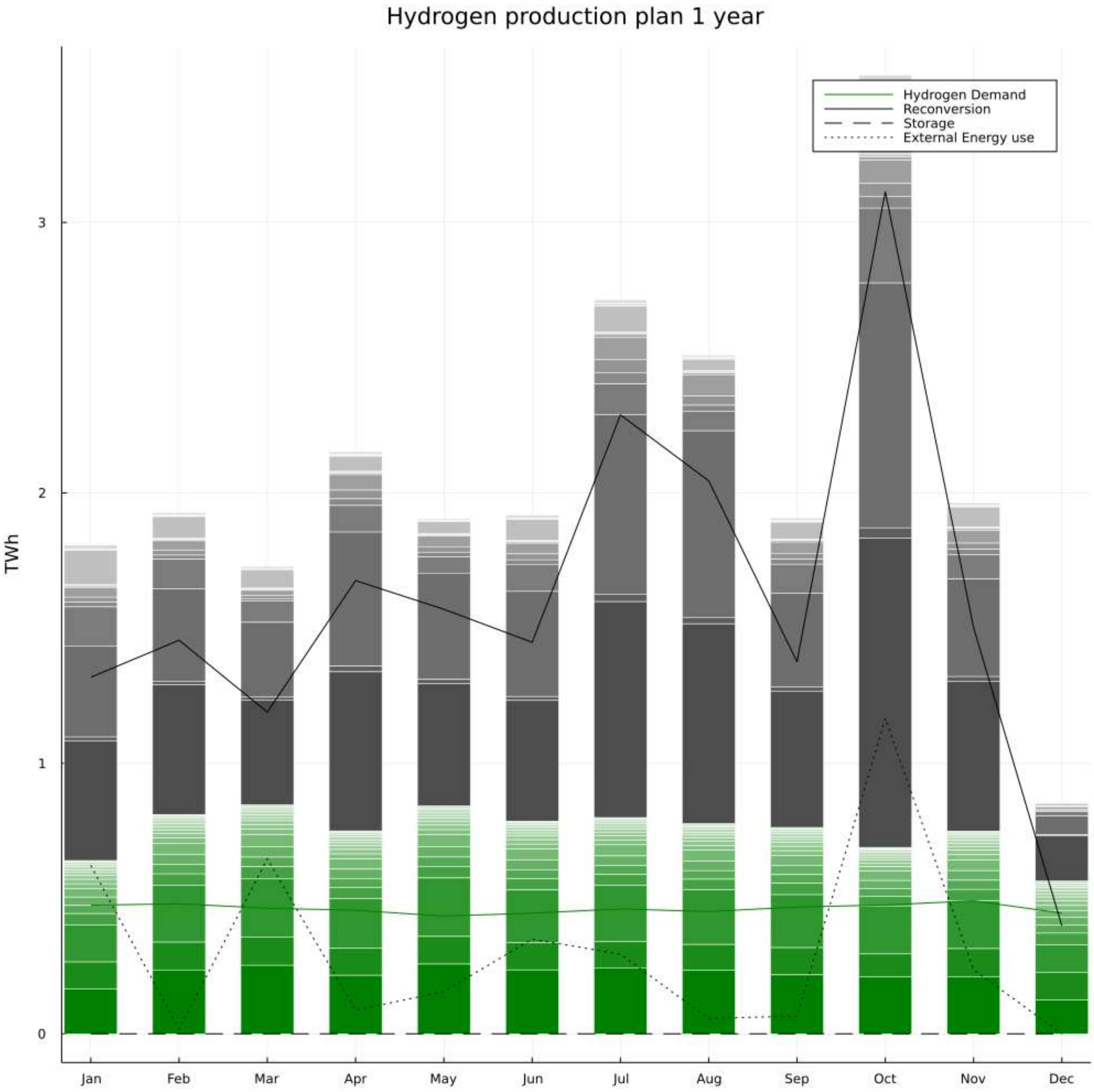

Figure 8: Production plan scenario "Low Renewables"

