Hydrogen Map Germany: Methodology

Version 1.0

Contents

1 Introduction

Numerous pilot projects on the topic of hydrogen production and usage already exist today and more are constantly being developed. There is also a lively interest in the use of hydrogen technologies for climate protection and the transformation of the energy system. This map shows the current status, the regional progress as well as the opportunities and potentials of hydrogen in the energy transition and climate protection.

In the long term, the "Hydrogen Map Germany" should offer the possibility to assess potential, consumption, costs and emission reductions on a regional level. The aim of this is to develop a comprehensive and freely accessible instrument that facilitates the start of concrete technical planning.

The method description for the "Hydrogen Map Germany" explains the procedure, assumptions and calculations carried out, which lead to the data sets integrated on the wasserstoffatlas.de website. The structure of this document is based on the structure of the "Hydrogen Map Germany" website.

First, an explanation of the *administrative level* is given, describing the different *administrative levels* that allow the selection of one or more regions for closer examination.

In the *evaluation*, the user has the opportunity to view or compare the selected regions with reference to the *technology pathway* and to download the associated data sets in the medium term.

The *inventory* includes the power-to-X (PtX) plants in Germany that have been recorded since 2012, hydrogen consumers in the transport and industry sectors, as well as biogenic and industrial CO_2 sources. In addition to the existing plants and those that have been decommissioned in the meantime, plants that are in the planning, construction or commissioning phase are also included as far as possible, whereby the focus is on PtX producers.

The setting options in *Potential* enable a precise selection of the technologies regarding the *technology path – power source for electrolysis* and *the technology path - electrolysis technology*. Furthermore, a distinction is made between different potentials (*calculation basis*). The *inventory* includes all plants that currently, in the near past or in the future produce or consume hydrogen or are available as a CO_2 source for downstream products of hydrogen. In the long term, the value chains for green hydrogen are to be represented regionally on this basis and considering the specific costs. This way, hydrogen can be compared with fossil energy sources in all sectors and applications (electricity, buildings, transport, industry) and the potential, costs and CO_2 avoidance of hydrogen use can be shown depending on the location.

2 Administrative Level

The *administrative levels* are based on the classification of territorial units for statistics of the European Union [1] (NUTS - French: Nomenclature des unités territoriales statistiques). In the table below, you will find the administrative levels that are available for selection on wasserstoffatlas.de, exemplary areas and a brief explanation. The "code" refers to the NUTS region whose name is given in the adjacent column. The respective example is added in round brackets.

Table 1: Administrative levels according to NUTS classification

Code (example)	Name (example)	Explanation
NUTS 0 (DE)	NUTS 0 NAME (Deutschland)	Country
NUTS 1 (DE1)	NUTS 1 NAME (Baden-Würtemberg)	State
NUTS 2 (DE11)	NUTS 2 NAME (Stuttgart)	Government district
NUTS 3 (DE111)	NUTS 3 NAME (Stuttgart, Stadtkreis)	County

3 Evaluation

The *evaluation* is used to take a selected region into closer consideration or to compare several selected regions of one administrative level with each other. The generation potential of a selected technology path is presented graphically. In addition, the locations and selected parameters of existing regional plants are recorded in tabular form.

3.1 Evaluation Potential

The corresponding figure presents the core results of the potential analysis in graphical form. A compact description of the contents can be found in front of the figure. In addition, the relevant selected settings for the *technology pathway* and the *calculation basis* are indicated and adjusted independently depending on the selected options. A comprehensive description of the setting options can be found in the Potential section.

In the figure itself, the potential identified for the selected region(s) is shown as a bar chart in gigawatt hours (GWh). A distinction is made between the potential for the various electricity sources for electrolysis, which is why the selection of these in the potential has no influence on the evaluation. This allows a comparison of the potential of the individual electricity sources and the identification of the energy source with the highest potential in the region(s). It should be noted that the sum of the potentials from *wind onshore* and *wind offshore*, *solar pv*, *biomass* and *hydropower* correspond to the total renewable energy potential.

For a better classification of the potential, the following estimated conversion of gigawatt hours into production goods or mileage can be made:

1 GWh H_2 ≙ 420 t raw steel ≙ 350.000 bus-km ≙ 375.000 truck-km ≙ 3.750.000 car-km [2, 3]

3.2 Evaluation Inventory

In this section of the evaluation, the locations of existing plants in the selected regions are listed in tabular form. Analogous to the *inventory* section, a differentiation is made between *production*, *H_2 consumption* and *CO_2 source*, which can be switched between by selection. In *production* the PtX plants of the selected region(s) are listed with name, location, year of commissioning, input power of the electrolysis in MW_{el} as well as the final product. It should be noted that plants that are currently under construction or in planning are also included. Under the tab *H_2 consumption*, the regional hydrogen consumers are shown with name, location and, if available, concrete consumption in TWh/a. This also includes hydrogen consumers that are currently being realised as well as plants that are currently being built or commissioned for the transport sector. For industrial hydrogen consumers, only existing plants are listed. For the *CO_2 sources*, the name, location and production capacity in Mt/a in the selected regions are given. The CO_2 producers primarily include existing plants.

4 Potential

The potential on wasserstoffatlas.de is initially presented as technical potential, whereby the possible potential is divided into *technical - surplus* and *technical - total*. In general, the concept of potential can be described more precisely by, for example, the technical potential or the economic potential, whereby technical is understood here as technical-ecological potential, taking the ecological restrictions as well as further regulatory measures into account, which are dealt with in more detail in the sub-chapters of the respective energy sources.

