TECHNO-ECONOMIC AND ENVIRONMENTAL ASSESSMENT OF GREEN HYDROGEN PRODUCTION BY ALKALINE AND PROTON EXCHANGE MEMBRANE ELECTROLYSIS – A REVIEW OF ASSUMPTIONS, HARMONIZED IMPACTS AND PROSPECTIVE ASPECTS

Phd and Postdoc Workshop "Prospective Assessment of Energy Technologies and Systems"

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Institute of Networked Energy Systems, Oldenburg

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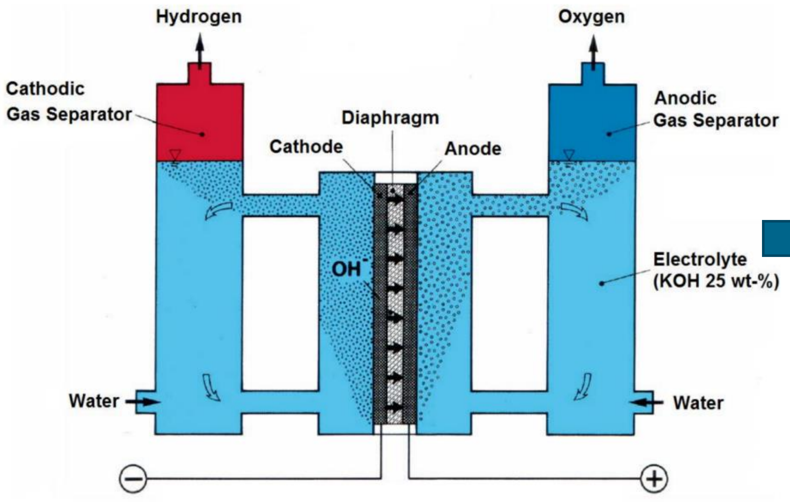
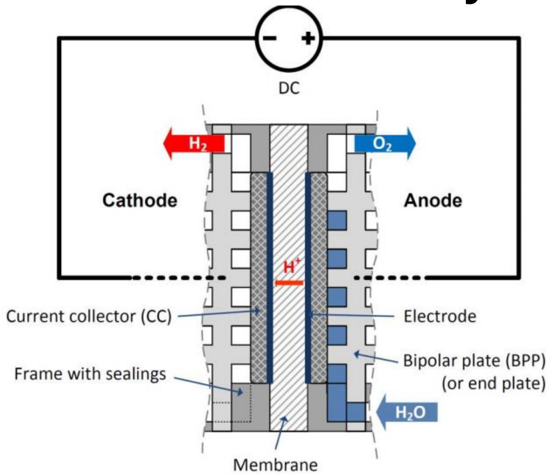
Agenda

- Introduction
- Environment assessment of Alkaline and Proton Exchange Membrane
  - Methodology
  - Static LCA
  - Prospective LCA
- Techno-economic analysis of electrolysis
  - Methodology
  - Data Sources for Techno-economic Assumptions for Water Electrolysis
- Conclusions

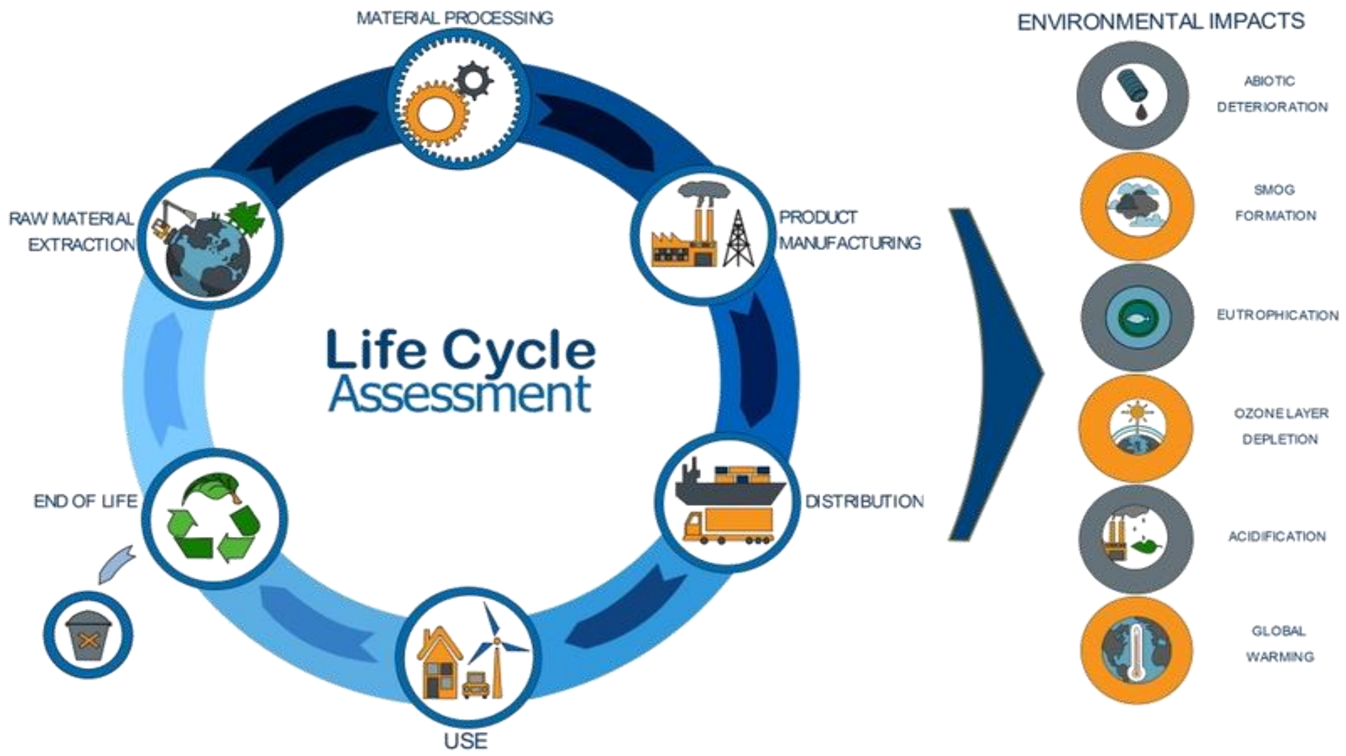
Hydrogen Production: Alkaline(AEL) & Proton Exchange Membrane Electrolysis (PEMEL)



Alkaline Electrolysis (AEL)



Proton exchange membrane Electrolysis (PEMEL)



Source: Detailed analyses of the system comparison of storable energy carriers from renewable: Annex (umweltbundesamt.de)

Environmental Assessment of Electrolysis Technologies

Assumed Hydrogen Supply Chain (Cradle to Gate)