3 Discussion

3.1 Quality of the model

Analysing the results for various scenarios, the underlying model revealed strengths and weaknesses that shall briefly be discussed in the following. Especially through scenario analyses, it became obvious that the aspect of missing Power-to-X technologies besides hydrogen is a severe flaw of this model that limits the interpretability of the last scenario. Unfortunately, the model lacks an implementation of sector-coupling, as well. Also, by introducing unlimited and immediate transport of power, regional advantages/disadvantages in power production and therefore Electrolysis capabilities are abandoned. Not necessarily connected with the model itself but still important in this work is that assuming the member states of Germany per sé as “regions” is not necessarily useful but brings complexity. Assuming regions as actual regions with similar, regional characteristics and proximity and thereby aggregating them to maybe 4 regions in Germany would have made sense. There is no real additional insight created by separating Rhineland-Palatinate and Saarland or Baden-Württemberg and Bavaria just because they are legally separated. Besides combining political regions as in the German case, it can also make sense to separate states if the model should be applied on another country with big states that are domestically very heterogeneous. In this work, combining regions would have saved computational time which has been a major problem when conducting scenario analyses and evaluating the model’s abilities and weaknesses in advance. Besides many regions, this problem was most probably caused by two transportational matrices (16x16) for each timesteps from which there were 8760, one for each hour in the example year. But this high resolution can offer very deep insights on the other hand, depending on the research interest. Aggregation can be done after computing the model, as it was used in this work. Besides the different levels of aggregation that this model offers, it also allows to easily add a new technology, take one out or vary production parameters. It also has the possibility to decide about many other aspects of the HSC itself, all production capacities, storage capacities, technologies used, where, when and how much to produce and how much to reconvert or transport. It finally allows to use hydrogen as a Power-to-X technology.

3.2 Conclusion

The aim of this paper was to create an HSC model in a decarbonised Germany in 2040. When, where and how should be produced how much hydrogen to meet the prospective demand in a cost-efficient way- were the main aspects of this work. To find answers, a mathematical model was taken from a previous research project and extended by regional levels, a transport of hydrogen and power between these regions, the possibility of reconversion and some further enhancements. To solve the model after this transformation, it was re-implemented in the Julia programming language and to deal with the uncertainty that came through assumptions for different variables in the year 2040, a base scenario was examined and then several variables changed to see how this HSC would look like in different scenarios for 2040. In most cases, a technology mix of Electrolysis and SMR was found to be optimal. Only in the scenario “Expensive Gas”, SMR was abandoned, in all other scenarios, we could find this mix, each with different portions for both technologies. In no scenario, the model decided to implement a centralised production and then distribute it afterwards, even though there have always been importing and exporting regions. There was also no case in which hydrogen was produced in large scale in an energy-rich time to store it for months until its reconversion. Nevertheless, it was used as a Power-to-X technology in smaller timeframes, as described in the base case. In this abstract, it could also be seen that hydrogen reconversion is preferred over the use of expensive, external energy that has been produced with fossil fuels, so at least in this situation, hydrogen can help to decarbonise the German energy system. In the last scenario, the model revealed a weakness and delivered results in an undesired frame, all other scenarios returned data that could be interpreted and compared. So, the model is able to depict the decarbonised energy system in parts and deliver data for further examinations on how a possible HSC could look like. However, the model has several limitations that must be taken into consideration when interpreting the results. Also, it is important to keep in mind that any result is only as good as the database that was used and especially here, research needs to be intensified because finding reliable input data is challenging.

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Appendix

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[illegible]

[illegible]

[illegible]

[illegible]

Table 10: Annual regional hydrogen demand [illegible]

	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table 11: Annual regional hydrogen demand [illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