The potential calculations are carried out at the district level, which corresponds to the NUTS 3 *administrative level*. The potentials of the other *administrative levels* are supplemented by summing up the included NUTS 3 regions. An overall consideration of a total NUTS 2, NUTS 1 and NUTS 0 level is not carried out, i.e., electricity generation and consumption are not considered beyond NUTS 3 borders *technical - surplus* at NUTS 0 level is not calculated from the total potential minus the total German electricity demand, but by the sum of the individual surplus potentials of all 401 NUTS 3 regions plus *wind offshore*.

4.1 Calculation Basis

The *calculation basis* determines how the potential of electricity production (and thus indirectly the potential of hydrogen production) is calculated.

4.1.1 Technical – Surplus

The potential calculation *technical - surplus* refers to the total technical potential minus the regional electricity consumption.

The regional electricity consumption is calculated from the four sectors "private households", "industry", "transport" and "tertiary sector" in NUTS 3 resolution. The data are taken from the load curves of the regional electricity demand of the FFE (Forschungsstelle für Energiewirtschaft e. V. and Forschungsgesellschaft für Energiewirtschaft mbH). The electricity demands of the individual sectors are provided by the FFE as a forecast for the year 2050 and are available in hourly resolution. The hours for the calculated year is 8760. If more hours are given in the respective sectors in the case of a leap year, the first 8760 hours are used. The regional resolution is available for all 401 NUTS 3 regions. For all calculations, the electricity demand from the year 2050 is used to account for the increasing electricity demand in the course of the direct electrification of various energy sectors. [4]

The *technical - surplus* potential is calculated for each energy source individually. Consequently, if a region cannot cover its own electricity demand in any hour of the example year, the surplus potential is zero. The option of combining any energy source does not exist; only *renewable total* and *Post-EEG* offer the possibility of offsetting the total or unsubsidised plants against the respective regional electricity demand.

Figure 1 shows the electricity generation under utilisation of the technical potentials and the electricity consumption in 2050 in the Schwandorf region in the first 100 hours of a year. If the electricity generation exceeds the electricity consumption, the surplus electricity can be used for the production of hydrogen by means of electrolysis. The area above the red electricity consumption line thus marks the potential technical surplus for the electricity source selection *renewables - total*. The same methodology is also used to calculate the technical surplus potential for individual energy sources. The shaded area in Figure 2 shows the potential for *wind onshore*, calculated from the electricity generation of this technology (using the technical potential) minus the total regional electricity consumption in the Schwandorf region.

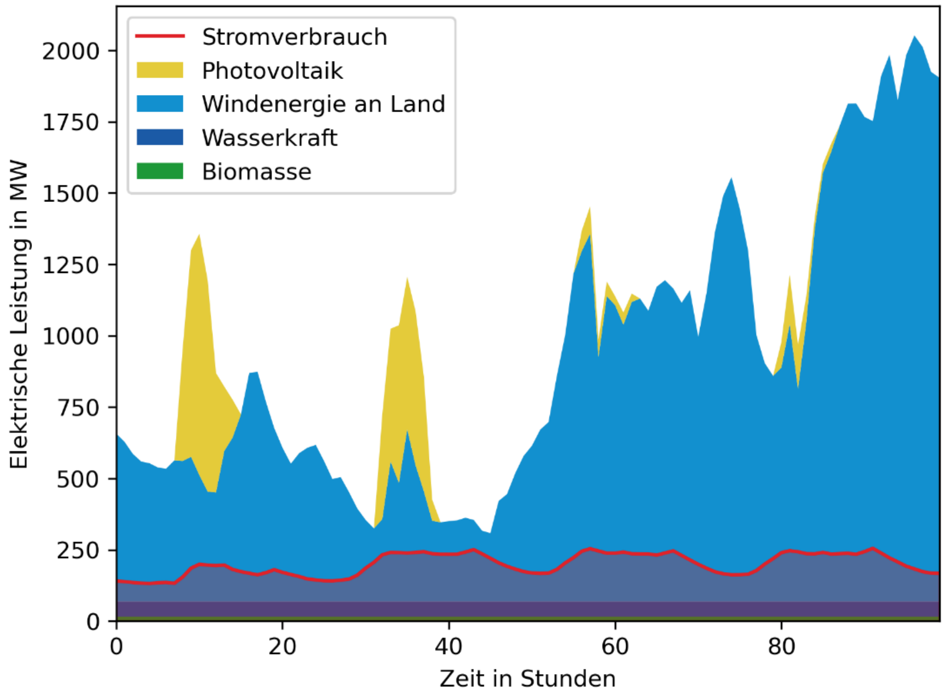

Figure 1: Electricity generation using the technical potentials and electricity consumption in 2050 in the Schwandorf region

The potential calculation *technical - surplus* takes into account the fact that electricity from renewable energies can be prioritised and directly used for the original electricity demand as well as electricity-based sector coupling (e.g. electromobility, heat pumps), as these paths have a higher (overall) efficiency than hydrogen or PtX paths, depending on the application [5].