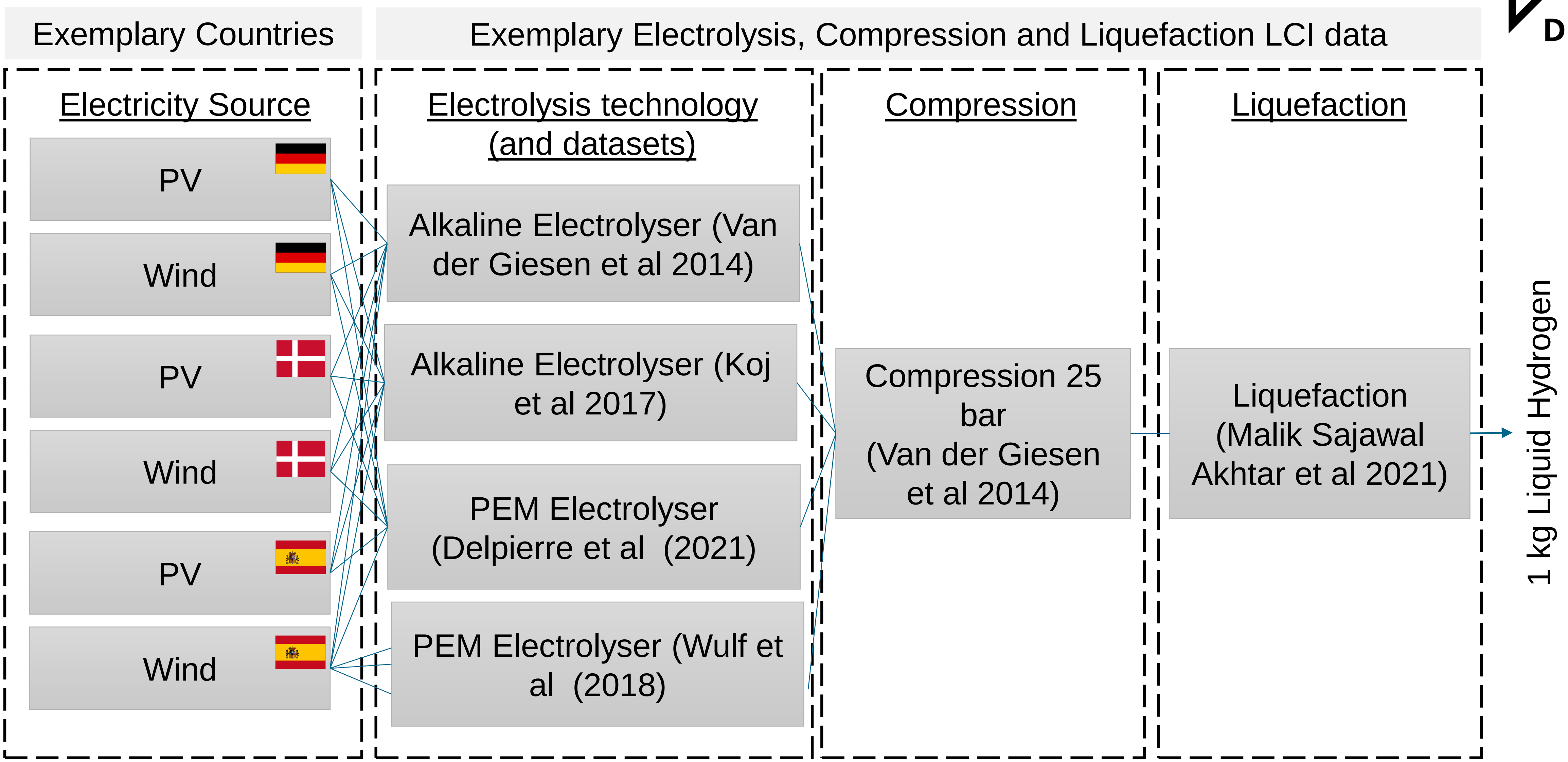


Figure 1: Exemplary hydrogen supply chain for selected countries and LCI datasets. Own plot

Exemplary Results:

Hydrogen Production (Electrolysis) + Compression (25bar) + Liquefaction

LCA Results: Comparison AEL and PEMEL

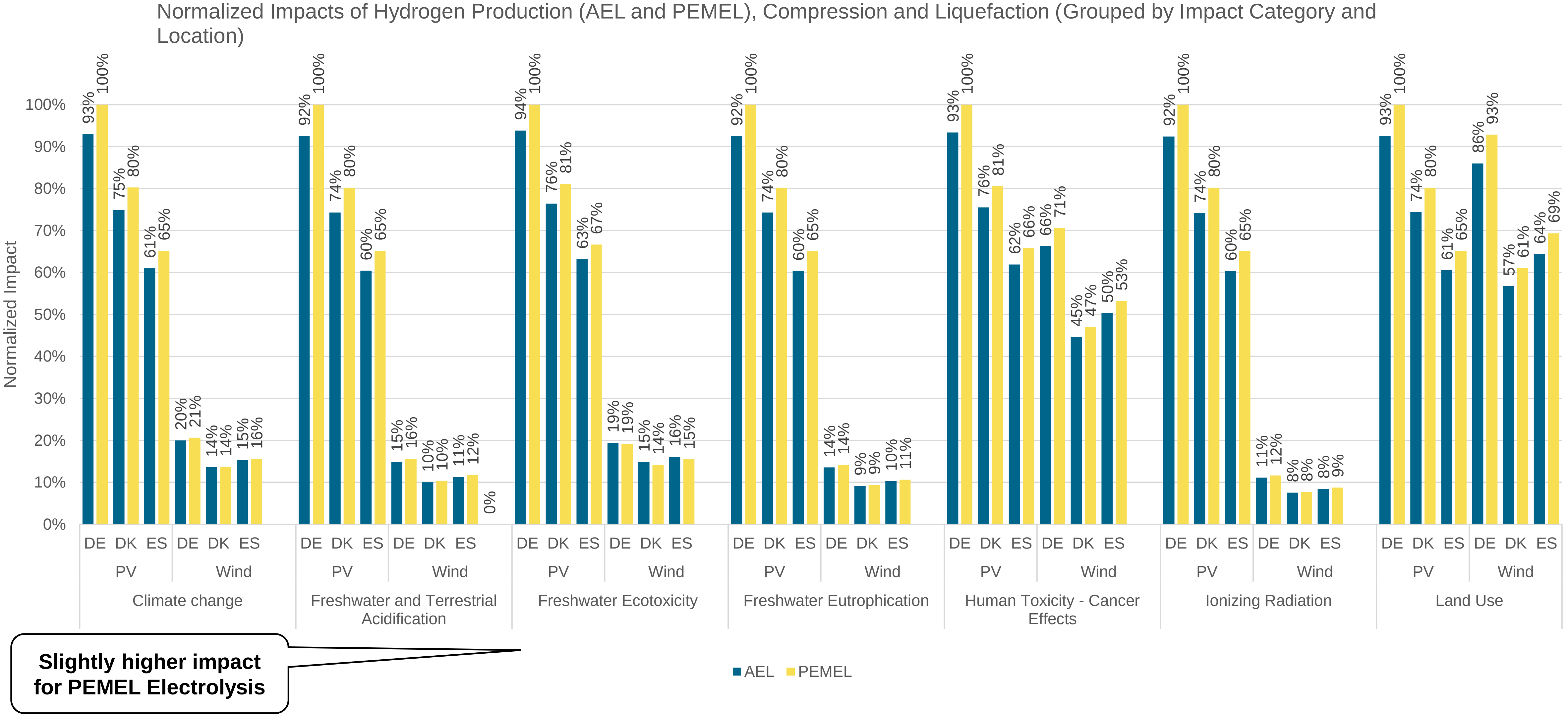


Figure 2: Comparison of the Impacts of production the production (AEL + PEMEL) compression and liquefaction of hydrogen for different electricity sources, locations. Source: own plot with LCI Data taken from (Koj et al 2017), (Delpierre et al 2021)

Prospective Exemplary Results:

Hydrogen Production (Electrolysis) + Compression (25bar) + Liquefaction

Methodology overview for Prospective Life Cycle assessment (pLCA)

- **Methodology:**
  - Integrated Assessment Models (IAMs) used for scenario analysis.
  - Prospective Life Cycle Assessment (LCA) conducted for alkaline and PEM electrolysis with compression and liquefaction.
- **Software**:
  - Open source software Premise and Activity Browser
- **IMAGE SSP2 Scenarios (2025, 2030 and 2035):**
  - Base
  - RCP19
  - RCP 26