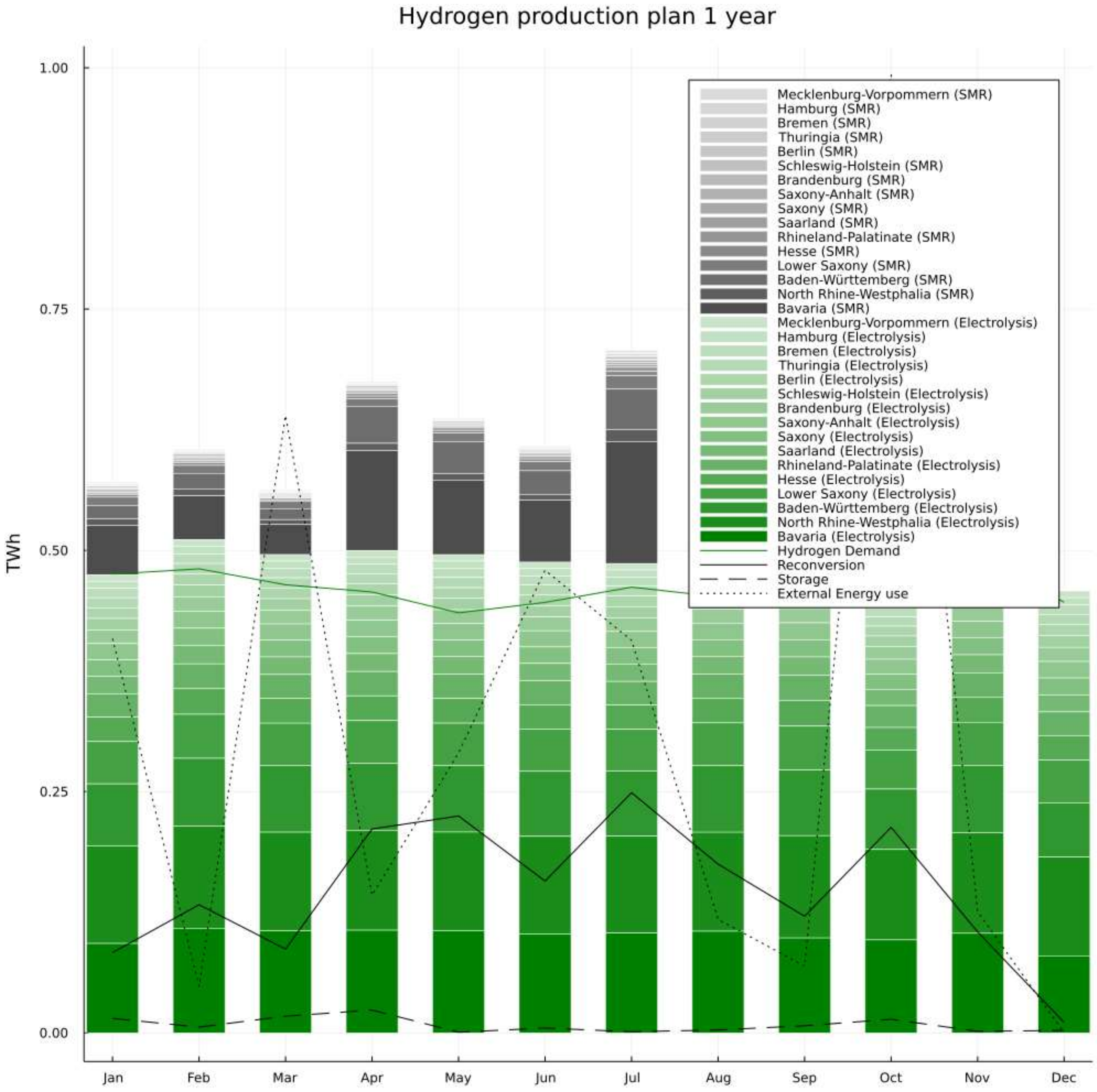

Figure 9: Assignment of bar fractions to regions

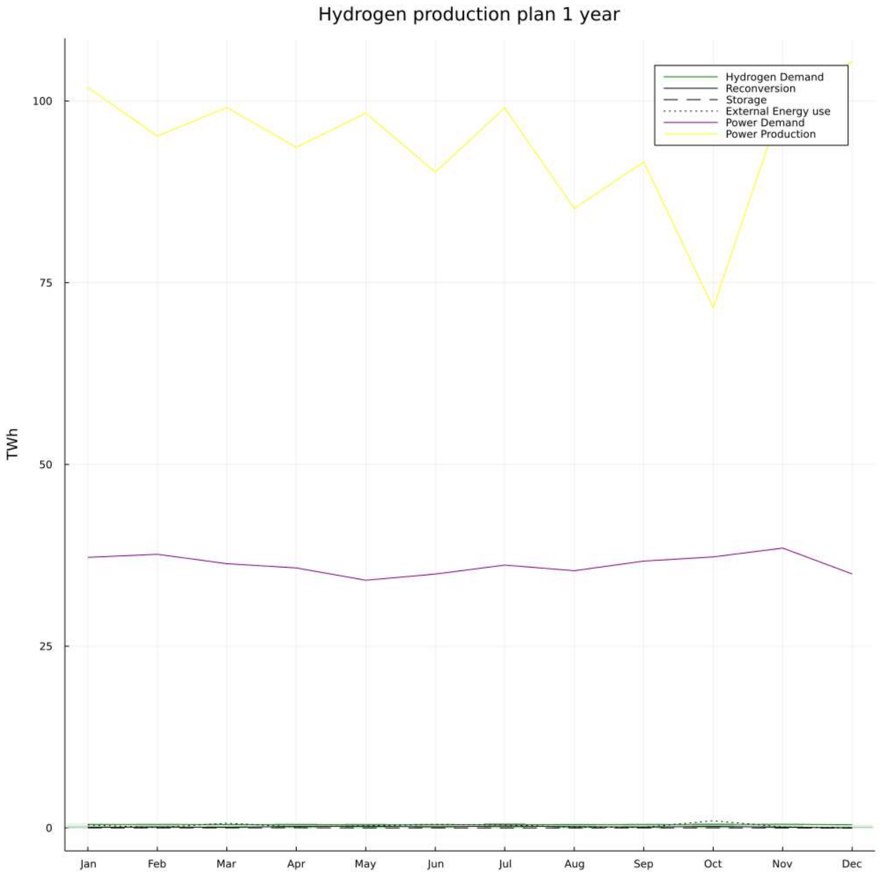

Figure 10: Dimensions for hydrogen and power production, Base model

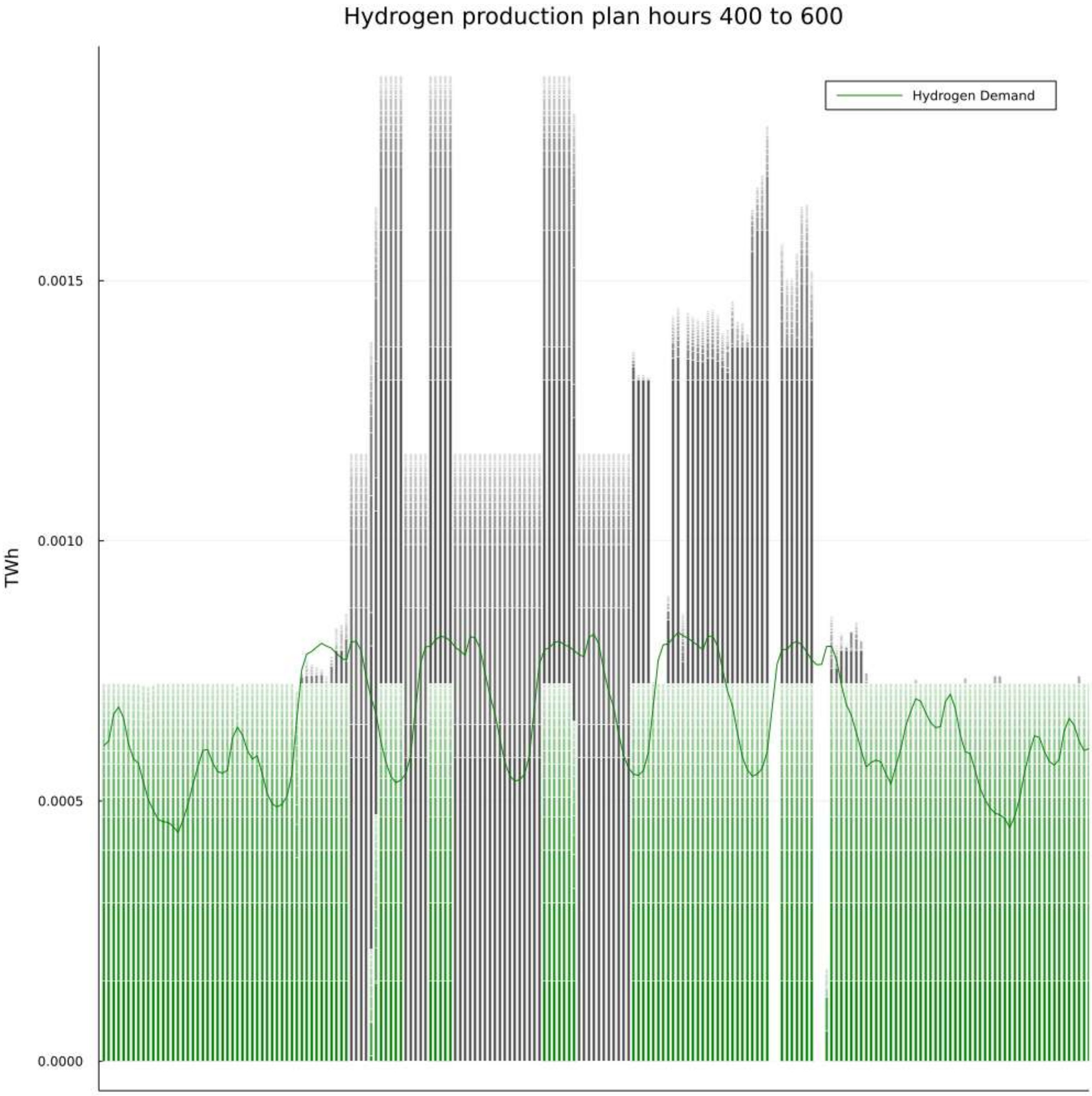

Figure 11: Production plan Base scenario hours 400 to 600 (Demand and Production)

Table 6: Results scenario "High hydrogen demand" with increased tax on CO2

Region	Import TWh	Export TWh	Storage Cap. TWh	Electrolysis Cap. TWh	SMR Cap. TWh