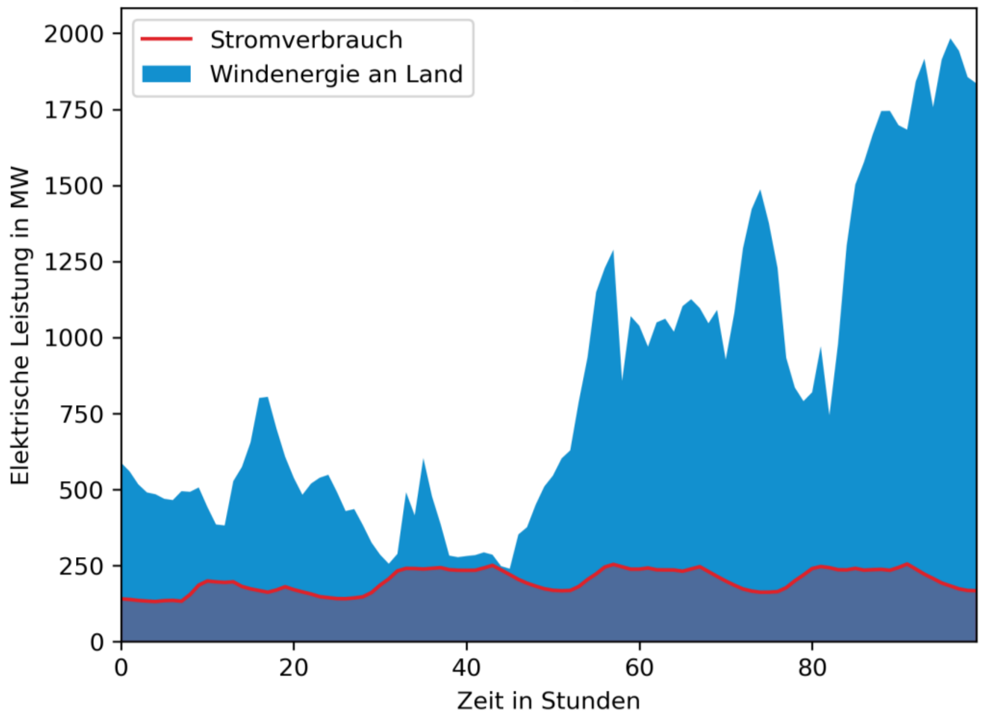

Figure 2: Electricity generation using the technical wind energy potential and electricity consumption in 2050 in the Schwandorf region

4.1.2 Technical – Total

Technical - total includes the technically usable potential from renewable energies within a region and a year. *Biomass* and *hydropower* are initially limited to the current expansion status due to the almost exhausted potential.

Further boundary conditions arise for:

- *Post-EEG plants*: completeness of data entries in the market master data register.
- *Solar pv*: e.g., availability of open space
- *Biomass*: competition for use with food production, therefore limited to current expansion status
- *Hydropower*: Largely exhausted potential, see chapter on hydropower
- *Wind onshore*: Distance regulations (e.g., to settlement areas, nature conservation areas)
- *Wind offshore*: Designated areas for use by wind energy

4.2 Path – Electricity Sources for Electrolysis

One of the following power sources is used for the calculation of the hydrogen potential.

4.2.1 Renewable Total

In the energy source *renewable total*, the other energy sources *wind offshore*, *wind onshore*, *solar pv*, *biomass* and *hydropower* are added up. The summation is done at the district level, except for *wind offshore*, which is added at the federal level. *Post-EEG plants* are not part of the total in *renewable total*.

4.2.2 Post-EEG Plants

Post-EEG plants (EEG - Renewable Energy Sources Act) include all electricity generation plants which, according to the information in the Marktstammdatenregister (MaStR), were commissioned at least twenty years ago and therefore do not receive EEG support in the selected year. The *post-EEG plants* are available for the years 2020-2040.

The basis for the calculated output is the net nominal output specified in the MaStR [6]. The EEG subsidy is granted for 20 years after commissioning. The commissioning date specified in the data set is therefore added to 20. The resulting date is assumed to be the post-EEG date. The prerequisite for processing is an existing commissioning date, a specified maritime location for *wind offshore* and a postcode for all other renewable energy sources. The postcode is necessary for the allocation to a NUTS region, the maritime location for the identification for *wind offshore*. The net nominal capacity is available for each of the 401 NUTS 3 regions and is summed up over five years, so there is an output for the years 2020, 2025, 2030, 2035, 2040 (2045 and 2050 will follow as soon as the data are available in 2025 and 2030 respectively). All plants that are not remunerated under the Renewable Energy Sources Act (EEG), for example, up to and including 31 December 2025, are grouped together under Post-EEG until 2025. In 2030, all plants that are no longer eligible for EEG support by 31.12.2030 are added, etc.

A comparison with performance data from the BMWi for the energy sources in Germany as a whole shows a negligible deviation of a few percentage points [7].

4.2.3 Wind Onshore

The potential analysis was carried out by us and exclusively with publicly available data. The procedure is described in detail below and is based on other potential studies [8, 9].