Prospective assumed Hydrogen Supply Chain (Cradle to Gate)

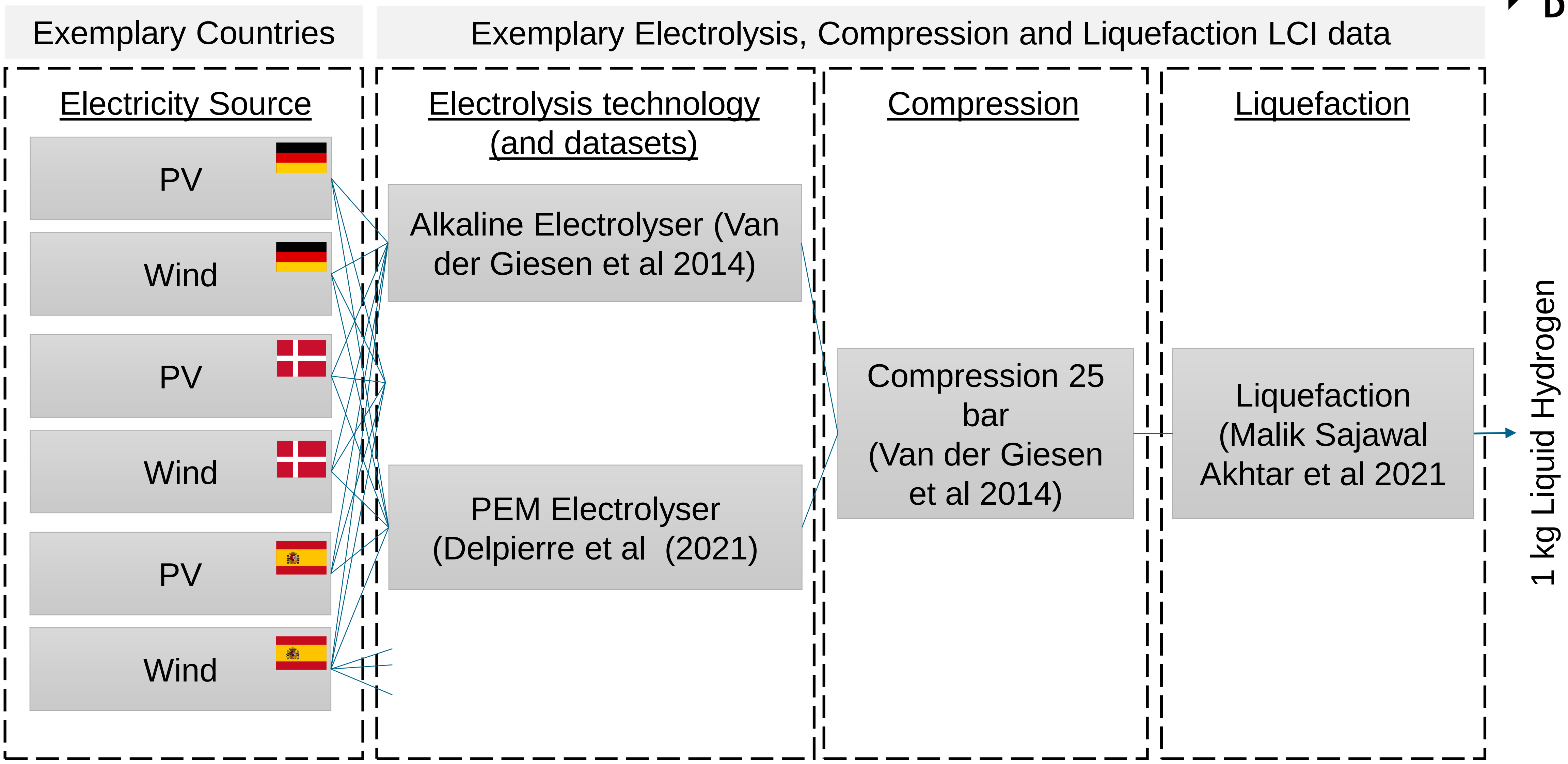


Figure 3: Exemplary hydrogen supply chain for selected countries and LCI datasets. Own plot

pLca Results: Prospective assessment of Proton exchange membrane (PEMEL)

Germany | Denmark | Spain

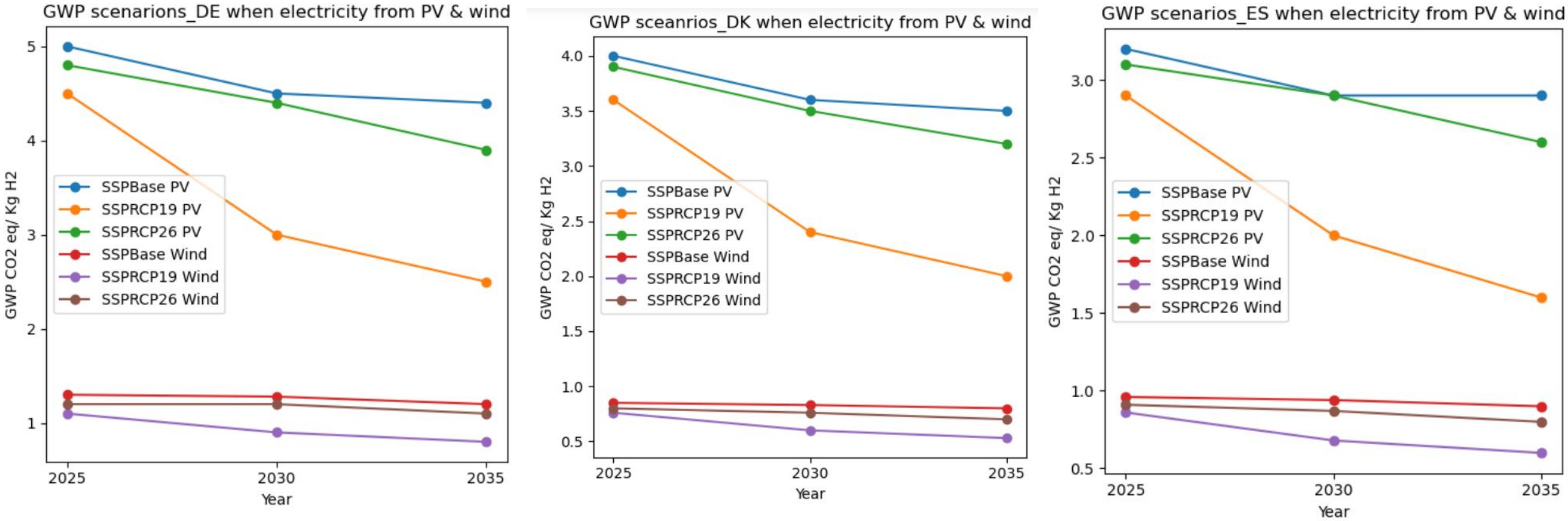


Figure 4: Results of global warming potential (CO_2 eq/Kg H_2) (PEMEL) production, compression and liquefaction of hydrogen for different electricity sources, locations and using LCI sources for electrolysis. Source: own plot with LCI Data taken from (Delpierre et al 2021).

pLca Results: Prospective assessment of Alkaline electrolysis (AEL)

