DVGW-Forschungsstelle am Engler-Bunte-Institut
des Karlsruher Instituts für Technologie

DVGW | ebi

www.dvgw-ebi.de

Ecological evaluation of hydrogen supply

Sensitivity analysis on GHG emissions of hydrogen

Maximilian Heneka, Friedemann Mörs | May 17, 2022

Summary

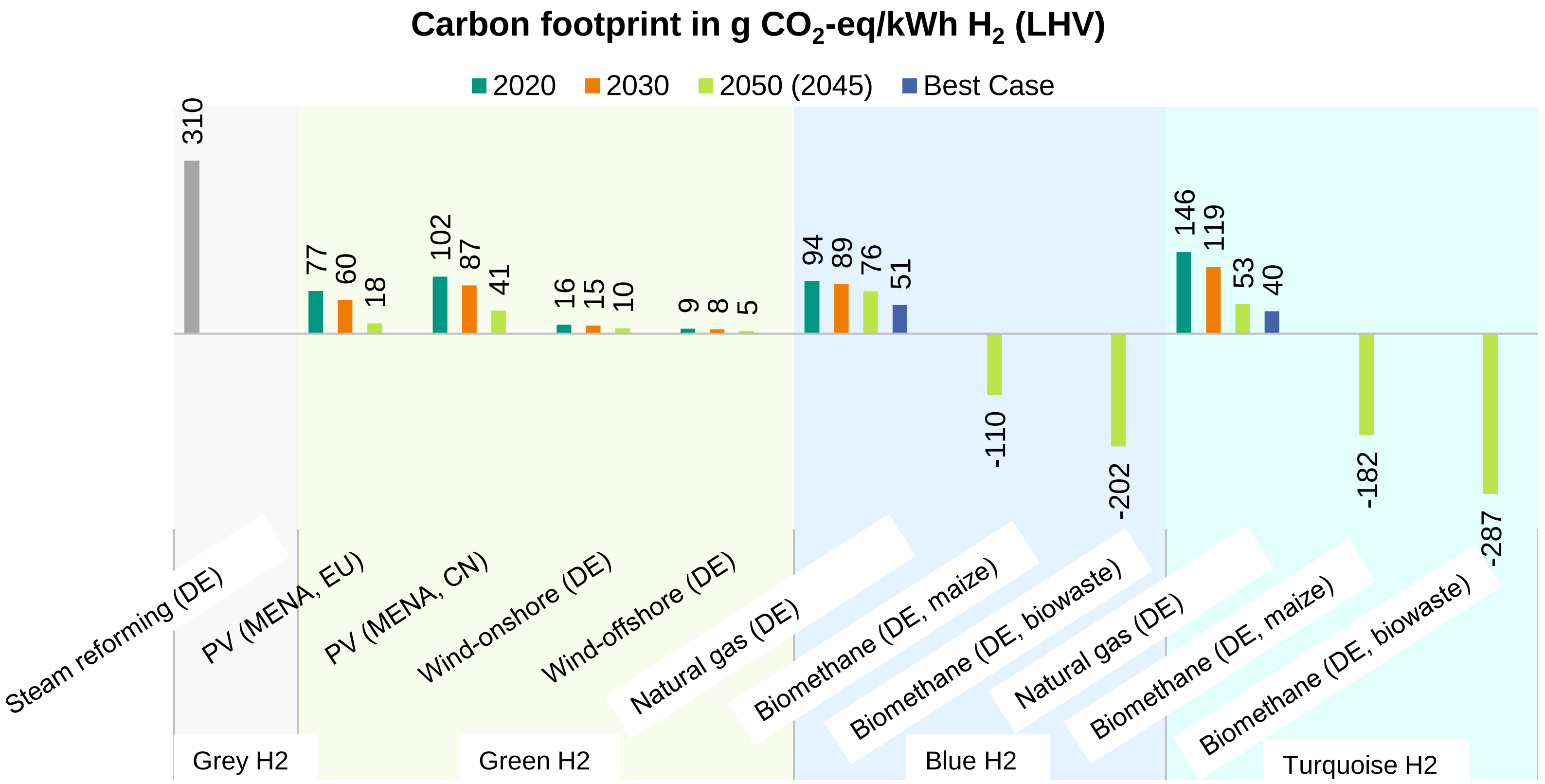
DVGW

Summary

- Already today, the generation of blue, turquoise and green hydrogen has the potential of reducing the specific GHG emissions by 50 - 95% compared to the state of the art (grey hydrogen). In Germany, the production of green hydrogen from offshore wind energy has the highest mitigation potential.
- Negative GHG emissions can be illustrated by means of the generation of blue and turquoise H_2 from biomethane as the CO_2 absorbed as solid carbon or gaseous CO_2 during biomass growth can be sequestered.
- Perspectively, GHG reductions between 75 and >95% can be achieved with blue, turquoise and green hydrogen.
  - In terms of green H_2, the upstream chain emissions of the electricity supply determine the GHG emissions of the hydrogen. Depending on the H_2 production site, the transport expenditure for pipeline transport must, where necessary, also be taken into consideration. Besides, for the production of green hydrogen from PV electricity, the upstream chain emissions for the manufacture of the PV modules are of crucial importance. Hence, when modules from China (year of production 2020) are used, the carbon footprint of PV electricity is higher by a factor of 1.75 than for modules manufactured in Europe. The main influencing factor in this is the electricity mix of the respective country of production.
  - For blue and turquoise H_2, the upstream chain emissions of the natural gases/methane used crucially influence the GHG emissions of the hydrogen. A further reduction of the upstream chain emissions of natural gas/methane beyond the 30% reduction target (best case) of the EU must therefore be aimed at.

DVGW | ebi

Overview of results



Definition of task

Definition of task

Within the scope of this brief study, the greenhouse gas emissions (GHG emissions) of the following hydrogen supply paths were analysed. The required procedural data were collected in the DVGW key project "Roadmap Gas 2050" (see report D 1.1*):

- Blue hydrogen from steam reforming with carbon capture and storage (CCS)
- Turquoise hydrogen from natural gas pyrolysis with storage of solid carbon
- Green hydrogen from water electrolysis with renewable electricity

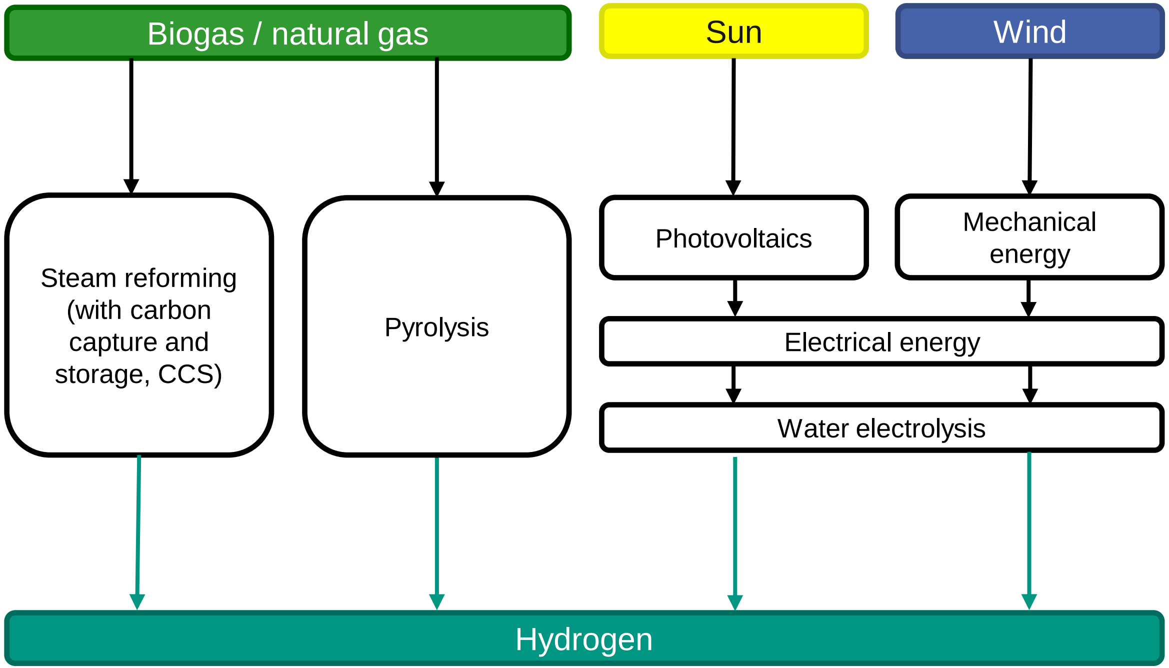
Based on the work in "Roadmap Gas 2050", a **sensitivity analysis in respect of the GHG emissions** was carried out. In the study at hand, the focus is on the following main points:

- Development of the GHG emissions of PV and wind power up to 2050 and classification in literature
- Development of the GHG emissions of green hydrogen from PV and wind power up to 2050
- Development of the GHG emissions of blue and turquoise H_2 incl. best case examination

* available in German: https://www.dvgw.de/medien/dvgw/forschung/berichte/g201824-abschlussbericht-d1.1-rmg2050-h2-Bereitstellung.pdf

DVGW | ebi

H_2 supply paths considered



Outline

- GHG emissions PV, wind and mains power
  - Introduction, methodology
  - Background data
  - Results and classification in literature
- GHG emissions green hydrogen
- GHG emissions blue and turquoise hydrogen

GHG emissions
PV, wind and mains power

Introduction, methodology

GEMIS (global emission model of integrated systems)

⇨ GHG emissions were calculated with GEMIS version 5.0

What is GEMIS?

- Freely available computer model with integrated data base for eco-balancing and material flow analyses
- Developer: *Öko-Institut*
- First program version published in 1989, since then continuously enhanced; funded among others by BMUV, BMBF and UBA.
- In April 2012, GEMIS was taken over by the *International Institute for Sustainability Analyses and Strategies* (IINAS).
- Must current version: 5.0 (published February 2021).

Download: https://iinas.org/downloads/gemis-downloads/

DVGW | ebi

GEMIS (Global Emission Model of Integrated Systems)
Methodology

Calculation of carbon footprint (CF) with GEMIS 5.0

- The GEMIS database comprises more than 10,000 processes from the areas energy sources, current and heat, material production and transport (incl. reference to sources)
- Each process supplies among others information on **technology data** (e.g. process efficiency), **raw material/energy requirement** or **environmental data** (e.g. direct emissions)
- At the same time, **transport processes** and their energy requirements are also considered.
- In addition, **preliminary construction work** or rather the raw materials and substances required for this are considered for each process.
- This results in a **process network** that interconnects individual processes by means of links, thus integrating the life cycles.
- With this, it is for instance possible to record both environmental effects (carbon footprint) as well as indirect effects across the entire process chain by means of upstream processes.
- The technology data/raw material and energy requirements of the processes can be adapted or own processes can be created.