Area potential

First, exclusion criteria are defined. These are divided into settlement, infrastructure and open space. Official datasets such as those from Geoportal (GeoP) are prioritised over unofficial ones such as those from OpenStreetMap (OSM). Table 2 shows all the criteria considered. If two datasets are specified, they are added together

Table 2: Exclusion criteria considered with the data set used

Category	Areas	Source 1	Source 2
Settlement	Commercial area	DLM	OSM
	Industrial area		OSM
	Settlement area	DLM	OSM
Infrastructure	Motorway	DLM	
	Mining		OSM
	Federal road	DLM	
	Airport	DLM	
	Airfield		OSM
	Overhead line	DLM	
	State border	DLM	
	Country border	DLM	
	Power plant		OSM
	Country road	DLM	
	Military area	DLM	OSM
	Radio tower	DLM	
	Railway		OSM
	Ropeway	DLM	
	other road	DLM	
	Onshore wind turbine	DLM	OSM
Conservation	Biosphere reserve	DLM	
	Flora-Fauna-Habitat-Area	GeoP	
	River		OSM
	Canal		OSM
	Coast	DLM	
	Landscape protection area	GeoP_Geodata.NRW	
	National park	DLM	
	Nature reserve	GeoP	
	Sand (ground composition)	DLM	
	Lake	DLM	
	Bird reserve	Natura	
	Forest area		OSM
	Marshland	GeoP	
Others	Slope15	Copernicus	
	Elevation1800	Copernicus	

Slope15 (slope of the terrain of more than 15°) and Elevation1800 (higher elevations than 1800 m above sea level) are excluded as possible building sites, but only when the potential areas are virtually occupied with wind turbines (turbine allocation).

Buffer zones

Buffer zones are added to the area data. This is done based on legal regulations or also distances customary that are observed with wind energy plants in practice. The distances used are summarised in Table 3. If the legal situation is not uniform, comparative values from the literature are used. Forest areas are declared as potential areas if they are not also a protected area.

Table 3: Exclusion criteria with buffer zones

Category	Areas	Distance in m
Settlement	Commercial area	400
	Industrial area	400
	Settlement area	1000
Infrastructure	Motorway	100
	Mining	100
	Federal road	80
	Airport	5000
	Airfield	1500
	Overhead line	120
	State border	100
	Country border	100
	Power plant	150
	Country road	100
	Military area	200
	Radio tower	500
	Railway	200
	Ropeway	300
	other road	80
	Onshore wind turbine	450
Conservation	Biosphere reserve	0
	Flora-Fauna-Habitat-Area	0
	River	65
	Canal	65
	Coast	0
	Landscape protection area	0
	National park	200
	Nature reserve	200
	Sand (ground composition)	0
	Lake	65
	Bird reserve	200
	Marshland	0
Others	Slope15	0
	Elevation1800	0

A potential area is the area to which none of the above categories applies. Consequently, a subtraction of the areas from the total area of Germany is carried out. A distance of 0 m means that only the exclusion area itself is excluded.

Allocation

The basis for the determination of the performance is the area potential. The available area is converted into a finite number of possible locations. A lattice structure is used for this. All possible sites are enriched with specific data of the average wind speed, wind direction, etc. The data is then used to determine the power potential. Three reference wind energy turbines are defined, which are used depending on the wind speed. The associated parameters are defined in Table 4 and are based on the wind classes defined in the IEC 61400 standard.

The turbines are distributed in descending order of mean wind speed at 100 m height. Distances between wind turbines are taken into account by elliptical exclusion zones around the turbines. The orientation of the ellipse is based on the main wind direction, the size of the selected reference turbine and whether or not the site is in a forest area.

The energy yield results from the capacity factors, which differ depending on the reference turbine (Global Wind Atlas). These appear very high in comparison with relevant literature. The simulations carried out by Global Wind Atlas [10] typically increase the representation of speed-up effects, which leads to higher capacity factors. Due to this, the capacity factors are reduced by 15 % across the board.

Table 4: Overview of the reference wind energy turbines

Turbine	Rotor diameter in m	Power in MW	Average wind speed min. in m/s	Average wind speed max. in m/s
IEC I	112	3,45	8,1	
IEC II	127	4,00	7,1	8,1
IEC III	138	4,20	4,5	7,1

Profile

The normalised feed-in profiles of the wind turbines at NUTS3 level are determined using the tool "atlite" [11]. In conjunction with the results of the presented potential analysis for onshore wind energy, which are also available at NUTS 3 level through spatial aggregation, this results in the hourly (potential) feed-in of wind energy plants in Germany in regional resolution.

4.2.4 Wind Offshore

The calculation is based on the BSH's (Bundesamt für Schifffahrt und Hydrographie) spatial development plan (Raumordnungsplan - ROP), which defines specific areas for wind energy use and generally specifies the ordinance in the North Sea and Baltic Sea.

All areas designated as areas for wind energy in the ROP are classified as potential areas. This includes all subcategories (priority area, reservation area, conditional priority area, conditional reservation area), which rank the potential areas. In addition, a further area is included, which is currently still reserved for shipping, but is soon to be reassessed and whose attribution as an area for wind power is considered probable. [12]

The determination of the power is carried out by using a corrected power density applied to a corrected area. The corrected area is the actually usable area surrounded by a buffer zone the size of the minimum distance to the nearest turbine.

The distance is calculated using the specific power of the rotor area p_{WEA} and the corrected power density p*:

$$Buffer = \frac{1}{4} \cdot d_{Rotor} \cdot \sqrt{\pi \cdot \frac{p_{WEA}}{p^*}}$$

The data used for the turbine configuration is assumed as follows. In addition, the wind conditions are assumed to be constant throughout the sea area (uniform full load hours):

Table 5: Parameters for the potential calculation of wind offshore [12]

Parameter	Value
Rotor diameter	220 m
Specific power	400 W/m²
Corrected power density	9 MW/km²
Full load hours	3200 h/a

4.2.5 Solar PV

The technical potential of *solar PV* in Germany is determined based on the results of [13], available at http://opendata.ffe.de/eem2019/. The technical potential in Germany is 574 TWh, of which 351 TWh is accounted for by ground-mounted systems and 223 TWh by photovoltaics on buildings. The determination of potential in [13] is based, among other things, on weather data and the consideration of technical parameters (e.g., low-light behaviour, inverter efficiency, etc.) and is presented below with a distinction between building and ground-mounted potential.