Germany

Denmark

Spain

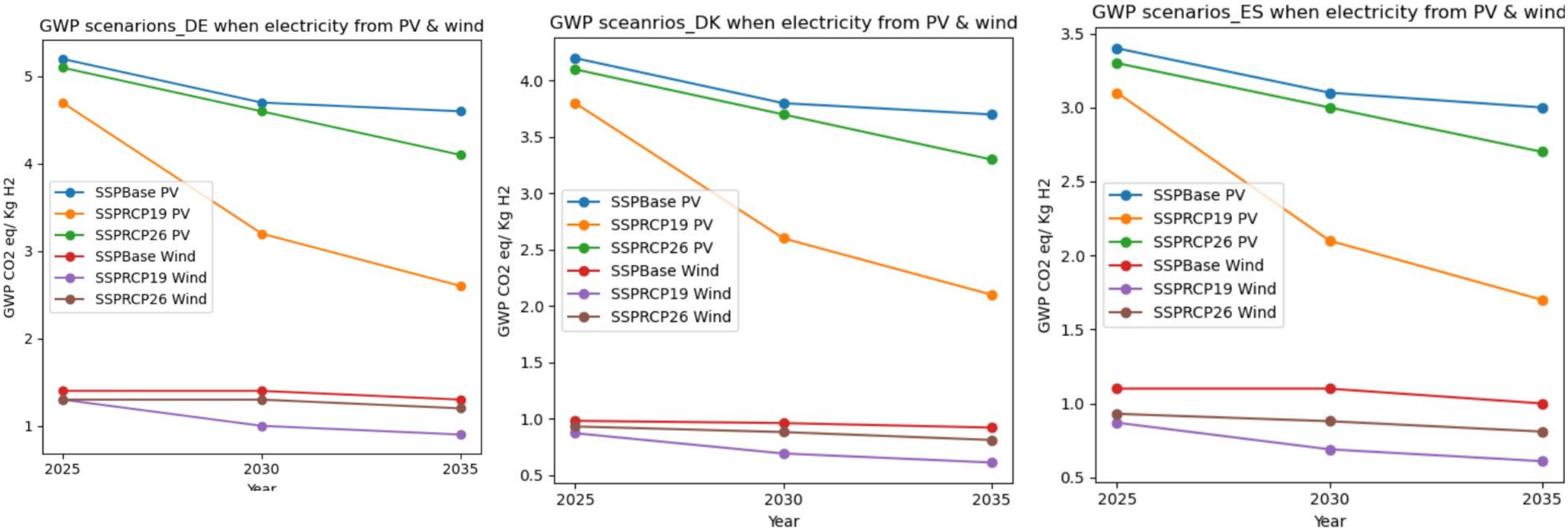


Figure 5 : Results of global warming potential (CO_2 eq/Kg H_2) (PEMEL) production, compression and liquefaction of hydrogen for different electricity sources, locations and using LCI sources for electrolysis. Source: own plot with LCI Data taken from (Van der giesen et al 2014).

Techno-economic Analysis of Hydrogen Production A Review of Methods and Data Sources

Methodology Overview

- By far, the most assessed indicator is the levelized cost of hydrogen production
- There are variations in the calculation of the indicator including (or excluding) different aspects

Authors	Calculation	Comment
Smolinka et al (2018) – IndWEDE Studie	$LCOH = \frac{LHV}{\eta_{ges}}\left(\left(\frac{i(1+i/100)^n}{(1+i/100)^n-1}+M/O\right)\frac{CAPEX}{FLH}+P_E\right)$	Simplified approach based on annuity of the CAPEX
Kuckshinrichs, Ketelaer and Koj (2017)	$LCOH = \frac{\sum_{t=0}^{t=n}\frac{PCI_t}{(1+i)^t}+\sum_{t=1}^{t=n}\frac{(A_t+E_t+EC_t+LP_t)}{(1+i)^t}-TR\times\sum_{t=1}^{t=n}\frac{\left(A_t+E_t+EC_t+Dep_{t+Int_t}\right)}{(1+i)^t}+}{\sum_{t=0}^{t=n}\frac{M_t}{(1+i)^t}+}$	Separation of equity and debt, inclusion of taxing effects per country
Koj et al - under Review (2024)	$LCOH = \frac{I_0+\sum_{t=1}^{t=n}\frac{(WC_t+EC_t+HC_t+RC_t+AC_t+OFC_t)}{(1+i)^t}}{\sum_{t=1}^{t=n}\frac{MHydrogen_t}{(1+i)^t}}$	Simplification of the previous equation for t=0 (I_0). Fixed and variable OPEX expanded

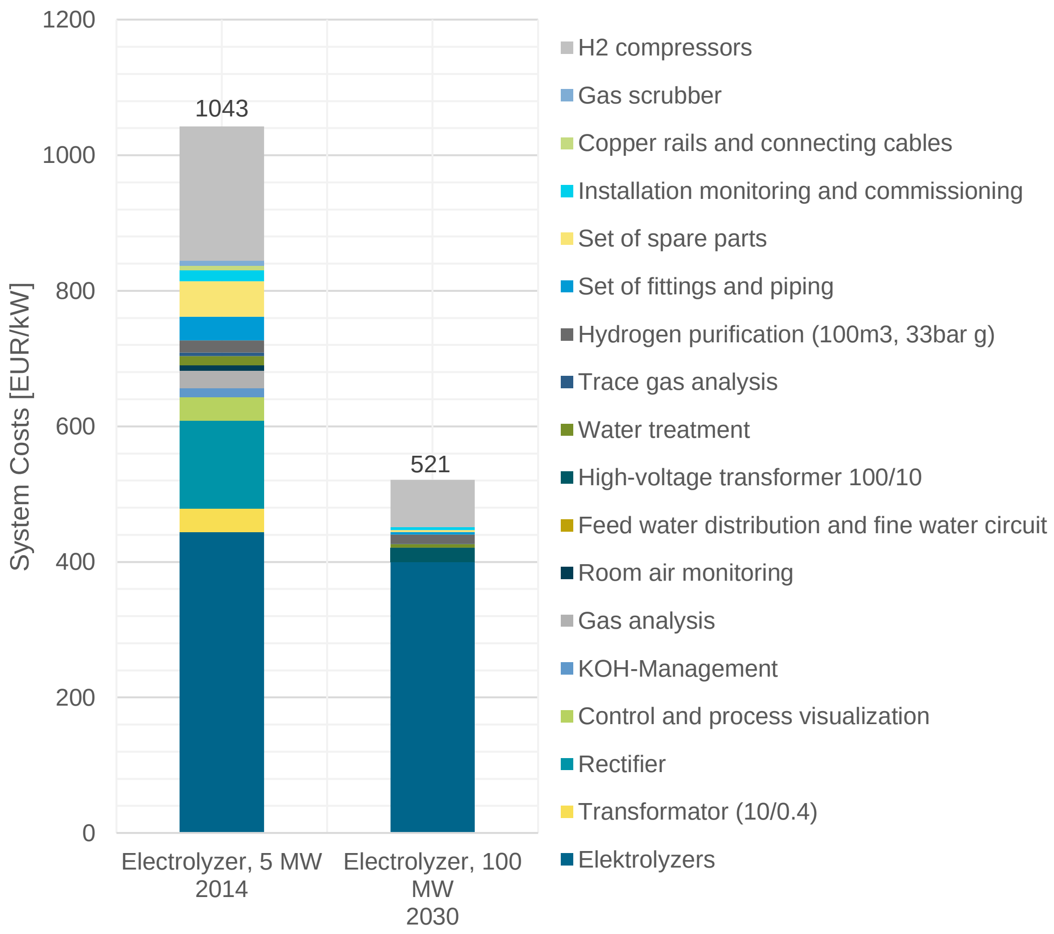
Data Sources for Techno-economic Assumptions for Water Electrolysis