DVGW | ebi

GHG emissions
PV, wind and mains power

Background data

DVGW

GHG emissions: PV, wind and mains power
Methodology

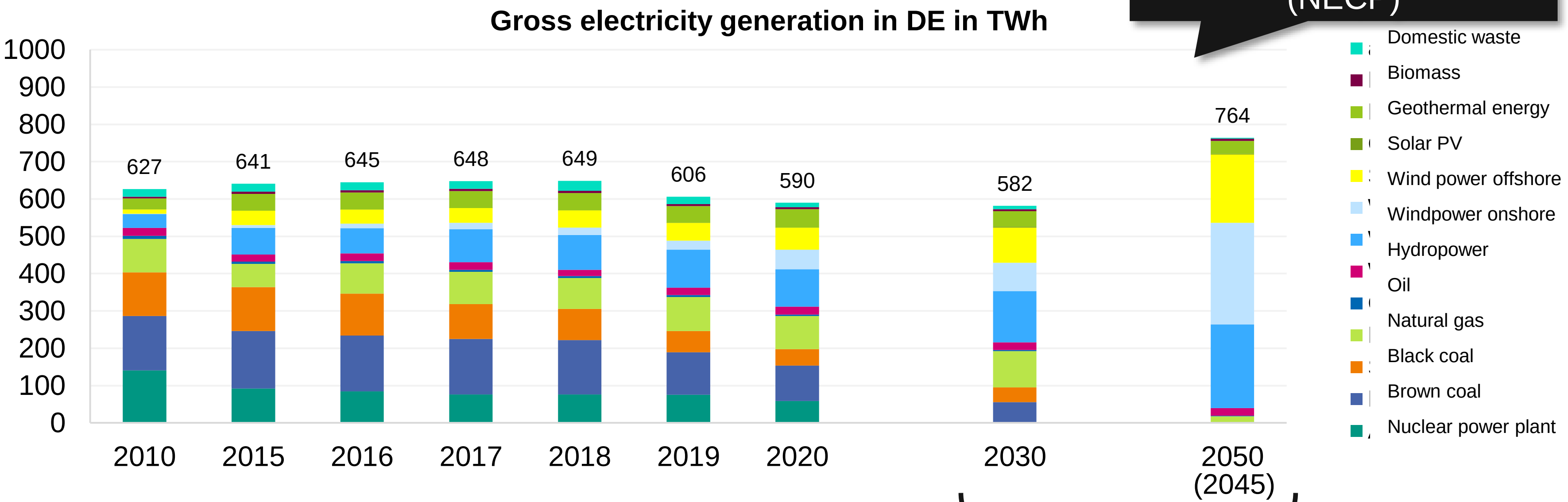
Introductory remarks:

- The type of renewable power source plays a crucial role for the carbon footprint of green hydrogen
- The manufacture of the power generation plants is associated with greenhouse gas emissions which are arising upstream, i.e. mainly during manufacture of the materials (e.g. steel, concrete, copper and aluminium). This will still be the case in the year 2050, even though the manufacturing processes (efficiency factors), material requirements and background processes (electricity mix, energy input, raw material provision) continue to improve.
- The manufacturing processes of the required materials and the associated energy requirements and emissions (= background system) are stored in GEMIS in form of a database.
- By mapping the PV and wind plants in GEMIS v 5.0 (= definition of plant size, mode of operation and full load hours, useful life), it is possible to calculate the specific GHG emissions for the provision of electricity (incl. upstream chain emissions).

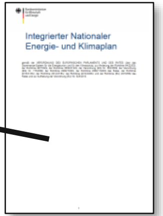
DVGW | ebi

Development – German electricity mix
Source: GEMIS v5.0 (NECP)

Electricity mix projections for 2030 and 2050 (2045) according to "National Energy and Climate Plan" (NECP)



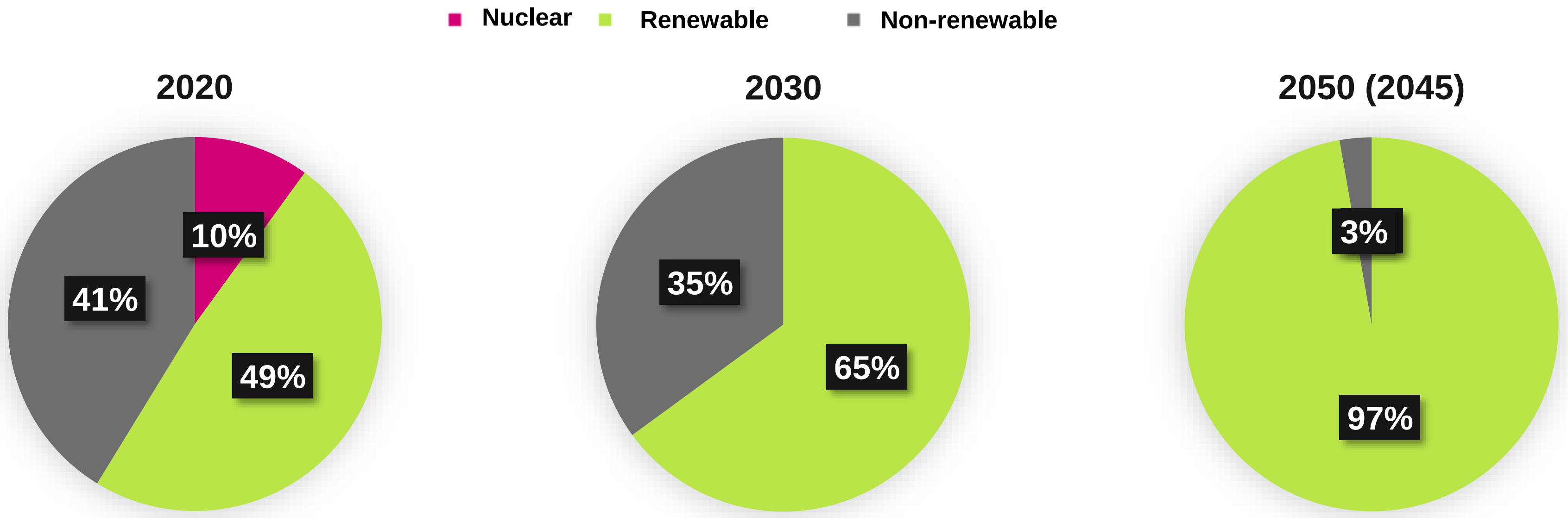
NECP: EU member states are obligated to provide information on national energy and climate policy. Final version was transmitted to the EU Commission on 10 June 2020



[3]

Carbon footprint – German electricity mix (without grid losses)

Source: GEMIS v5.0 (NECP)



352 g CO_2-eq/kWh | **261 g CO_2-eq/kWh** | **30 g CO_2-eq/kWh**

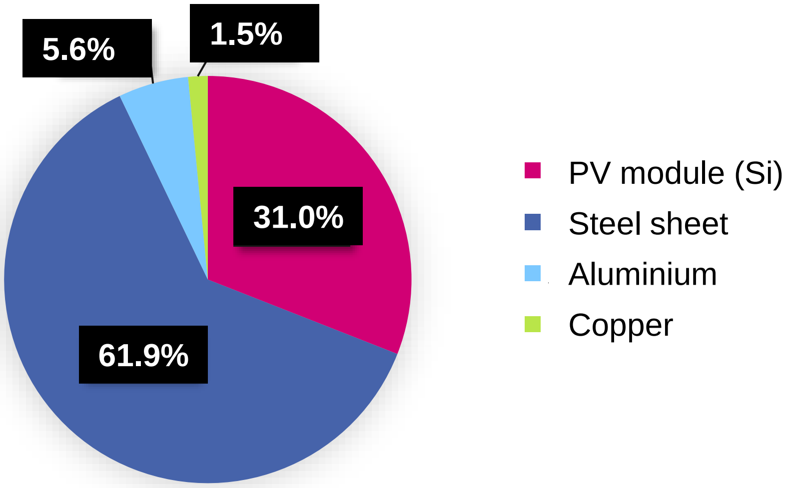
Due to the amended Climate Protection Act 2021 it is to be assumed that clearly higher GHG reductions will already be achieved by **2030**. The values for 2030 determined in this presentation should accordingly be regarded as **conservative**.

DVGW ebi

Carbon footprint – PV / wind energy
GEMIS assumptions

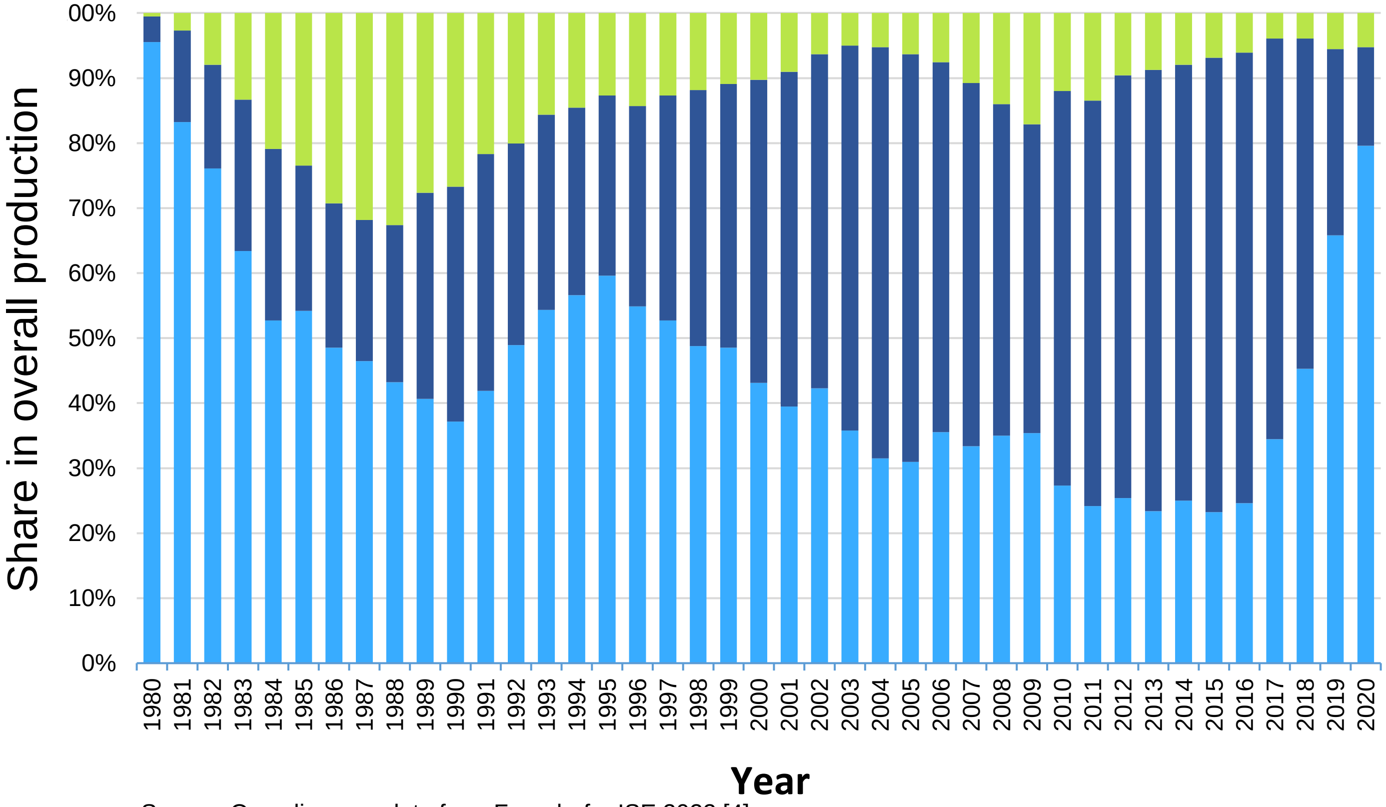
- **PV plant (PVP):**
  - Monochrystalline silicon modules
  - Site: MENA
  - Irradiance: 2000 kWh/(m^2*a)
  - Full load hours: 2475 h/a
  - Module efficiency:
    – 2020: 18%
    – 2030: 20%
    – 2050: 22%