The potential for ground-mounted systems is determined in three steps. First, the available area is determined considering land use (CLC database) and nature conservation areas [13] with an additional 500 m buffer zone. Furthermore, so-called disadvantaged areas, in which agricultural use is not possible or only possible to a limited extent, are considered. In a second step, the available area is multiplied by an assumed power density of 400 kWp/ha to determine the installable power. In a third step, the competition for use with food cultivation is addressed. According to [14], 14 % of the cultivable land area in Germany is used for the cultivation of energy crops. According to [13, 15, 16], half of this (i.e., 7% of the cultivable land area) is used for ground-mounted photovoltaic systems. Competition for use with food production is completely ruled out by excluding the corresponding shares of land from the determination of potential.

The determination of the potential on buildings is based on the FFE building model [13]. The building model considers the number of residential buildings, residential units and roof areas per age class, settlement type and building type. In [13] it is pointed out that local solar registers can have a higher accuracy, but these are usually not available on a supra-regional level (e.g., Germany) and are therefore not very suitable for a comparison between regions. Agricultural and commercial buildings are taken into account using the methodology described in [17]. Based on the determined available roof area in combination with weather data and technical parameters, the technical potential of photovoltaics on buildings in Germany is 223 TWh.

The normalised feed-in profiles of photovoltaic systems at NUTS 3 level are determined using the tool "atlite" [11]. In conjunction with the results from [13], which are also available at NUTS 3 level, these results in the hourly (potential) feed-in of photovoltaic systems in Germany in regional resolution.

4.2.6 Biomass

The basis for the determination of the *biomass* potential for Germany are the data records of the MaStR [18]. Based on this, the current expansion status of biomass useage can be assigned regionally. Additional unused potential for electricity generation was limited by [19, 20] to about 37 to 49 TWh. This is a theoretical potential. Furthermore, the use of biomass for energy is in competition with food production and material use. Accordingly, the complete utilisation of the theoretically existing biomass potential is controversial. For this reason, the biomass potential is currently limited to the current expansion status according to the MaStR. However, open potentials are conceivable, especially in the use of biomass waste products and sewage gas, which have not been included in the previous studies. Accordingly, this represents a data gap at the moment, which is why further investigations and research are currently being carried out in this regard. This may lead to an adjustment of the regional biomass potential in the "Hydrogen Map Germany" in the further course of the project.

Full Load hours and profile

Based on the regional capacity potential (derived from the MaStR), the energy potential is determined by an average plant utilisation rate. This average plant utilisation rate is calculated from the installed capacity and the amount of electricity generated by all biogas plants in Germany based on data from energy-charts.info. Accordingly, the average plant utilisation rate of biogas plants in Germany over the years 2019, 2020 and 2021 is 55%, which equals 4782 full load hours. Although biogas plants can achieve higher full-load hours due to their largely weather-independent mode of operation, the flexibility bonus introduced in the EEG leads to an incentive for flexible operation and thus reduced full-load hours [20]. Due to the trend towards lower full load hours, the average plant utilisation of the last three years (and no older data) is used for the calculation and set at 4782 full load hours, which is within the upper and lower limits estimated in [21].

To calculate an hourly profile of electricity feed-in, the full load hours are distributed evenly over all hours of a year (8760 h). No spatial differentiation is made between the NUTS 3 regions.

4.2.7 Hydropower

Analogous to the potential for biomass, the data sets primarily are based on the MaStR [18], which allocates the current expansion status of *hydropower* at the district level. Furthermore, [22] considers a remaining potential of 2.52 TWh to be realistic. This can be considered almost negligible compared to the potentials from wind and solar energy. More recent studies show potentials of up to 4 TWh at large waters and 0.6 TWh at medium-sized or small waters [23]. The exploitation of the potential, which can only be tapped through the construction of new plants, is made more difficult by regulatory framework conditions, such as in the EU Directive 2000/60/EC. Environmental associations also view the further expansion of hydropower in individual federal states as critical [24]. For this reason and taking the comparatively limited potential into account, the potential for hydropower is limited to the current expansion status at the moment. However, further investigations are being carried out in order to specify the potential in more detail, which enables to adjust the hydropower potential at a later stage.

Full Load hours and profile

Based on the regional capacity potential (derived from the MaStR), the energy potential is determined by an average plant utilisation rate. This average plant utilisation rate is calculated from the installed capacity and the amount of electricity generated by run-of-river power in Germany based on data from energy-charts.info. According to this, the average plant utilisation rate of run-of-river power in Germany over the years 2002 to 2021 is 44.3%, which equals 3881 full-load hours. To calculate an hourly profile of electricity feed-in, the full-load hours are distributed evenly over all hours of a year (8760 h). No spatial differentiation between the NUTS 3 regions is assumed.

4.3 Technology Path – Electrolysis Technology

Electrolysis is a chemical process in which water is decomposed into hydrogen and oxygen by applying an electrical voltage. The technical realisation of this conversion step depends on the process under consideration. In the "Hydrogen Map Germany" project, the electrical voltage is provided by the renewable energy sources described above. The focus is therefore on the production of "green" hydrogen. Alternative possibilities for producing "grey" or "turquoise" hydrogen, for example, are not considered.