- Different data sources persuit different objectives

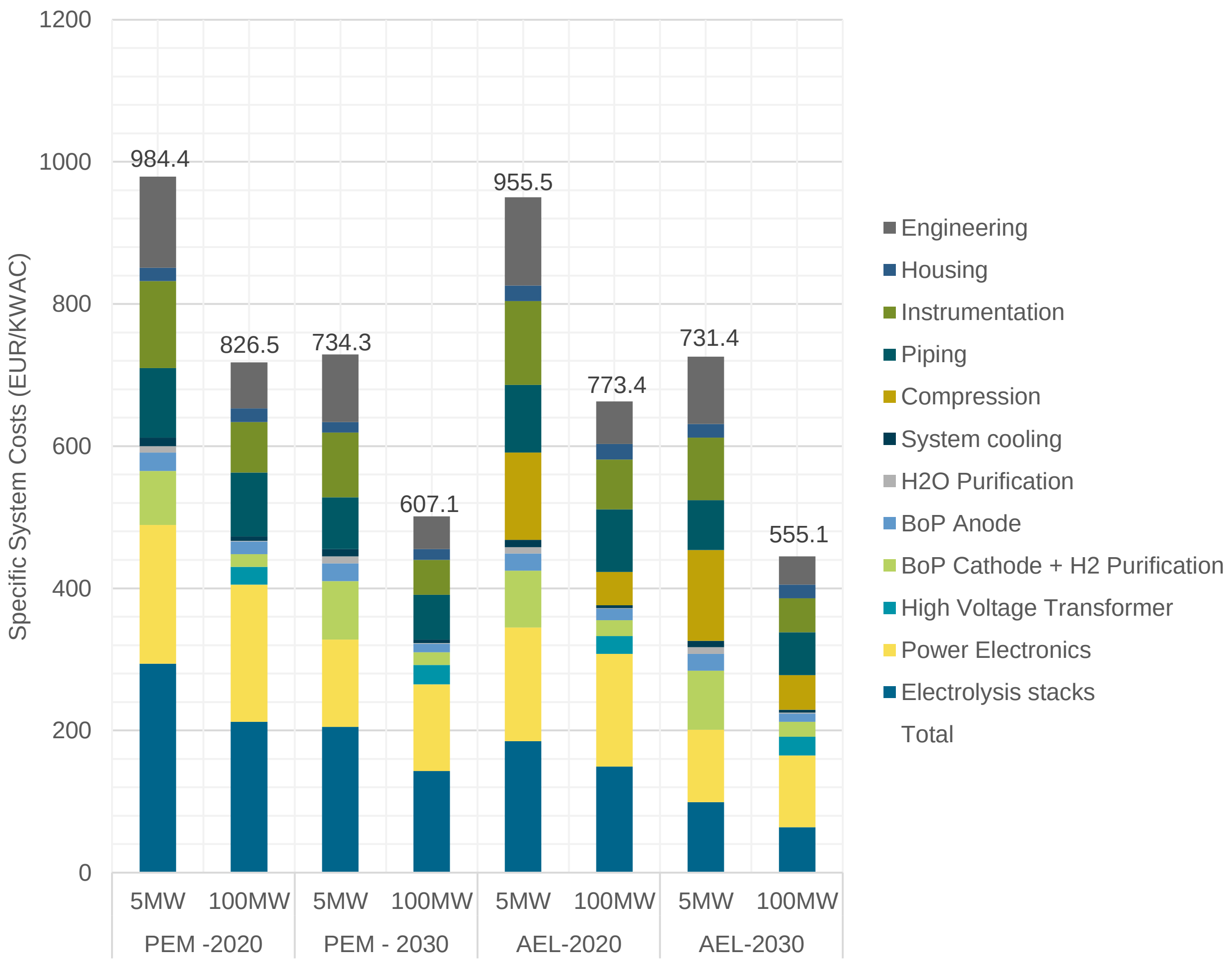
Type of Document	Institutions / Authors	Research Questions/Purpose
Techno-economic Assessments of Electrolysis Technologies	PLAN-DELIKAD (2014), Holst et al(2021) - Fraunhofer ISE / Mayvas et al (2018), Colella et al (2014) – NREL / Bristowe and Smallbone (2021)	How much does it cost to produce electrolyzers at certain production level?
Industry Datasheets	Elogen, Cummins, iGas, ITM Power, McPhy, NEL, Sunfire, ThyssenKrupp Nucera	Indicative technical features of the devices. Prices/Costs are seldom released by manufacturers
Research agenda and targets from national/international institutions	CHJU, US DOE, IRENA, IEA	What are the goals for future research? Implications for the energy system?
Techno-economic Assessments of Hydrogen Production	To name a few… Bhandari and Shah (2021) / Yates er al (2020) / Glenk and Reichelstein (2019) / Kuckshinrichs, Ketaler and Koj (2017) / Bertuccioli et al (2014)	What is the production cost of hydrogen under determined inputs (representing a particular scenario)?
Learning curves	i.e. Böhm et al. (2018)	What’s the temporal cost evolution based on the cumulative production of the devices?

Techno-economic Assessments of Electrolysis Technologies

Capital Costs of AEL Electrolysis Systems
Results of the Project PLAN-DELYKAD

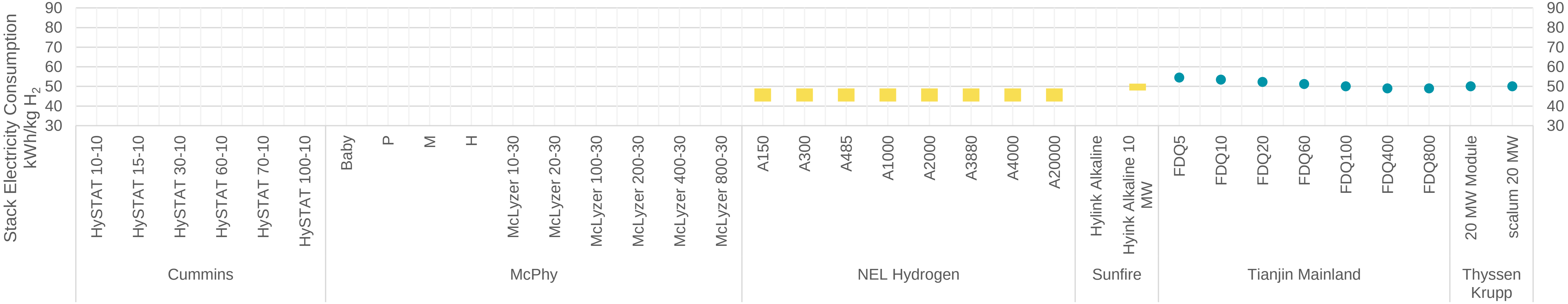


Capital Costs of AEL and PEMEL Electrolysis Systems
Holst et al. (2021)

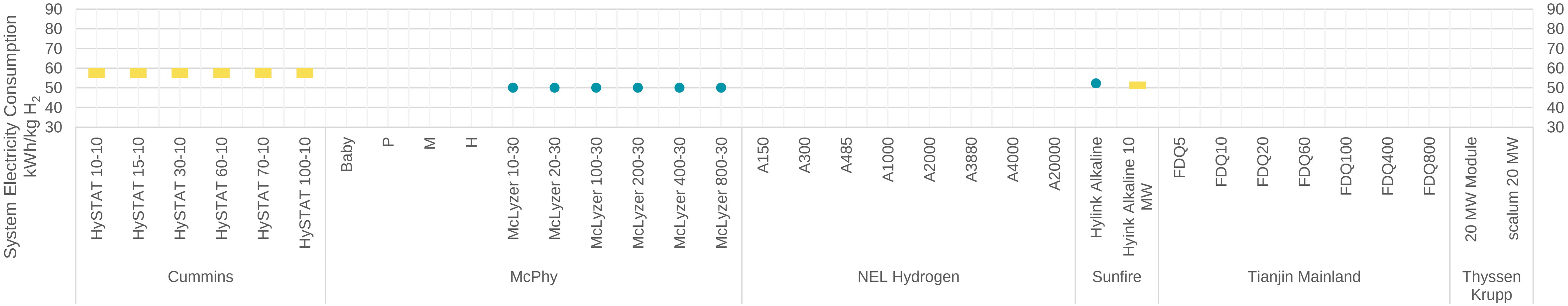


Industry Datasheets - Alkaline Electrolysis (AEL)