Material mix PV plant



Development by 2050 (2045):
Material mix remains constant but the underlying industrial processes are changing (efficiency, electricity mix, manufacturing methods)

Excursion: PV plants
PV module types



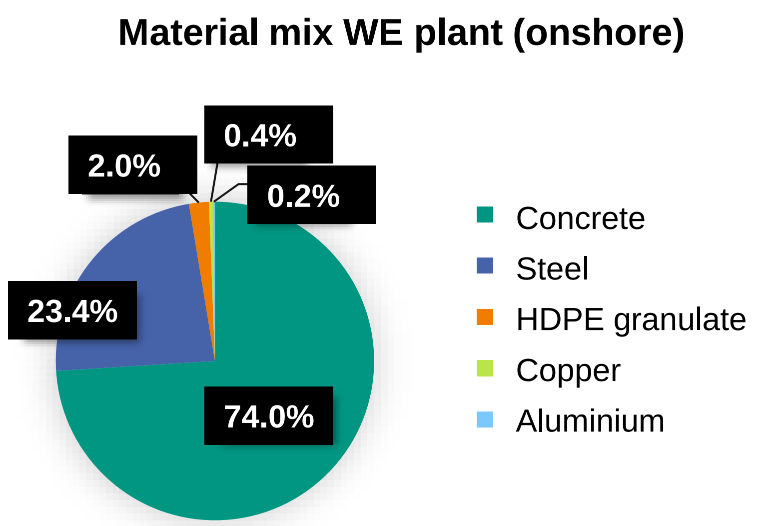
Production 2020: (in GWp)

Thin Film	7.7
Multi-Si	23.3
Mono-Si	120.6

Source: Own diagram, data from Fraunhofer ISE 2022 [4]

Carbon footprint – PV / wind energy
GEMIS assumptions

- **Wind energy plant onshore (WEP):**
  - Output[1]:
    - 2020: 2.2 MW
    - 2030: 3.3 MW
    - 2050: 6 MW
  - Full load hours: 2200 h/a
  - Service life: 20 a



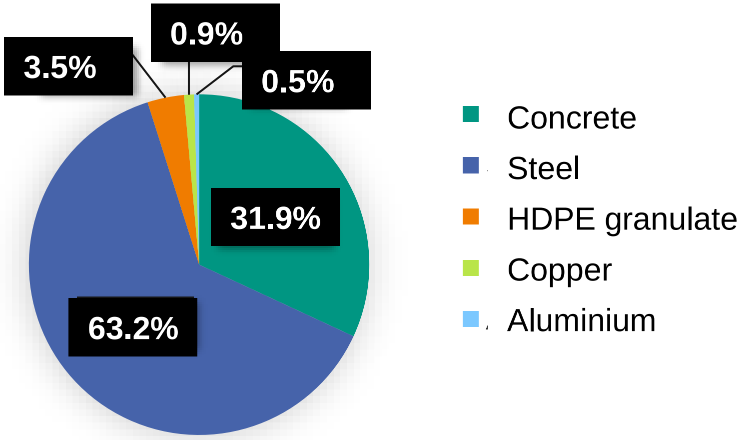
Development by 2050 (2045):
Material mix remains constant but the underlying industrial processes are changing (efficiency, electricity mix, manufacturing methods)

[1]: Assumptions are based on UBA 2021 [5]

Carbon footprint – PV / wind energy
GEMIS assumptions

- **Wind energy plant offshore (WEP):**
  - Output[1]:
    - – 2020: 3.6 MW
    - – 2030: 11 MW
    - – 2050: 20 MW
  - Full load hours: 3800 h/a
  - Service life: 20 a

Material mix WE plant (offshore)



Development by 2050 (2045):
Material mix remains constant but the underlying industrial processes are changing (efficiency, electricity mix, manufacturing methods)

[1]: Assumptions are based on UBA 2021 [5]

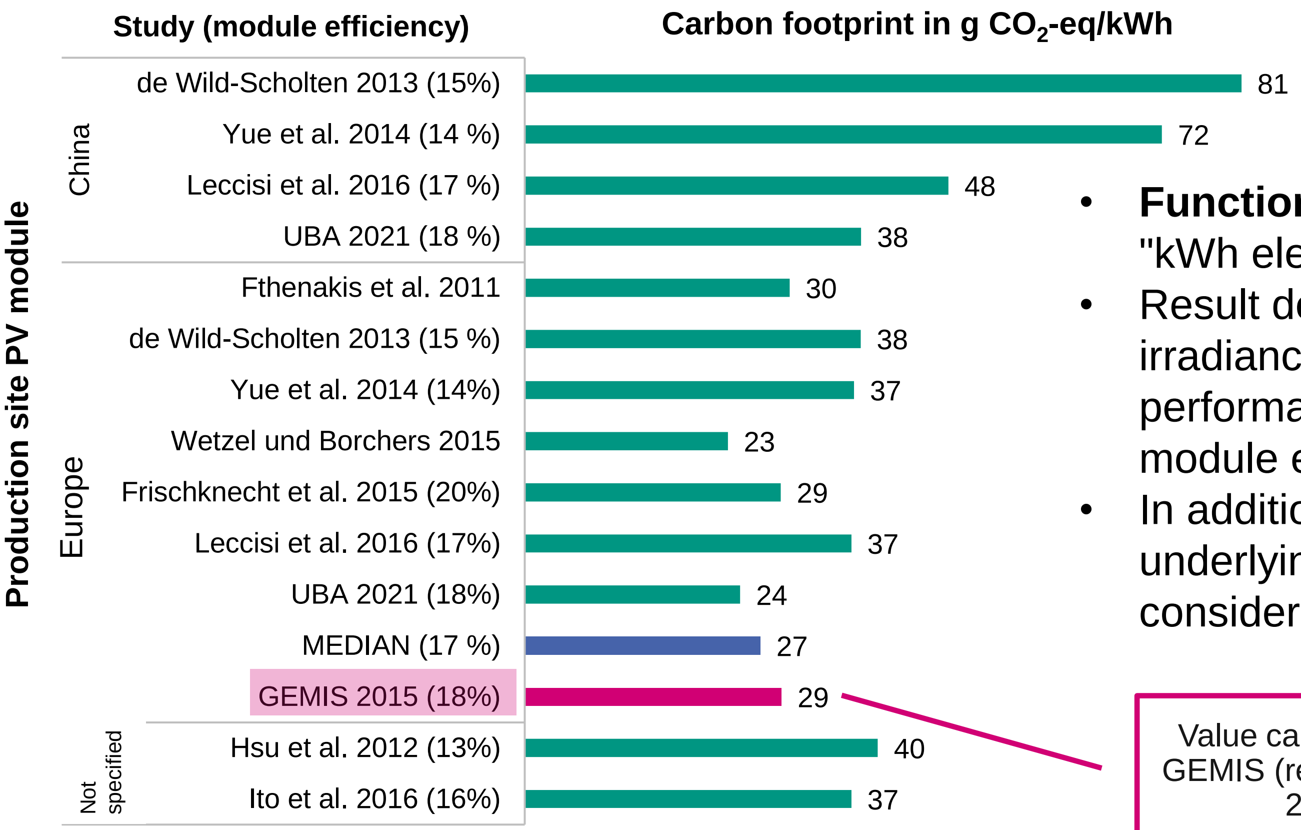
DVGW ebi

GHG emissions
PV, wind and mains power

Results and classification in literature

Values in literature – PV plant (monocrystalline Si-module)