At present, the *Alk. Electrolysis* (Alkaline Electrolysis)*, PEM Electrolysis* (Proton exchange membrane electrolysis) and *SOEC* (Solid Oxide Electrolysis) are integrated in the "Hydrogen Map Germany". These technologies have been selected because of their many years of testing, commercial availability and flexibility in site selection.

The feasibility of integrating less established electrolysis technologies is currently being examined. In addition to the availability of meaningful technical and economic data, it is also being investigated whether relevant ancillary conditions, such as the use of waste heat from industry, can be mapped with sufficient quality in the "Hydrogen Map Germany", bearing the respective temperature level in mind.

4.3.1 None - no Electrolysis

If the option *None* is selected, no conversion of the renewable electricity to hydrogen takes place. The potential of the selected renewable energy sources is therefore shown. Further conversion steps are not selectable with this setting.

4.3.2 Alk. Electrolysis (Alkaline Electrolysis)

In *alk. electrolysis*, electrodes are immersed in a circulating solution of water and potassium hydroxide (20-40 wt.%). The two half-cells are separated by an ion-conducting membrane. [2, 25]

The concrete current requirement resulting from the application of an electrical voltage or the resulting efficiency for hydrogen production in the *alk. electrolysis* depends on various parameters, such as the materials used, the size of the plant and the operating concept. For the period from 2017 to 2020, the literature [2, 26–28] indicates an efficiency range of about 43 % to 67 % in relation to the calorific value. By 2050, these studies derive a development of the average efficiencies to approx. 61 % to over 74 %. In the "Hydrogen Map Germany", based on these studies, an average efficiency of approx. 65 % is assumed for 2020, with a development towards 69 % for the year 2050. The efficiency of electrolysis is related to the lower calorific value.

4.3.3 PEM Electrolysis (Proton exchange membrane electrolysis)

Instead of the ion-conducting membrane (see *alk. electrolysis*), the *PEM electrolysis* has a proton-conducting membrane that is connected to the electrodes on both sides. A solid, highly porous polymer electrolyte lies between the electrodes and the associated bipolar plates. This allows current to flow from the bipolar plates to the electrode as well as the transport of water and the product gases.

For *PEM electrolysis*, studies [2, 26–28] indicate efficiencies of about 40 % to 67 % for the period from 2017 to 2020. Up to the year 2050, the studies show a development of the efficiency to about 64 % to over 74 %. In the present project, analogous to the procedure for *alk. electrolysis*, an average efficiency of around 62 % was assumed for 2020, with a development towards 68 % for the year 2050.

4.3.4 SOEC (Solid Oxide Electrolysis)

In *SOEC* or high-temperature electrolysis, water vapour is split. Therefore, in contrast to *alk. electrolysis* and *PEM electrolysis*, no evaporation of the liquid water in the electrolysis by electrical energy is necessary. Instead, external evaporation can be realised, for example, through industrial waste heat. This significantly reduces the electrical energy requirement compared to the other electrolysis technologies. Furthermore, the energy for separating oxygen and hydrogen is also provided by high-temperature heat, which means that a lower cell voltage can be applied than with the alternatives described. This results in high current-related efficiencies.

SOEC is not currently included as a selectable technology pathway in the "Hydrogen Map Germany". It is currently being examined whether and how integration is possible. The consideration of industrial waste heat is problematic, as both its quantity and the associated temperature level are relevant parameters that influence the system efficiency. Therefore, due to the thermal energy demand, there is also a certain local dependency of solid oxide electrolysis, which makes a general integration into the "Hydrogen Map Germany" difficult. In addition, the TRL of this technology is still very low compared to the other two, which makes large-scale use in the industrial environment unlikely in the next few years.

5 Inventory

The locations of producers of hydrogen or PtX products, selected H_2 consumers and CO_2 sources that are in operation, in planning or shut down are recorded in *Inventory*. A distinction is made between the setting options according to *by quantity/output* or *by number*. This differentiation is based on the characteristics of these setting options.

By quantity/capacity, the order of magnitude of the existing plants in a category can be displayed and thus not only the locations can be shown graphically, but also the specified technical parameters of the plants can be visually put in relation to each other. However, different parameters are shown for the categories *green production*, *H_2 consumption* and *CO_2 source*. While *green production* is illustrated in MW, *H_2 consumption* and *CO_2 source* are displayed in TWh/a and Mt/a respectively. Accordingly, these stock categories cannot be presented together. For this reason, the unit-independent setting *option by number* was added. This allows a simultaneous selection of all categories. However, this setting option does not allow to classify the order of magnitude of the existing plants.

5.1 Green Production

The *green production* category includes the theoretically sustainable producers of hydrogen, methane and other hydrocarbons such as methanol. Since most of these are laboratory or demonstration plants, sustainable operation using renewable energy sources cannot be guaranteed in all cases. For the plants, an attempt was made to determine the name, city, coordinates, product, operating status, year of project start or end, input power of the electrolysis and technologies used. Further information was recorded where available, but not categorically researched for the "Hydrogen Map Germany" project. It should be emphasised that the year of the project start does not necessarily lie in the past for the plants included. Plants were also included which are currently still in the planning, approval or construction phase, or which have yet to be commissioned. However, these plants are only integrated if the necessary parameters are available.

The plant location and the planned plant capacity are necessary for mapping. The location is preferably assigned via geodata (longitude/latitude). If these are not available, the plant can still be integrated via the city. In this case, the plant is placed at NUTS 3 level in the corresponding city centre. If neither geodata nor information on the city are available, the facility cannot be assigned and is not included in the map. In addition, plants for which no information on the input power of the electrolysis is available are not included.