Brandenburg	0.00	0.03239	0.001574924	0.000440553	0.000337921
Berlin	0.01167	0.00	0.001294449	0.000339269	0.000196172
Baden-Württemberg	0.31554	0.00	0.014595586	0.001700017	0.001357509
Bavaria	0.27560	0.00	0.019601855	0.00210395	0.00179098
Bremen	0.01697	0.00	0.000980222	0.000298876	0.000153647
Hesse	0.00	0.02515	0.004360368	0.000773401	0.000570129
Hamburg	0.01396	0.00	0.00063164	0.000232798	0.000119367
Mecklenburg-Vorpommern	0.00	0.08037	0.000534598	0.000207551	0.000267529
Lower Saxony	0.00	0.35058	0.003165849	0.001362718	0.00146762
North Rhine-Westphalia	0.00	0.02819	0.014457397	0.003124307	0.002127097
Rhineland-Palatinate	0.00	0.00296	0.004570935	0.000743504	0.000510829
Schleswig-Holstein	0.00	0.13560	0.000773308	0.000368966	0.000468883
Saarland	0.07530	0.00	0.00372916	0.000548936	0.000370832
Saxony	0.00640	0.00	0.002736603	0.000528756	0.000374936
Saxony-Anhalt	0.00	0.05986	0.00193553	0.000519271	0.000448906
Thuringia	0.00	0.00036	0.001607768	0.000321386	0.000232563
Sum	**0.71545**	**0.71545**	**0.07655**	**0.01361**	**0.01079**