Carbon footprint in g CO_2-eq/kWh

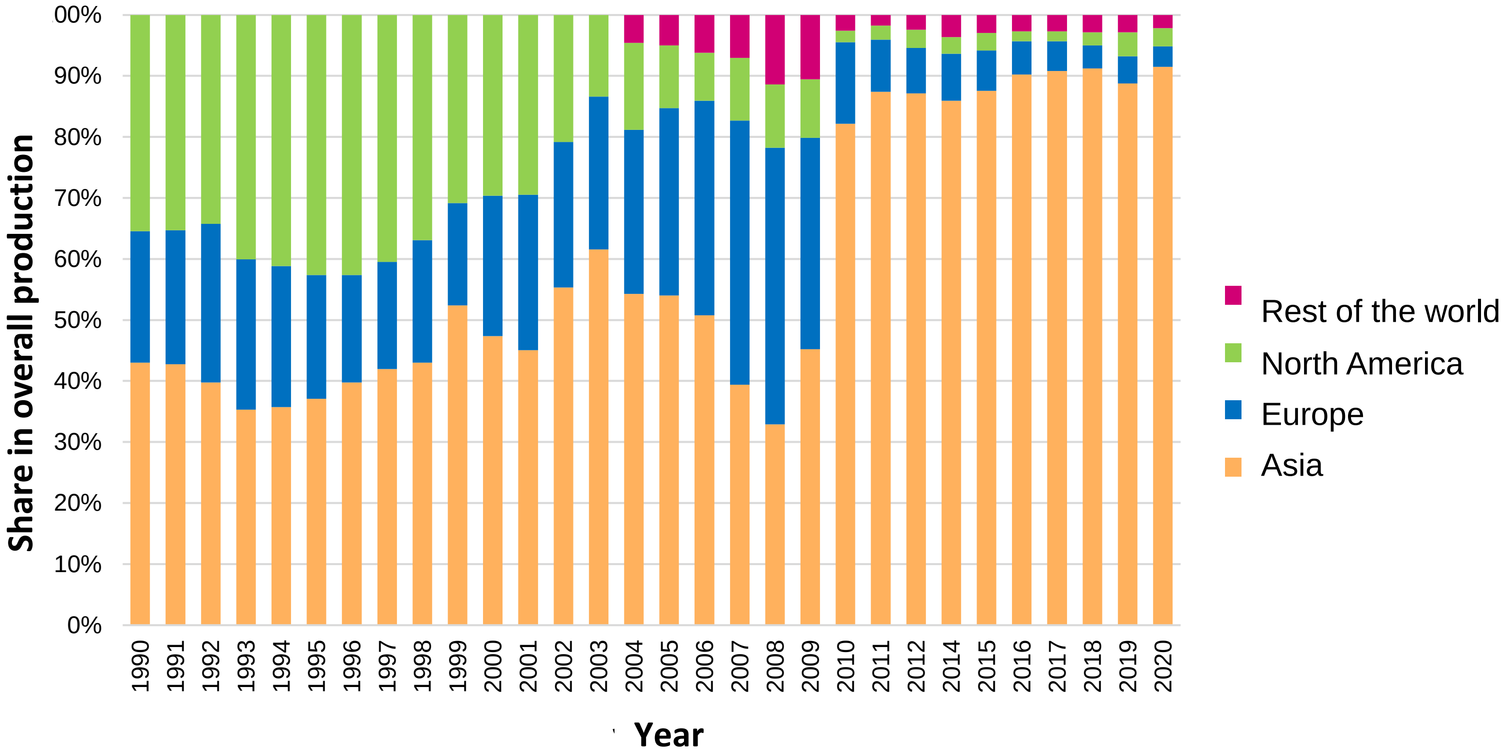


- **Functional unit**:
  "kWh electricity fed into the grid"
- Result depends on site (here: solar irradiance: 1700 W/(m²*a)), performance ratio (here: 0.8) and module efficiency (here: 14-20%)
- In addition, production site and underlying electricity mix have a considerable influence!

Value calculated with GEMIS (reference year 2015)

Excursion: PV plants

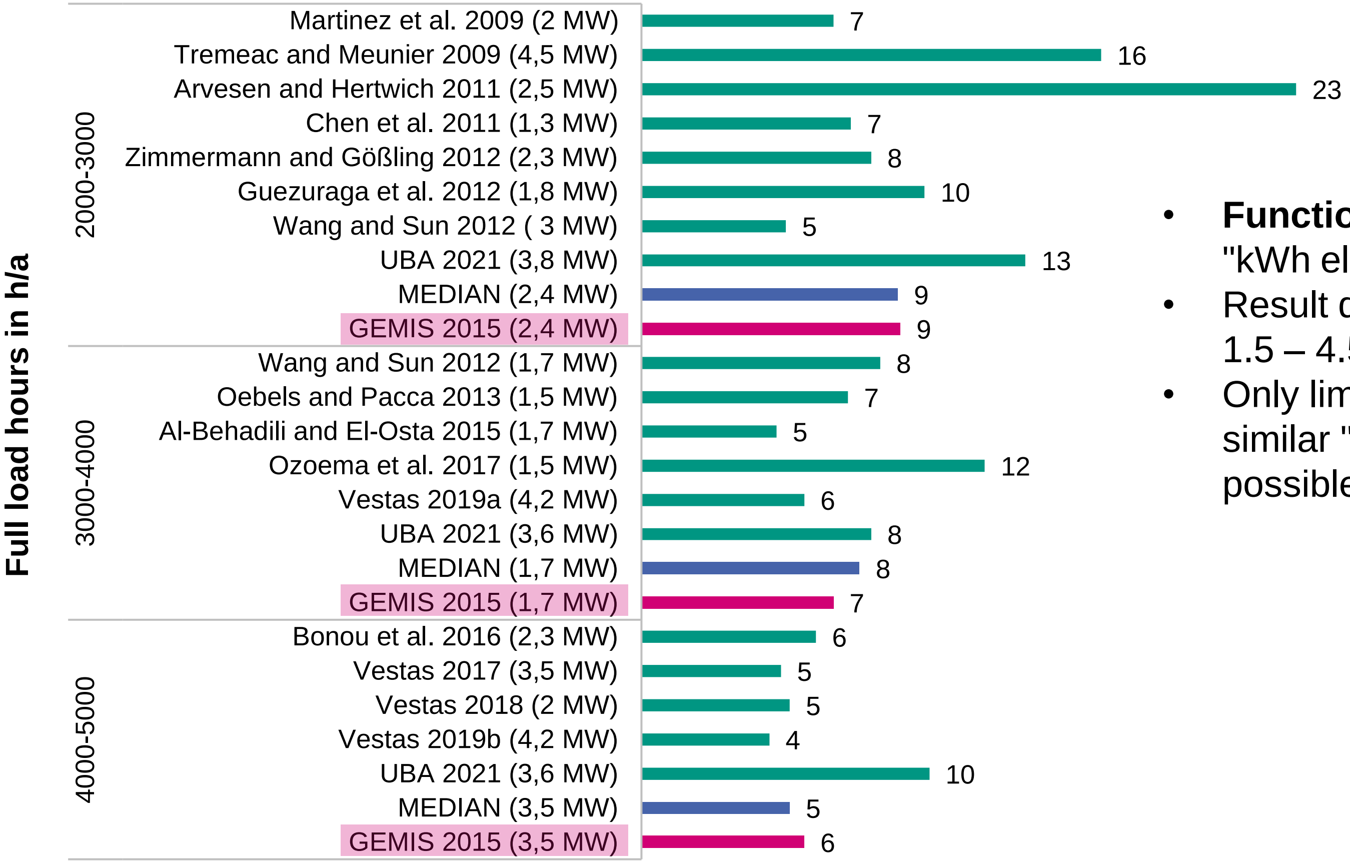
Production sites PV modules



Source: Own diagram, data from Fraunhofer ISE 2022 [4]

Literature research – wind energy plant (onshore)

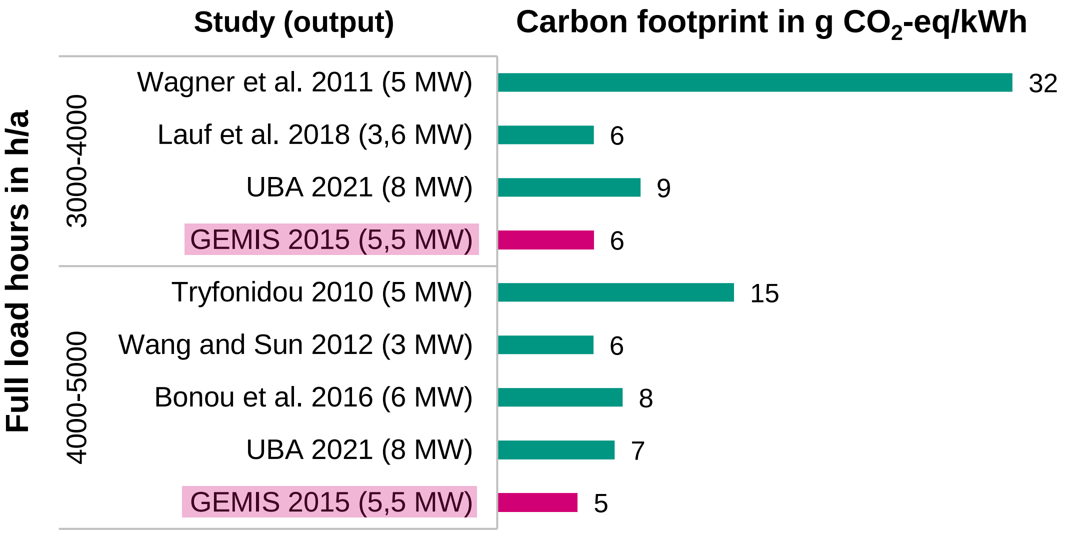
Carbon footprint in g CO_2-eq/kWh



- **Functional unit**: "kWh electricity fed into the grid"
- Result depends on plant output (here: 1.5 – 4.5 MW) and full load hours
- Only limited comparability within similar "electricity yield ranges" possible!

Literature research – wind energy plant (offshore)

Carbon footprint in g CO_2-eq/kWh



- **Functional unit**:
  "kWh electricity fed into the grid"
- Result depends on plant output (here: 3 – 8 MW) and full load hours
- Only limited comparability within similar "electricity yield ranges" possible!

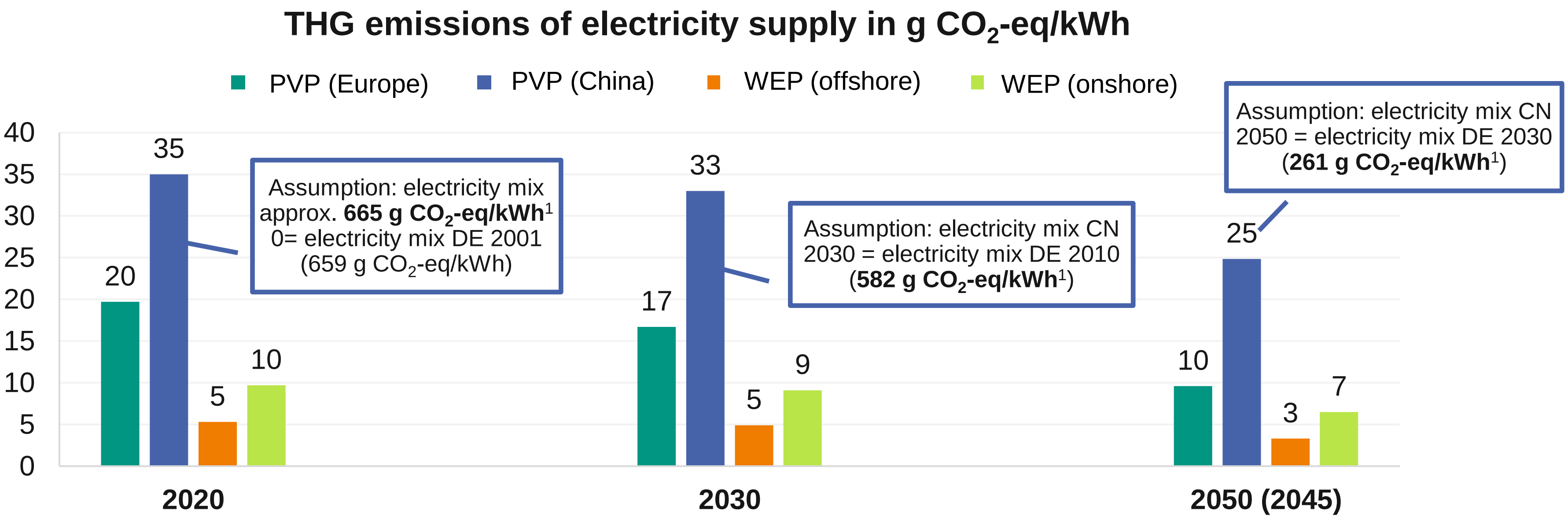
No essential difference between offshore and onshore plants.
Higher output is offset by additional expenses for erection of the plant and connection to the network (submarine cable).