All other parameters are not required for the inclusion of the plants in the "Hydrogen Map Germany“, but are included if they are available. The product category specifies which end products (hydrogen, methane, other hydrocarbons) are produced. Under status, the operating status (in operation, out of operation, under construction) is recorded. The project start indicates the year in which the realisation of the plant or the correlating research project is started. Similarly, the end of the project represents the completion of the research project or the decommissioning of the plant. The conversion process is also listed. The electrolysis technology used (alkaline electrolysis, PEM electrolysis, high-temperature electrolysis or AEM electrolysis) and, if applicable, the methanation (biological or chemical) are listed.

5.2 H_2 Consumption

The mapping of hydrogen consumers is focused and limited to:

- hydrogen refuelling stations,
- refineries,
- ammonia production,
- other chemical products and

The mapping of hydrogen refuelling stations is carried out using the data on https://h2-Map.eu/. This includes both plants that are currently in operation and those that are in the process of being realised or are yet to be commissioned. A site-specific quantification of the hydrogen consumption of hydrogen refuelling stations is not carried out due to the lack of data availability and the (still) low total consumption. The total demand of hydrogen filling stations in Germany is provided on H2-live.de.

The information on the locations and the corresponding demand for hydrogen in refineries, ammonia production and other chemical products is taken from the study [29]. In addition, the locations are supplemented by various sources such as [30, 31].

In addition, the locations of other hydrogen consumers for the manufacture of chemical products were researched. However, the resulting data sets are currently incomplete, which is why they are not currently included in the "Hydrogen Map Germany". Their completion is in progress. The integration of further hydrogen consumers in the chemical industry, such as in methanol production, will therefore take place in the further course of the work, depending on the availability of data.

5.3 CO_2 Source

CO_2 is not only a greenhouse gas, but also a raw material for climate-neutral energy systems and processes. It is needed for the production of e.g., renewable methane (PtG process) or synthetic fuels/e-fuels (PtL process). The "Hydrogen Map Germany" records the current locations of *CO_2 sources*, which consist of three categories:

- Plants with an annual load exceeding 100 kt/a (PRTR register),
- biomethane processing plants and

- bioethanol plants

Plants with an annual CO_2 emission of more than 100 kt/a are covered by the E-PRTR (European Pollutant Release and Transfer Register) and processed for the "Hydrogen Map Germany". This includes different sectors (e.g., energy sector, food industry, metal industry), whereby the energy sector is the largest emitter.

The importance of biogenic *CO_2 sources* takes on a special role during the transformation of the energy system. Biogenic *CO_2 sources* are considered CO_2 neutral because the CO_2 emitted in the subsequent combustion or processing process was removed from the atmosphere within a regenerative time frame. For this reason, the "Hydrogen Map Germany" includes biogenic sources such as biomethane processing plants [32] and bioethanol plants [33]. Another climate-neutral *CO_2 source* is DAC (Direct Air Capture), in which CO_2 is extracted from the atmosphere. However, this process is not bound to certain locations; at least theoretically, its use is conceivable almost everywhere. For this reason (and the lack of large-scale use at the present time), CO_2 from DAC is not listed as a source in the "Hydrogen Map Germany".

In the context of the first release, no distinction is made between the future sustainability of the *CO_2 source* is made. It is to be expected that especially fossil *CO_2 sources* will no longer be available in the next years and decades during the energy transition and the formulated objective of "climate neutrality". Thus, a reduction in process emissions is also to be expected, among other things by means of CDA (Carbon Direct Avoidance) (e.g., iron direct reduction in steel production). CCS (Carbon Capture Storage) also reduces CO_2 emissions from fossil sources. For a more detailed assessment of the sustainability of various *CO_2 sources*, refer to [33].

6 References

1. (2022) NUTS-Klassifikation: Die Einteilung der Europäischen Union in EU-Regionen. https://www.destatis.de/Europa/DE/Methoden-Metadaten/Klassifikationen/UebersichtKlassifikationen_NUTS.html. Accessed 07 Mar 2022
2. Smolinka T, Wiebke N, Sterchele P et al. (2018) Sudie_IndWEDe - Industrialisierung der Wasserelektrolyse in Deutschland: Chancen und Herausforderungen für nachhaltigen Wasserstoff für Verkehr, Strom und Wärme, Stand: September 2018. NOW GmbH, Berlin
3. Weigel M (2015) Ganzheitliche Bewertung zukünftig verfügbarer primärer Stahlherstellungsverfahren. Wuppertal, Univ., Diss., 2014, Universitätsbibliothek Wuppertal
4. FfE e. V. (2021) Load Curves: of the sectors Tertiary, Industry, Private Households and Transport
5. Ueckerdt F, Bauer C, Dirnaichner A et al. (2021) Potential and risks of hydrogen-based e-fuels in climate change mitigation. Nat Clim Chang 11:384–393. https://doi.org/10.1038/s41558-021-01032-7
6. Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen MaStR Marktstammdatenregister. https://www.marktstammdatenregister.de/MaStR/Datendownload. Accessed 15 Mar 2022
7. BMWi Zeitreihen zur Entwicklung der erneuerbaren Energien in Deutschland 2020: Tabellenblatt 4. Accessed September 2021
8. Lütkehus I, Salecker H, Adlunger K (2013) Potenzial der Windenergie an Land: Studie zur Ermittlung des bundesweiten Flächen- und Leistungspotenzials der Windenergienutzung an Land