Reported Electricity Consumption at Stack Level



Reported Electricity Consumption at System Level



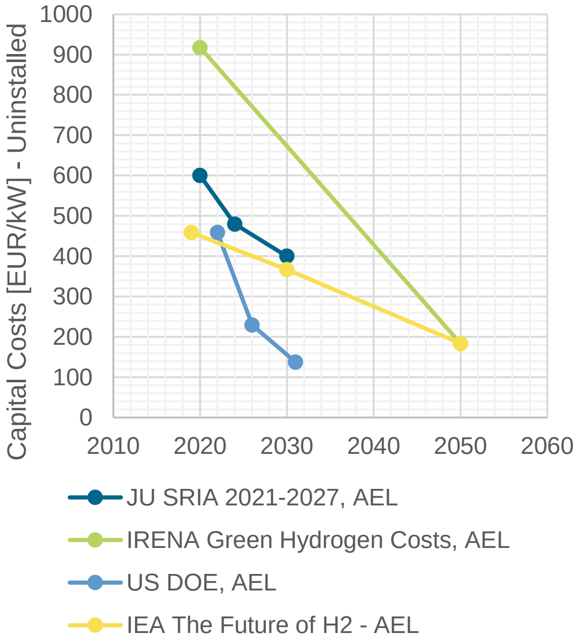
Assumption for harmonization: 1 kg H_2 = 11.13 Nm^3 H_2

Research Agenda and Targets from National/International Institutions

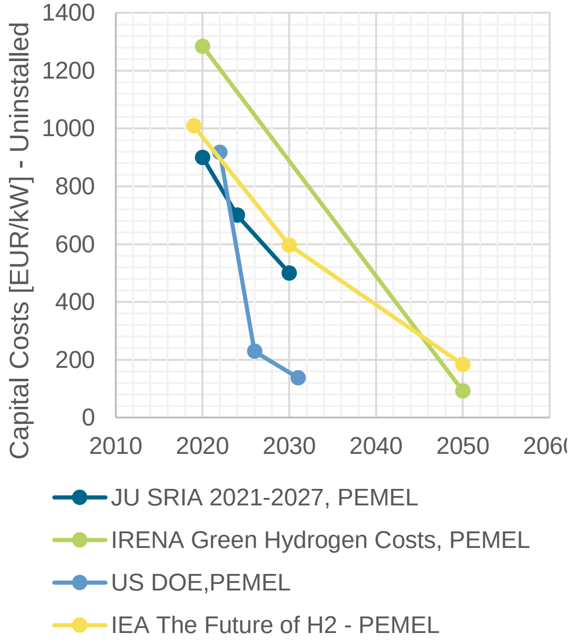
DLR

Capital Costs of Electrolysis Systems

AEL

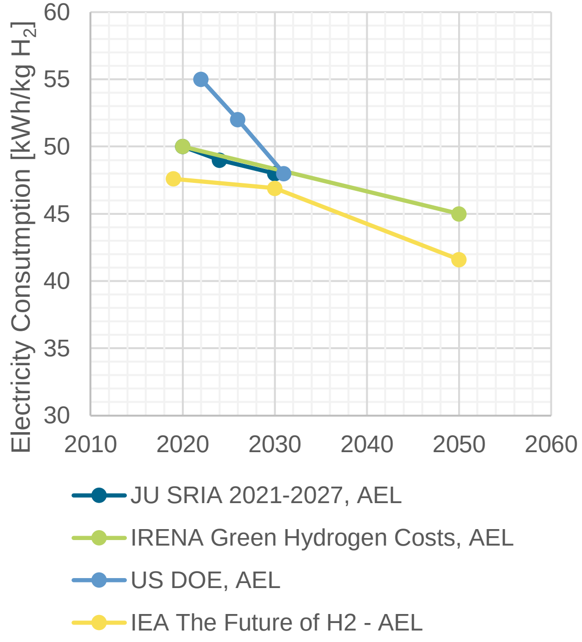


PEMEL

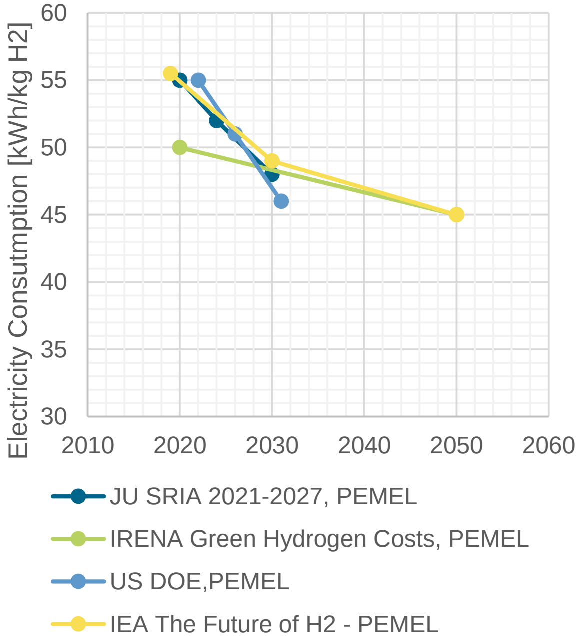


Electricity Consumption at System Level

AEL



PEMEL



*Most optimistic values shown in plot for IRENA and IEA – Original values in ranges

Techno-economic Assessments of Hydrogen Production

Authors and year	Technology	Electricity input (kWh/kg)	System Costs [EUR/kW]	WACC [%]	Electricity Source
Bhandari and Shah (2021)	AEMEL	54,5	800	4%	PV
	PEMEL	69,0	1000		
Yates et al (2020)	-	50-58	625 - 813	5,75%	PV
Glenk and Reichelstein (2019)	-	52,6	2287 (DE) 1843 (US)	4% (DE) 6% (US)	Wind and electricity
Kuckshinrichs, Ketaler and Koj (2017)	AEMEL	53,9	1070	RoE: 7% IoD: 4.5% WACC: 4%	Grid (Austria, Germany, Spain)
Bertuccioli et al (2014)	AEMEL	50-78	1000-1200	-	Germany, Spain, UK, Poland and Finland
	PEMEL	50-83	1856-2320		

Conclusion

Environmental Assessment:

- The main hotspot in AEL and PEMEL is mainly from electricity source.
- Higher GWP if PV used as electricity source because the electricity sourced from PV has a higher GWP footprint.
- Within the results of PV, impacts for Spain are lower due to the higher solar resource in that selected location.
- In Prospective assessment of AEL and PEMEL, Electricity source of Image RCP19 played a key role in **significant reduction** of Global warming potential.

Techno-economic Assessment:

- The main indicator – levelized cost of hydrogen – can also include or exclude more or less parameters depending on the depth and objective of the study.
- The analysed sources offer different levels of detail and studied cases.
- Comparability can be an issue because each study might include or exclude different aspects.
- Although not analyzed here, besides the equipment techno-economic assumptions, the electricity price and the case in which the electrolyzer is considered can change completely the results of the assessment.
- Validation is often an issue, but transparency could be improved in the assessments.