Interim conclusion
Evaluation of literature

- LCA studies only look at the past (primary data)
- Calculations in GEMIS integrate well into the hitherto existing studies landscape
- As for PV, GEMIS is based on German production site data. However, more than 90% of PV modules are manufactured in Asia (67% in China). The production site China was therefore considered as additional sensitivity (→ value in literature UBA 2021 [5]).

DVGW | ebi

Carbon footprint – PV / wind energy
Source: GEMIS v5.0



PV plants have a higher carbon footprint than wind energy plants.
Offshore WEP exhibit the lowest carbon footprint (higher full load hours and plant output)

[1]: Source: GEMIS v 5.0, Carbon footprint PV module (China) acc. to UBA 2021 [5]

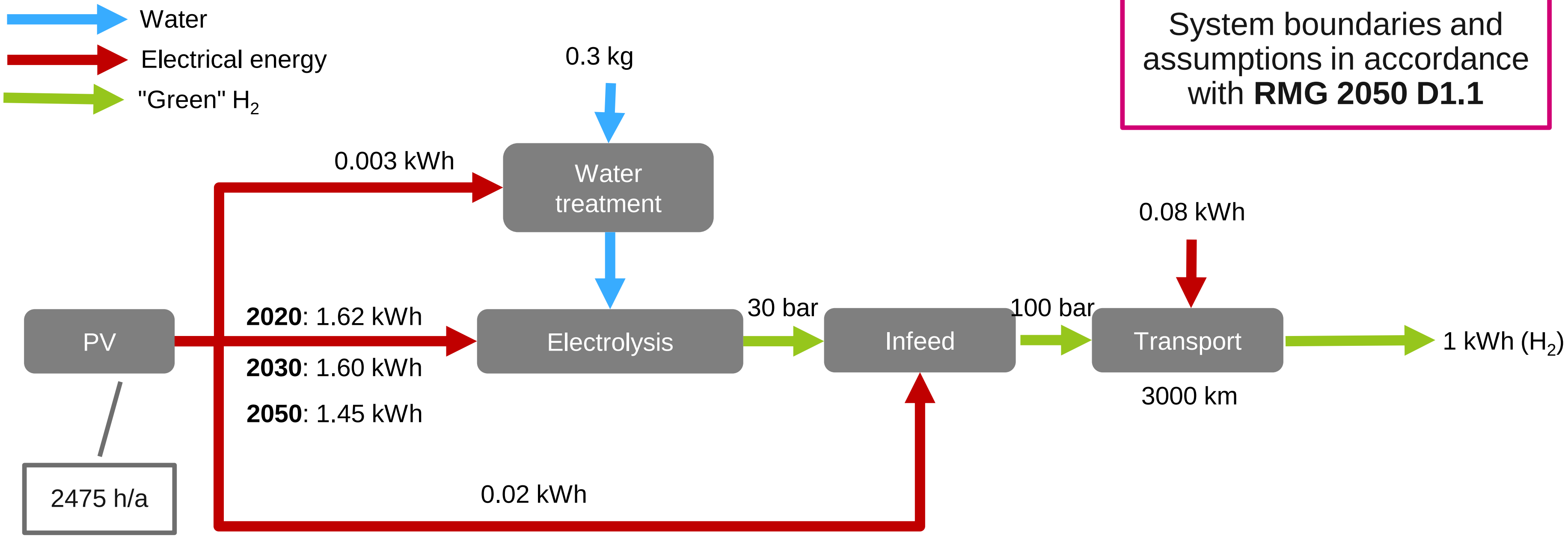
GHG emissions

Green hydrogen

Calculation of carbon footprint (CF) with GEMIS 5.0

- The **functional unit** was specified as 1 kWh (lower calorific value) hydrogen at 30 bar
- The energy sources are made available in **Germany**. If the H_2 production does not take place in Germany, transport up to the national border is taken into account.
- Three different **base years** were considered: The present-day situation, based on the year 2020, a medium-term development ("2030") and a long-term development ("2050")
- **System boundaries**: For this brief study the approach "**cradle to product"** was chosen. In the course of this, all processes along the hydrogen generation and supply chain are considered. The following utilisation phase and any end-of-life processes are outside the system boundaries.
- **Operating mode** renewable energy plants: The operating hours of the electrolysers correspond to those of the associated power source. Example: PV plants in MENA achieve 2475 full load hours per year. Irrespective of the diurnal cycle, the synthesis plants are only operated for this time each year. Possible technical consequences of intermittent operation (catalytic converter aging, efficiencies of start-up processes) are disregarded
- Preliminary construction work for the electrolysis and infrastructure were disregarded as these only make up a small portion of the carbon footprint over the service life [6, 7, 8, 9].

System boundaries – Green H_2 from PV electricity from MENA

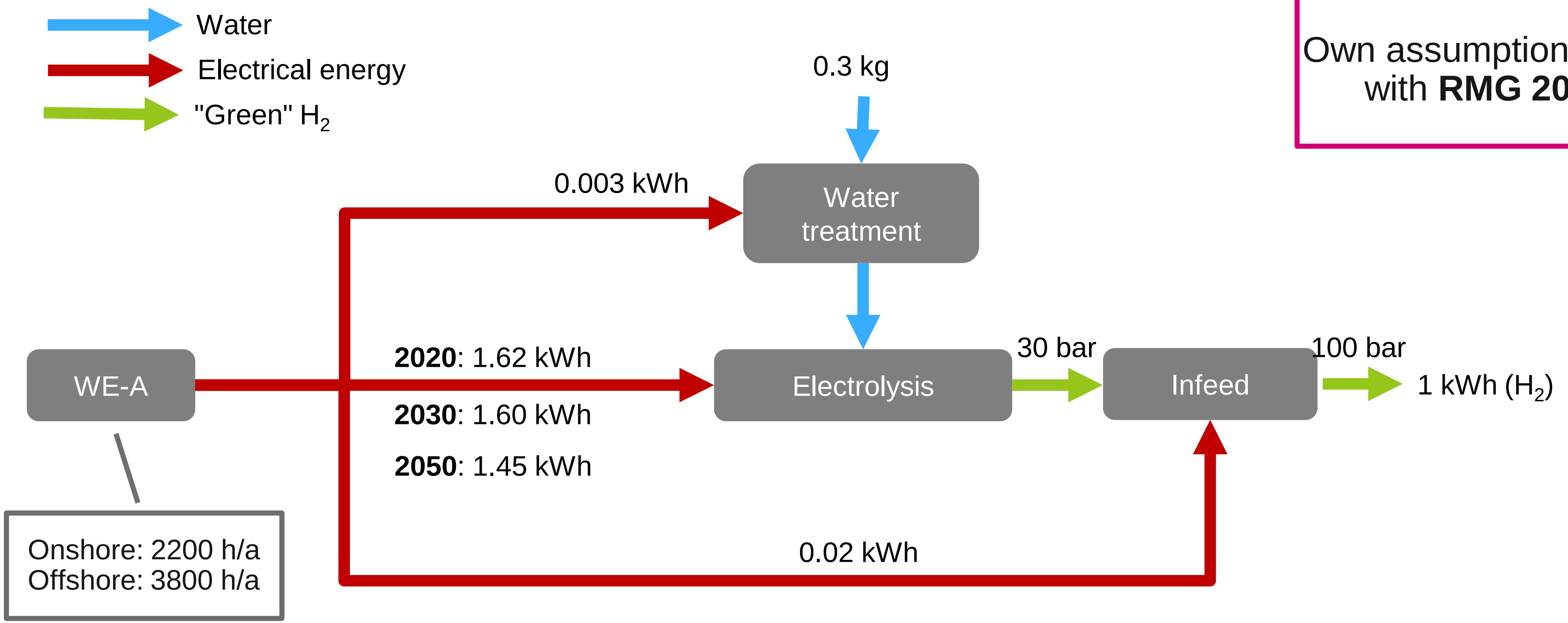


System boundaries and assumptions in accordance with **RMG 2050 D1.1**

Base years considered: 2020, 2030, 2050
Preliminary construction work of electrolysis disregarded [6, 7, 8, 9]

DVGW ebi

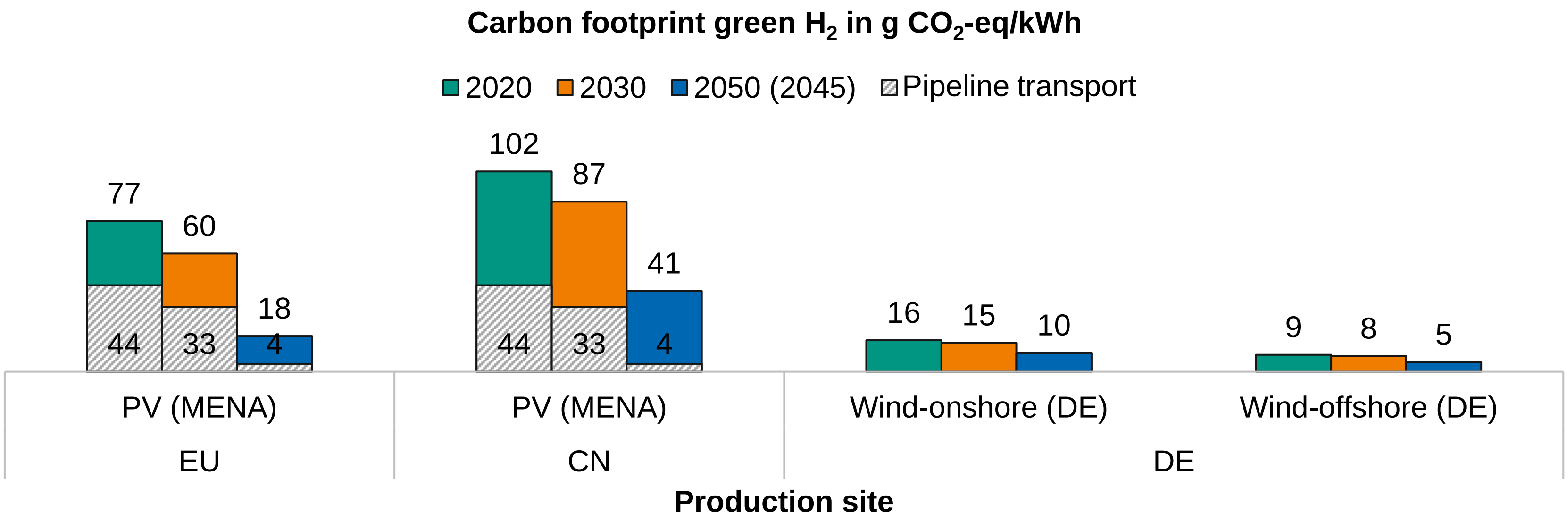
System boundaries – Green H_2 from wind energy (DE)