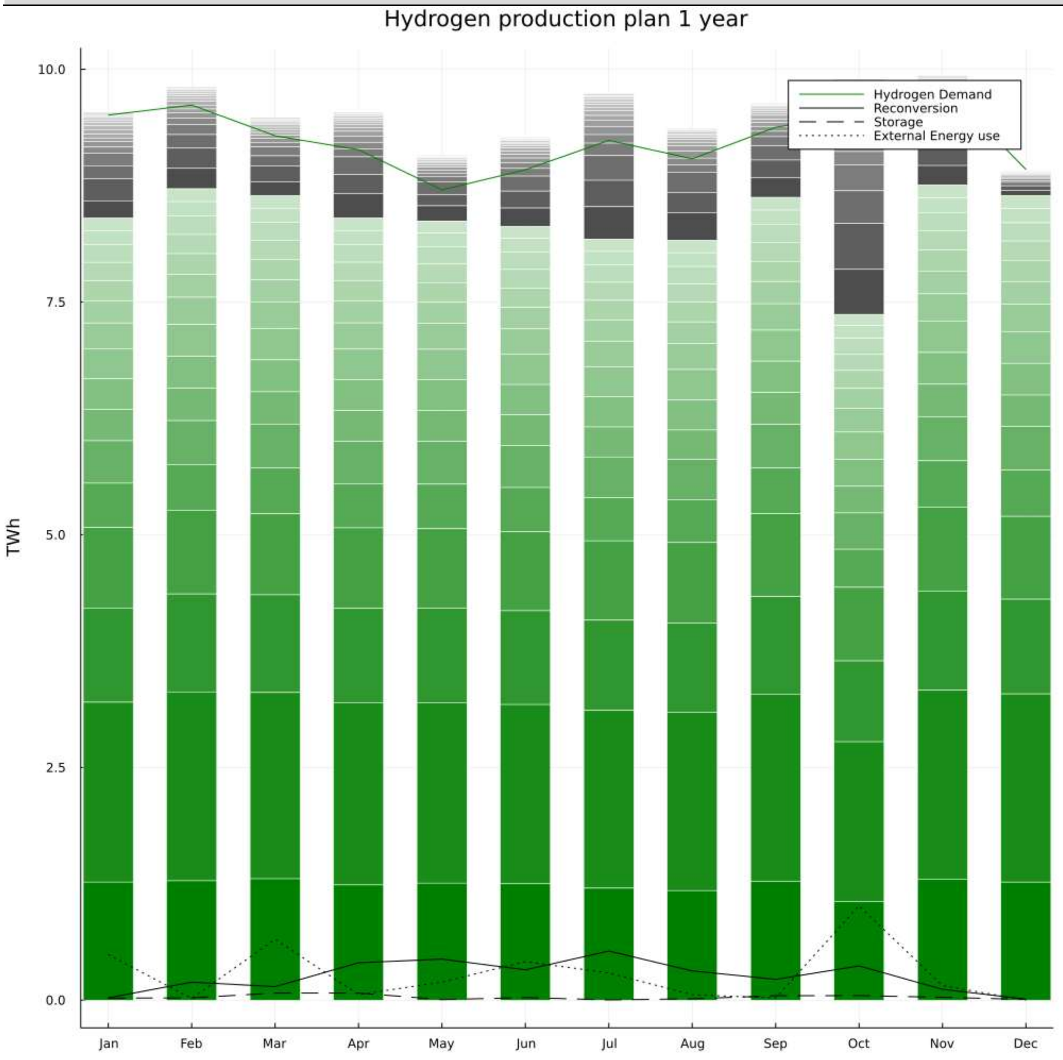

Figure 12: Production plan scenario "High hydrogen demand" with increased tax on CO2

4 Summary in German

Diese Arbeit ist die Fortführung einer Seminararbeit aus dem Model Operations Research – Methods for Network Engineering. Ziel dieser Arbeit ist die Analyse einer möglichen Wasserstoffproduktion und – verwendung im Jahr 2040. Dabei wird ein Optimierungsmodell, das ursprünglich aus besagter Seminararbeit stammt um verschiedene Aspekte mit dem Ziel bisher festgestellte Schwachstellen zu überwinden und der Realität näher zu kommen erweitert. Die bedeutendsten Erweiterungen sind die Einführung von Regionen innerhalb Deutschlands, womit keine zentrale Produktion mehr stattfinden muss und die Eröffnung der Möglichkeit, bereits produzierten Wasserstoff zurück in Strom zu wandeln und zwischen verschiedenen Regionen innerhalb Deutschlands zu transportieren. Das Modell wurde in der Progammiersprache „Julia“ implementiert, so konnten verschiedene Szenarien berechnet und analysiert werden. Die wichtigsten Erkenntnisse aus den Analysen waren, dass sich je nach Szenario der Technologiemix zur Produktion ändert, jedoch immer nur Elektrolyse und/oder SMR verwendet werden und dass das Modell stets eine dezentrale Produktion anwendet. Außerdem gab es in keinem Szenario den Fall, dass Wasserstoff zu energiereichen Zeit im großen Stil vorproduziert, und über Monate gespeichert wurde, um diesen in energiearmen Zeiten zu verwenden oder in Strom zu wandeln. In kürzeren Zeiträumen war dieses Verhalten allerdings durchaus zu beobachten. Neben diesen Erkenntnissen hat das Modell jedoch auch verschiedene Schwächen offenbart, die für bessere Anwendbarkeit und Realitätsnähe behoben werden müssten, wie das Fehlen anderer Power-To-X Technologien.