References

Environmental Assessment

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- Wulf, C., & Kaltschmitt, M. (2018). Hydrogen supply chains for mobility—environmental and economic assessment. Sustainability, 10(6), 1699.

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Techno-.economic Assessment

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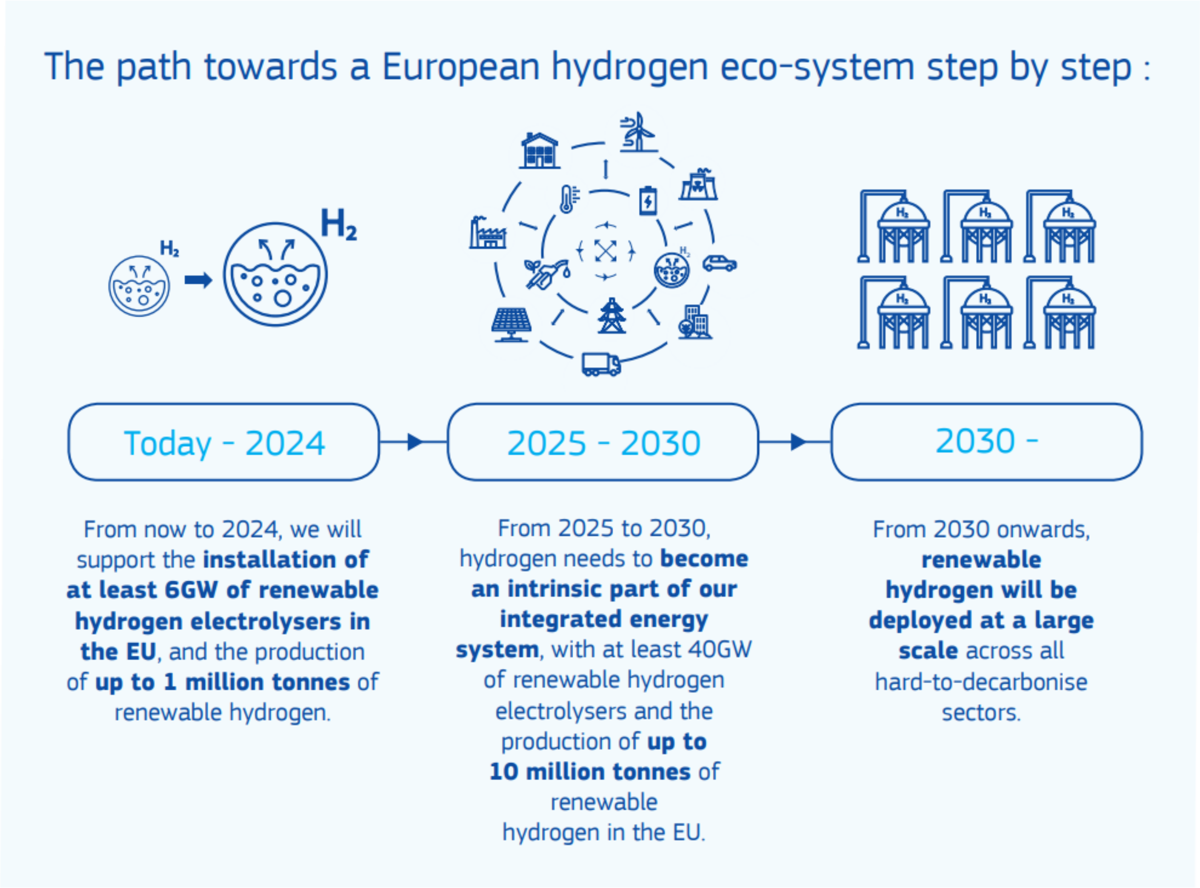
- DOE Technical Targets for Liquid Alkaline Electrolysis. Available at: https://www.energy.gov/eere/fuelcells/technical-targets-liquid-alkaline-electrolysis
- DOE Technical Targets for Proton Exchange Membrane Electrolysis: https://www.energy.gov/eere/fuelcells/technical-targets-proton-exchange-membrane-electrolysis

Thank you for your attention!

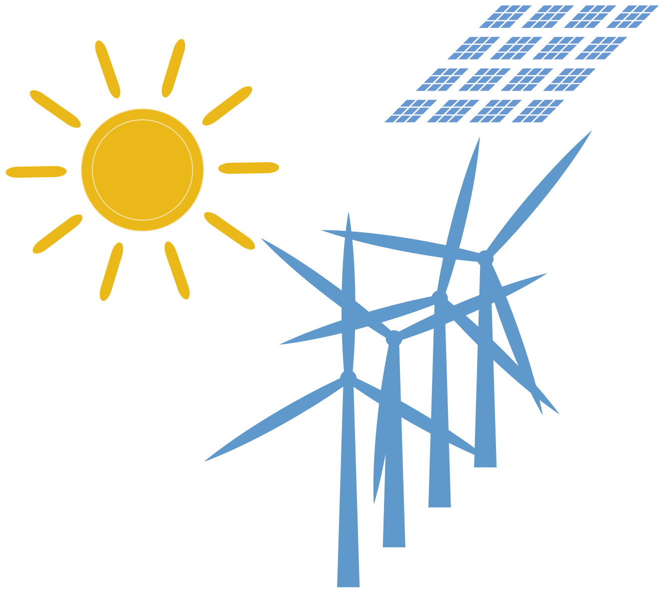
Annex

Introduction and Motivation:
Hydrogen Strategy for Climate Neutral Europe



Source:EU_Hydrogen_Strategy.pdf.pdf (europa.eu)