Own assumptions (consistent with **RMG 2050 D1.1**)

Base years considered: 2020, 2030, 2050
Preliminary construction work of electrolysis disregarded [6, 7, 8, 9]

Results – GHG calculations green H_2



A large portion of the emissions of H_2 from MENA (PV) is caused by pipeline transport
(assumption: compressor operated with mains current)

GHG emissions

Blue and turquoise hydrogen

DVGW

GHG emissions of blue and turquoise hydrogen
Methodology

The approach to calculate the GHG emissions of blue and turquoise hydrogen is based on the deliverable 1.1 of the project "Roadmap Gas 2050" [17]. The mass and energy balances are based on detailed process modelling with the software CHEMCAD®. The GHG emissions of the input material flows, the direct CO_2 emissions from the process and the emissions of CO_2 transport and sequestration were determined on this basis. The upstream chain emissions were defined as follows:

- The following source was taken into account for the **natural gas/methane upstream chain emissions**: natural gas via pipeline from Russia and Norway, natural gas via LNG from the USA and domestic biogas (see next transparency). A sensitivity analysis was carried out on this basis.
- The **upstream chain emissions of the German electricity mix** today, 2030 and 2050 are based on the NECP (see calculation with regard to green hydrogen)
- The **upstream chain emissions of the water used** were specified as 10 g CO_2-eq/kg (H2O) [17]
- The **emissions from CO_2 separation, transport and sequestration** were made up as follows: the electrical energy requirement (upstream chain emissions electricity) for CO_2 separation (carbon capture) and the direct CO_2 emissions are based on the process modelling. 35 g CO_2-eq/kg (CO_2) were specified for CO_2 transport and sequestration (carbon storage) [18]

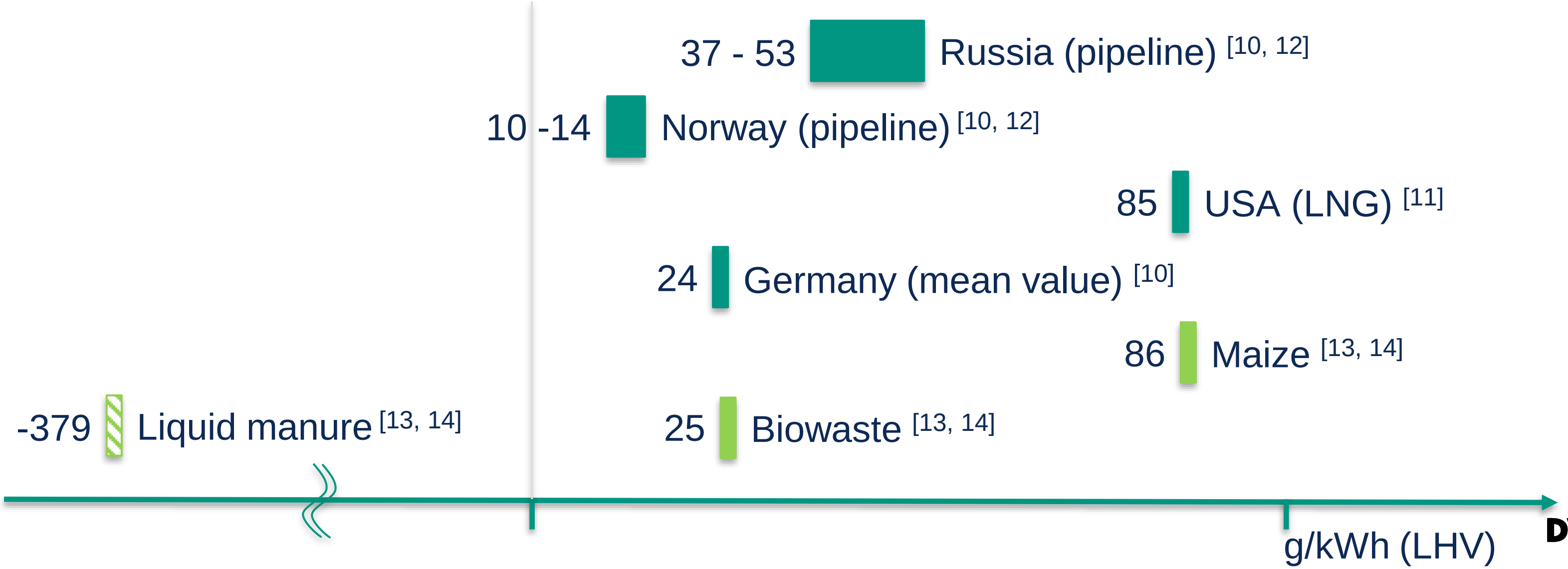
The emissions for preliminary construction work can be disregarded due to the long service life and the high material throughput [6].

DVGW ebi

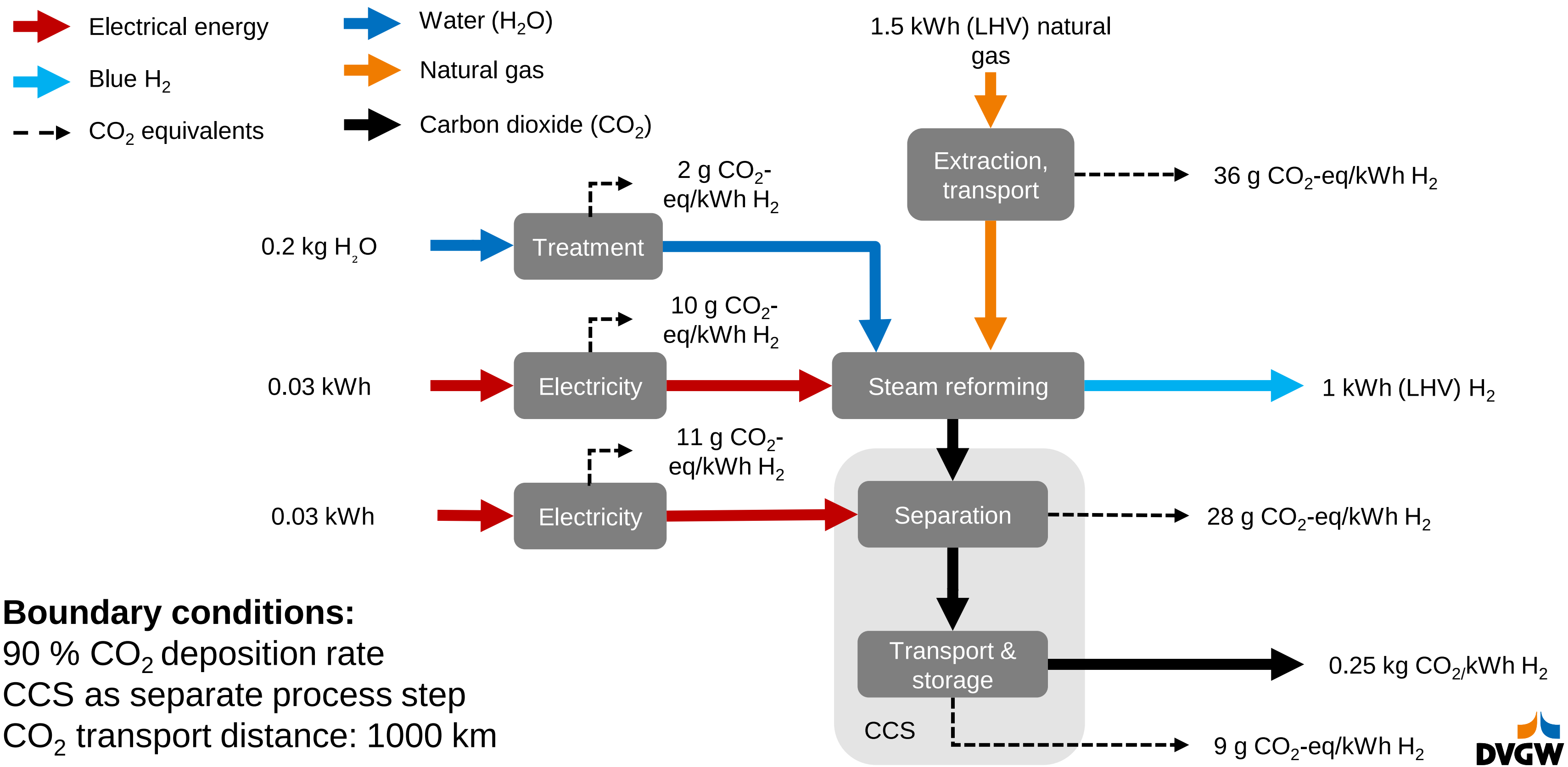
Literature review of the CO_2 upstream chain emissions of natural gas and domestic biogas

<u>Included in upstream chain emissions:</u>

- Extraction, treatment, transport, distribution in DE (CO_2 and methane emissions)
- For LNG additionally: liquefaction, LNG transport, regasification
- Biogas: provision of substrate, plant, plant operation



GHG emissions blue hydrogen - Germany (mean value) 2020



Boundary conditions:
90 % CO_2 deposition rate
CCS as separate process step
CO_2 transport distance: 1000 km