9. Frank Masurowski Eine deutschlandweite Potenzialanalyse für die Onshore-Windenergie mittels GIS einschließlich der Bewertung von Siedlungsdistanzenänderungen, Helmholtz Zentrum für Umweltforschung - UFZ Leipzig, Department Ökologische Systemanalyse
10. Technical University of Denmark (2022) Global Wind Atlas. https://globalwindatlas.info/. Accessed 21 Mar 2022
11. Hofmann F, Hampp J, Neumann F et al. (2021) atlite: A Lightweight Python Package for Calculating Renewable Power Potentials and Time Series. JOSS 6:3294. https://doi.org/10.21105/joss.03294
12. Bundesamt für Seeschifffahrt und Hydrographie (2020) Flächenentwicklungsplan 2020 für die deutsche Nord- und Ostsee
13. Michael Ebner, Claudia Fiedler, Fabian Jetter et al. (2019) Regionalized Potential Assessment of Variable Renewable Energy Sources in Europe. In: 2019 16th International Conference on the European Energy Market (EEM). IEEE
14. Becker, Peters, Kemnitz (2018) nbau und Verwendung nachwachsender Rohstoffe in Deutschland
15. Andreas Kemmler, Aurel Wünsch, Heiko Burret (2021) Entwicklung des Bruttostromverbrauchs bis 2030: Berechnungsergebnisse aus dem Szenario 1
16. Gastautor (2020) Ist die Bevölkerung gegen Windenergie? - ee mag. eemag
17. Tobias Schmid, Fabian Jetter, Marc Gallet (2016) Konzept und Daten zur Regionalisierung von erneuerbarenEnergien: Grundlage für die Abbildung regionalisierter Szenarien imNetzentwicklungsplan Strom 2030 Version 2017
18. Bundesnetzagentur Markstammdatenregister: Gesamtdatenauszug. Accessed 21 Sep 2021
19. Seyfert U, Buchhorn M, Bunzel K et al. (2010) Globale und regionale räumliche Verteilung von Biomassepotenzialen: Anhang I - Regionale Biomassepotenziale, Berlin
20. Brosowski A, Adler P, Erdmann G et al. (2015) Biomassepotenziale von Rest- und Abfallstoffen - Status quo in Deutschland: Schlussbericht zum Vorhaben : Laufzeit: 01.10.2014 bis 31.03.2015. DBFZ Deutsches Biomasseforschungszentrum gemeinnützige GmbH, Leipzig
21. Kost C, Shammugam S, Fluri V et al. (2021) Stromgestehungskosten Erneuerbare Energien
22. Universität Stuttgart (IHS), Fichtner GmbH & Co. KG, Hydrotec Ing.-Ges. für Wasser und Umwelt mbH (2010) Potentialermittlung für den Ausbau der Wasserkraftnutzung in Deutschland: Kurzfassung, Aachen
23. Consentec GmbH, Fichtner GmbH, Hydrotec Ing.-Ges. für Wasser und Umwelt mbH, Universität Stuttgart (2019) Vorbereitung und Begleitung bei der Erstellung eines Erfahrungsberichts gemäß § 97 Erneuerbare-Energien-Gesetz: Teilvorhaben II d: Wasserkraft, Aachen
24. BUND Naturschutz in Bayern e.V. Kein weiterer Ausbau der Wasserkraft in Bayern! https://www.bund-naturschutz.de/natur-und-landschaft/fluesse-und-auen-in-bayern/bedrohung/wasserkraft-bayern. Accessed 15 Mar 2022
25. Forschungsstelle für Energiewirtschaft e. V. und Forschungsgesellschaft für Energiewirtschaft mbH (2019) Elektrolyse – Die Schlüsseltechnologie für Power-to-X. https://www.ffe.de/veroeffentlichungen/elektrolyse-die-schluesseltechnologie-fuer-power-to-x/. Accessed 15 Mar 2022
26. Buttler A, Spliethoff H (2018) Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review. Renewable and Sustainable Energy Reviews 82:2440–2454. https://doi.org/10.1016/j.rser.2017.09.003
27. Zauner A, Böhm, H. Rosenfeld, D. C., Tichler R (2019) Innovative large-scale energy storage technologies and Power-to-Gas concepts after optimization: D7.7 Analysis on future technology options and on techno-economic optimization

28. International Renewable Energy Agency (ed) (2020) Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5°C Climate Goal
29. Agora Energiewende, AFRY Management Consulting (2021) No-regret hydrogen: Charting early steps for H_2 infrastructure in Europe
30. (2017) Genehmigungsbescheid vom 05. Mai 2017, Az.: 53.0039/16/G16-K: Wesentliche Änderungen der Anlage zur Herstellung von Ammoniak (Ammoniak-Anlage) auf dem Werksgelände Köln der Firma INEOS Köln GmbH, Kön
31. egw:wirtschaftsförderung Entwicklungsgesellschaft Westholstein mbH Elbehafen Zeitungsserie Yara: Gute Ernte. https://www.chemcoastpark.de/de/unternehmen/#yara-brunsbuttel. Accessed 15 Mar 2022
32. Deutsche Energie-Agentur GmbH (2021) Einspeiseatlas. https://www.biogaspartner.de/einspeiseatlas/
33. Froehlich T, Blömer S, Münter D et al. (2019) CO_2 Quellen für die PtX Herstellung in Deutschland Technologien, Umweltwirkung, Verfügbarkeit, Heidelberg