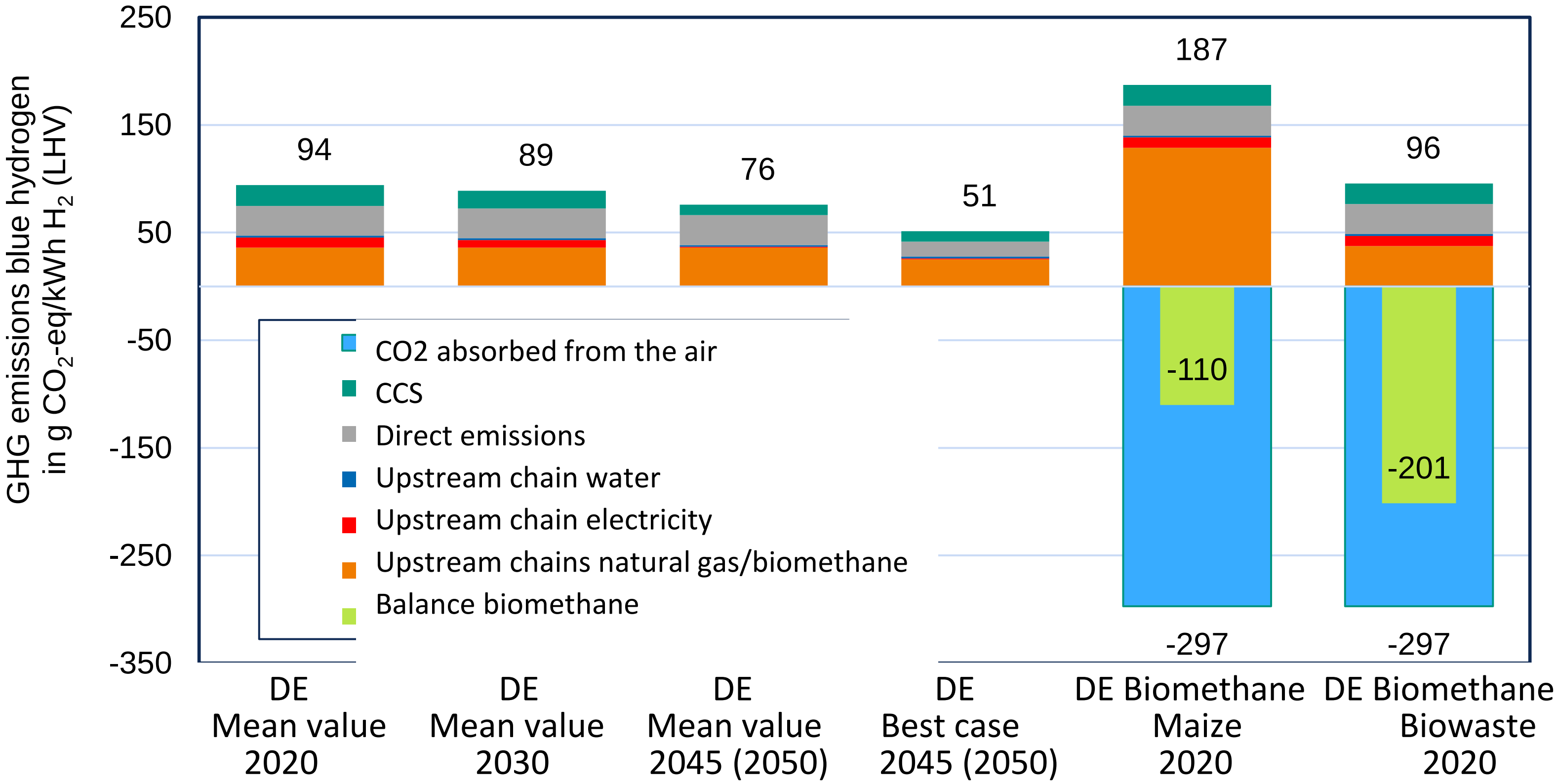
Blue hydrogen
Best case assumption

The following assumptions were made for the best case of blue hydrogen produced in Germany:

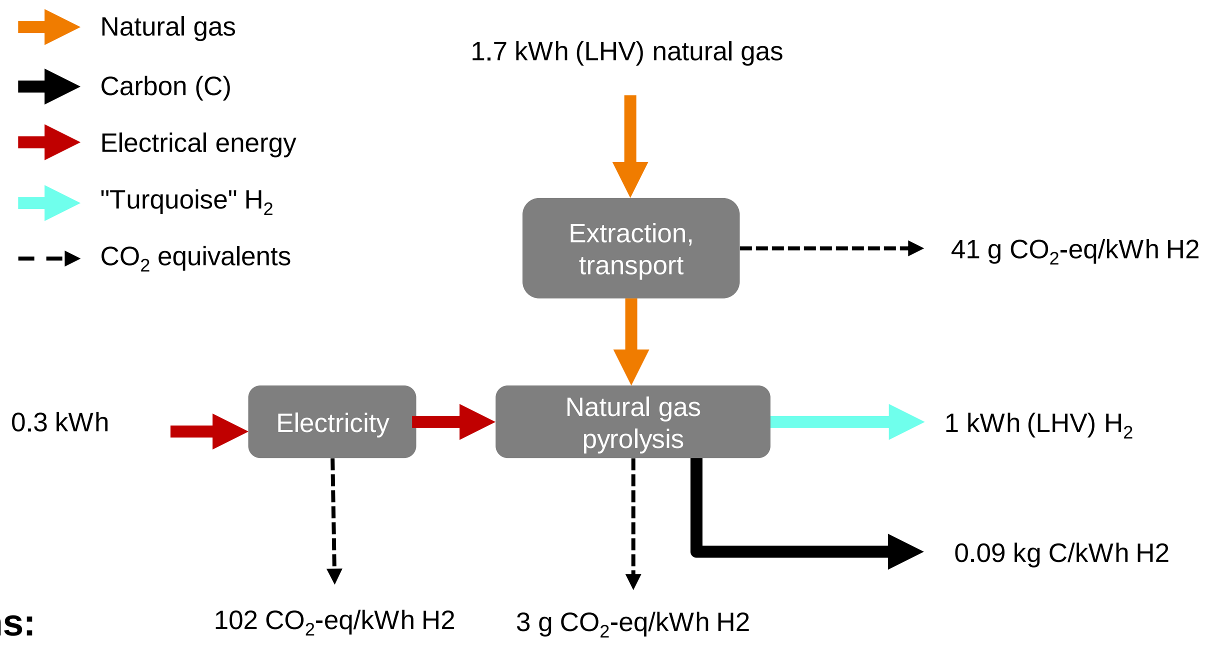
- 30% reduction of the natural gas/methane upstream chain emission based on the upstream chain emissions in Germany (mean value) [1]
- 95% deposition degree instead of 90% deposition degree. No increase of the power requirement for CO_2 separation and no increase of the GHG emissions for CO_2 transport and sequestration (carbon storage) were taken into consideration in this connection.

DVGW | ebi

GHG emissions blue hydrogen



GHG emissions turquoise hydrogen - Germany mean value 2020



Boundary conditions:
No re-use of the carbon was considered

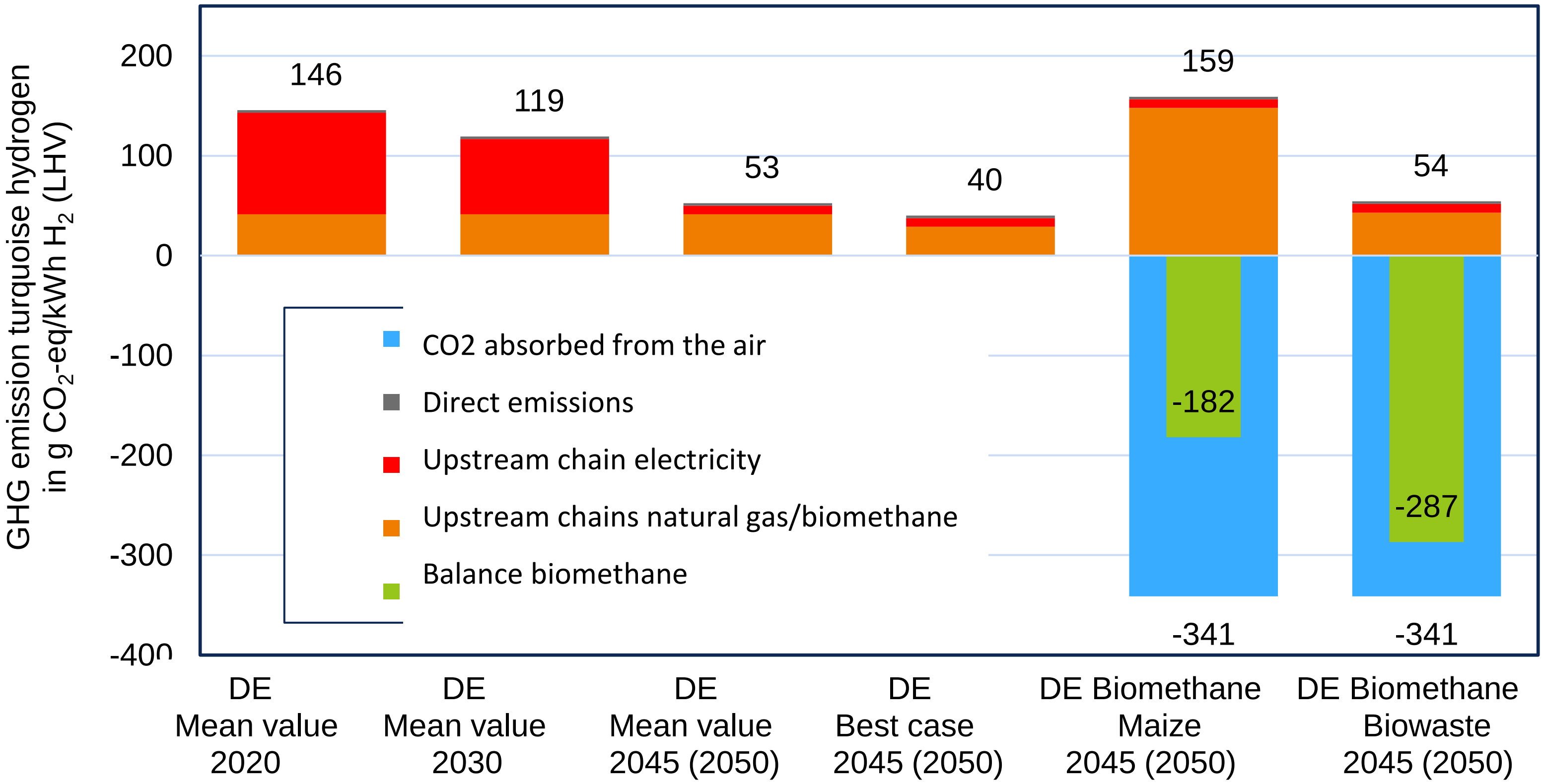
Turquoise hydrogen
Best case assumption

The following assumptions were made for the best case of turquoise hydrogen produced in Germany:

- 30% reduction of the natural gas/methane upstream chain emissions based on the upstream chain emissions in Germany (mean value) [1]

DVGW | ebi

GHG emissions turquoise hydrogen



Excursion:

H_2 certification

Excursion: H_2 certification
Example: TÜV SÜD, CertifHy

	CertifHy	TÜV SÜD
Type	Voluntary standard	Voluntary standard
Categories	"Green" or "Low carbon" (CCS)	"Green"
System boundaries	Well-to-Gate	Well-to-Gate (use optional)
Product	H_2 (3 MPa, purity: 99.9 %)	H_2 (3 MPa, purity: 99.9 %)
Preliminary construction work	Not taken into consideration	Not taken into consideration
Reference value	91 g CO_2-eq/MJ (calorific value) 328 g CO_2-eq/kWh (calorific value)	94 g CO_2-eq/MJ (calorific value) 338 g CO_2-eq/kWh (calorific value)
Reduction target	-60 % compared to reference value (upgrade to -70 % is intended)	-70 % compared to reference value
Threshold	36 g CO_2-eq/MJ (calorific value) 131 g CO_2-eq/kWh (calorific value)	28 g CO_2-eq/MJ (calorific value) 101 g CO_2-eq/kWh (calorific value)

[15, 16]

- Bound GHG emissions from the manufacture, construction or shutdown of plants are not taken into consideration
- None of the systems stipulates a future course for its GHG threshold values. The threshold values for "Green H_2" or "Low carbon H_2" will most probably be updated as needed on the basis of comprehensive political resolutions (e.g. RED II).

Appendix

Literature

No.	Source
[1]	Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL: on methane emissions reduction in the energy sector and amending Regulation (EU), 2021.
[2]	German Federal Environmental Agency, Greenhouse gas mitigation goals of Germany. [Online] Available at: https://www.umweltbundesamt.de/daten/klima/treibhausgasminderungsziele-deutschlands#inter-nationale-vereinbarungen-weisen-den-weg (accessed on: 11 February 2022).
[3]	Federal Ministry for Economic Affairs and Energy, "Integrated National Energy and Climate Plan: in accordance with the REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the governance system for the Energy Union and for climate protection and amending Directive 94/22/EC, Directive 98/70/EC, Directive 2009/31/EC, Regulation (EC) No. 663/2009, Regulation (EC) No. 715/2009, Directive 2009/73/EC, Council Directive 2009/119/EC, Directive 2010/31/EU, Directive 2012/27/EU, Directive 2013/30/EU and Council Directive (EU) 2015/652 and repealing Regulation (EU) No. 525/201", June 2020. [Online] Available at: https://www.bmwi.de/Redaktion/DE/Downloads/I/integrierter-nationaler-energie-klimaplan.pdf?__blob=publicationFile&v=4. Accessed on: 17 February 2022.
[4]	Fraunhofer ISE, "Photovoltaics Report 2022", February 2022 [Online] Available at: https://www.ise.fraunhofer.de/de/veroeffentlichungen/studien/photovoltaics-report.html. Accessed on: 18 March 2022
[5]	Jasmin Hengstler, Manfred Russ, Alexander Stoffregen, Aline Hendrich, Dr. Michael Held, Ann-Kathrin Briem, "Update and assessment of the life cycle assessments of wind energy and photovoltaic plants taking into consideration current developments in technology" („Aktualisierung und Bewertung der Ökobilanzen von Windenergie- und Photovoltaikanlagen unter Berücksichtigung aktueller Technologieentwicklungen"), German Federal Environmental Agency (UBA), 2021. Accessed on: 12 November 2021.
[6]	IFEU, DLR - German Aerospace Centre and JOANNEUM RESEARCH, "System comparison storable energy sources from renewable energies: Final report" („Systemvergleich speicherbarer Energieträger aus erneuerbaren Energien: Abschlussbericht"), Dessau-Roßlau, texts 68/2020, Nov. 2019.
[7]	M. Delpierre, J. Quist, J. Mertens, A. Prieur-Vernat and S. Cucurachi, "Assessing the environmental impacts of wind-based hydrogen production in the Netherlands using ex-ante LCA and scenarios analysis", Journal of Cleaner Production, volume 299, p. 126866, 2021, doi: 10.1016/j.jclepro.2021.126866.
[8]	K. Bareiß, C. de La Rua, M. Möckl and T. Hamacher, "Life cycle assessment of hydrogen from proton exchange membrane water electrolysis in future energy systems", Applied Energy, volume 237, p. 862–872, 2019, doi: 10.1016/j.apenergy.2019.01.001.
[9]	R. Bhandari, C. A. Trudewind and P. Zapp, "Life cycle assessment of hydrogen production via electrolysis – a review", Journal of Cleaner Production, 2013, doi: 10.1016/j.jclepro.2013.07.048.

DVGW | ebi

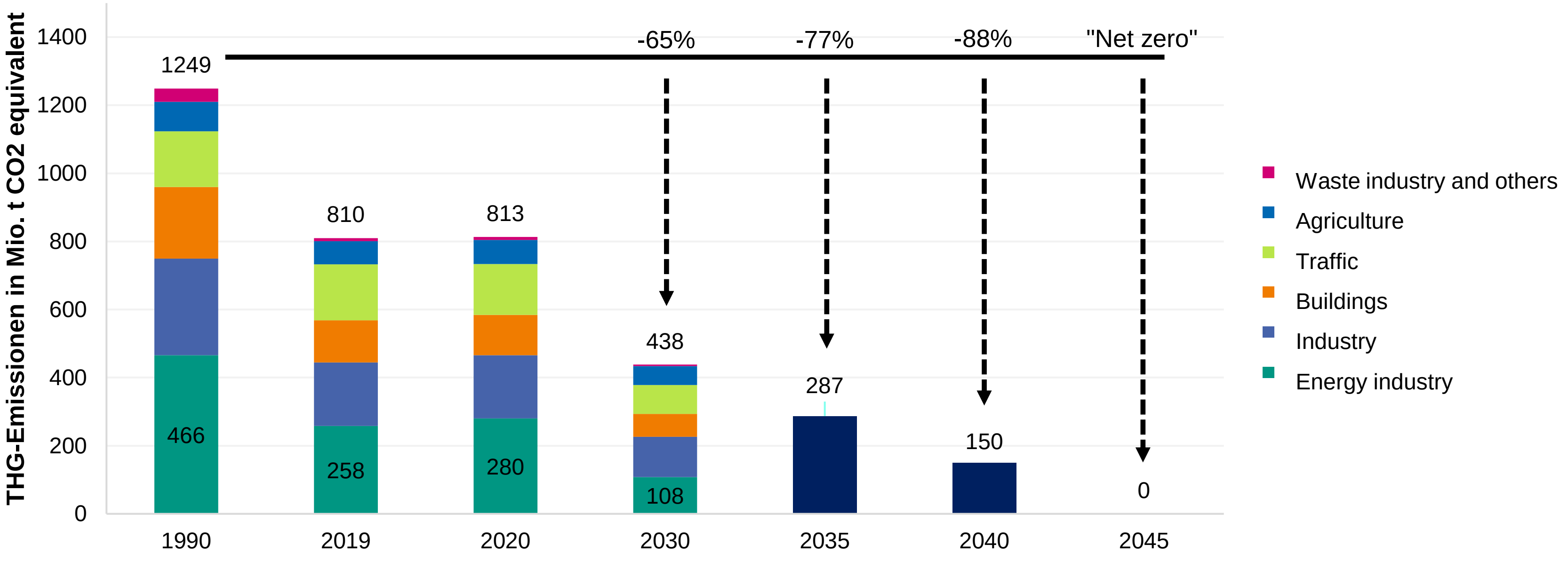
Literature

No.	Source
[10]	Große et al. (2021): Carbon Footprint of Natural Gas 1.1. Final report. Published by Zukunft Gas GmbH
[11]	Russ, Manfred (2017): Greenhouse gas profiles for natural gas transports. Comparison of additional natural gas imports to Europe through the Nord Stream 2 Pipeline and LNG import alternatives. Final report. (Treibhausgas-Profile für Erdgas-Transporte. Vergleich zusätzlicher Erd-gas-Importe nach Europa durch die Nord Stream 2 Pipeline und LNG-Importalternativen. Abschlussbericht) Published by thinkstep AG
[12]	Wachsmuth et al. (2021): How climate-friendly is LNG? Brief study to evaluate the upstream chain emissions arising from the use of liquefied natural gas (LNG).(Wie klimafreundlich ist LNG? Kurzstudie zur Bewertung der Vorkettenemissionen bei Nutzung von verflüssigtem Erdgas (LNG)) Published by German Federal Environmental Agency (UBA)
[13]	Prussi et al. (2020): JEC Well-to-tank report v5. Well-to-wheels analysis of future automotive fuels and powertrains in the European context.
[14]	Heneka et al. (2018): Comparative evaluation of PtX processes for renewable fuel supply. Final report PtX study (Vergleichende Bewertung von PtX-Prozessen zur Bereitstellung von Kraftstoffen aus erneuerbaren Quellen. Abschlussbericht PtX-Studie)
[15]	E4tech and Ludwig-Bölkow-Systemtechnik GmbH, "Options for a UK low carbon hydrogen standard: Final report", London, May 2021. [Online]. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1024173/Options_for_a_UK_low_carbon_hydrogen_standard_report.pdf. Accessed on: 1 April 2022.
[16]	German Energy Agency und World Energy Council - Germany, publisher, "Global Harmonisation of Hydrogen Certification: Overview of global regulations and standards for renewable hydrogen", Berlin, January 2022. [Online]. Available at: https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2022/REPORT_Global_Harmonisation_of_Hydrogen_Certification.pdf. Accessed on: 2 May 2022.
[17]	Leiblein et al. (2020): Roadmap Gas 2050 Deliverable D1.1. Evaluation of alternative methods for the supply of green and blue H2. (Bewertung von alternativen Verfahren zur Bereitstellung von grünem und blauem H2.) DVGW funding code G 201824. Published by German Technical and Scientific Association for Gas and Water (DVGW). DVGW research centre at the Engler-Bunte-Institute; DBI Gas- und Umwelttechnik GmbH; Gas- und Wärme-Institut Essen e.V.
[18]	Anvik, Harald (2019): Report - Full chain CO2 footprint.

DVGW ebi

Carbon footprint – German electricity mix
Source: Federal Climate Protection Act [2]

Permissible annual emission quantities according to Federal Climate Protection Act (KSG) [2]



by Maximilian Heneka and Friedemann Mörs

DVGW Research Center at Engler-Bunte-Institut of Karlsruhe Institute of Technology (KIT)

Translated by Doris Mann

DVGW