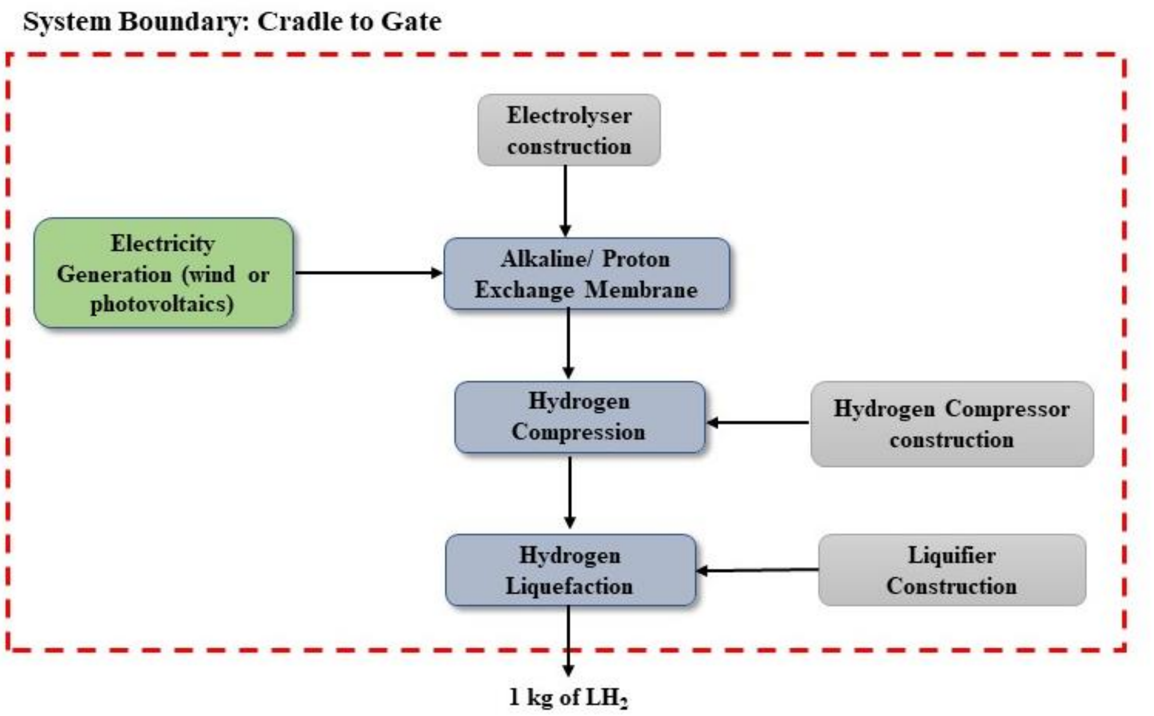
Source:Hydrogen_Factsheet_EN.pdf.pdf

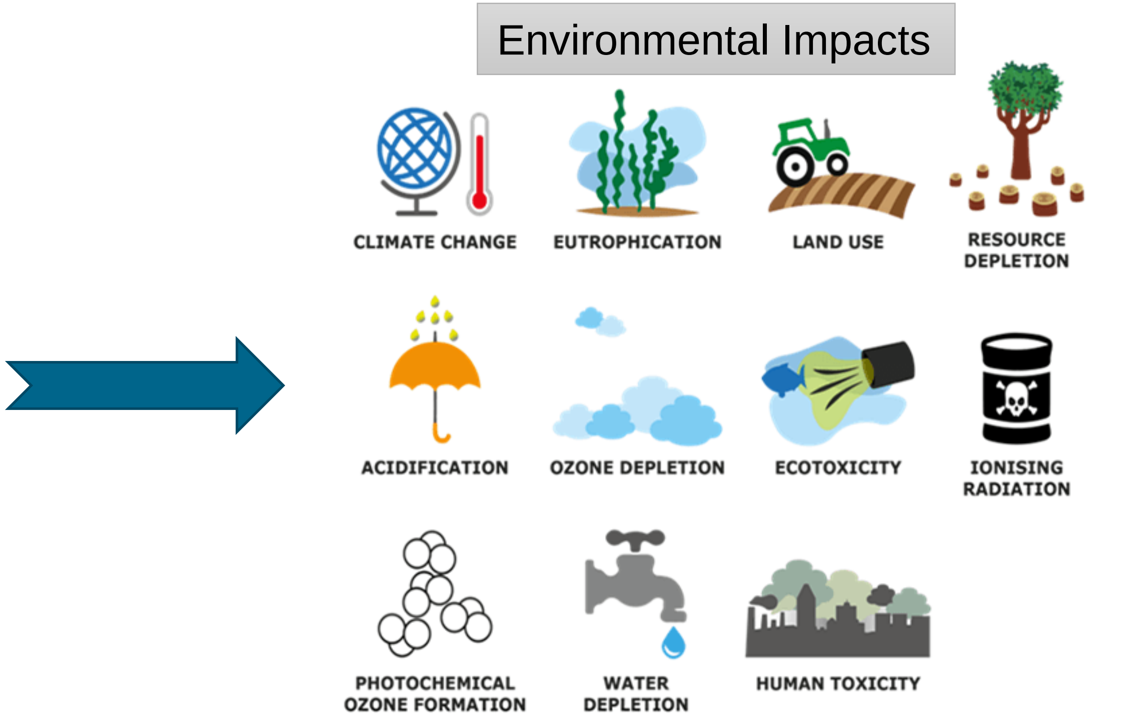


Source:DLR

Methodology Overview

- **Goal**: Life cycle assessment of Alkaline (AEL) and Proton exchange membrane (PEMEL) electrolysis using different datasets
- **Functional unit** : 1 kg of LH_2 (LHV)
- **Impact assessment method** : Environmental Footprint 3.0
- **Software and Database**: Activity Browser & Ecoinvent Database 3.9.1
- **Location :** Germany, Denmark and Spain





https://rmis.jrc.ec.europa.eu/?page=environmental-impacts-along-the-supply-chain-3dfccf

Figure 1: Schematic overview of hydrogen supply chain used in this study (Cradle to Gate). Source: Own plot

LCA Results: Comparison of Alkaline Electrolysis (AEL) Datasets, Locations and Electricity Sources

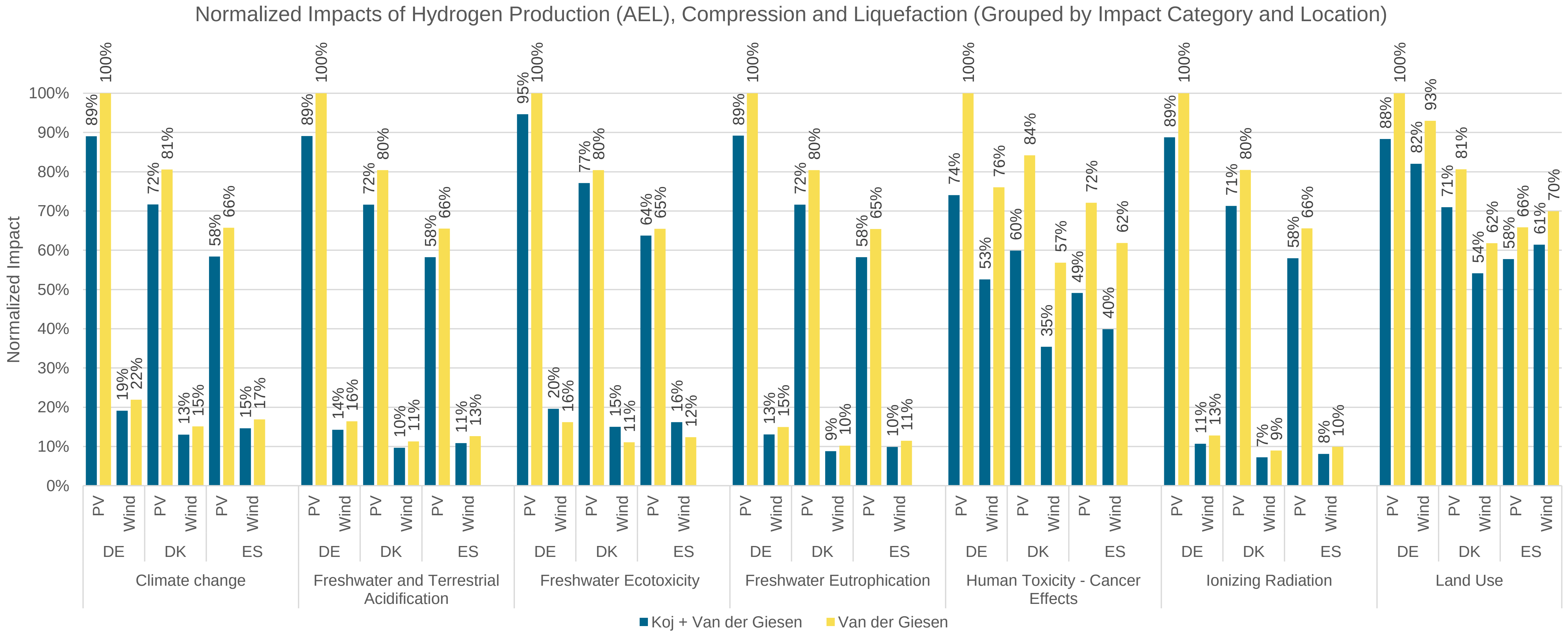


Figure 2: Comparison of the impacts of production the production (AEL), compression and liquefaction of hydrogen for different electricity sources, locations and using two different LCI sources for electrolysis. Source: own plot with LCI Data taken from (van der Giesen et al 2014) and (Koj et al 2017)

LCA Results: Comparison of Proton exchange membrane(PEMEL) Datasets, Locations and Electricity Sources

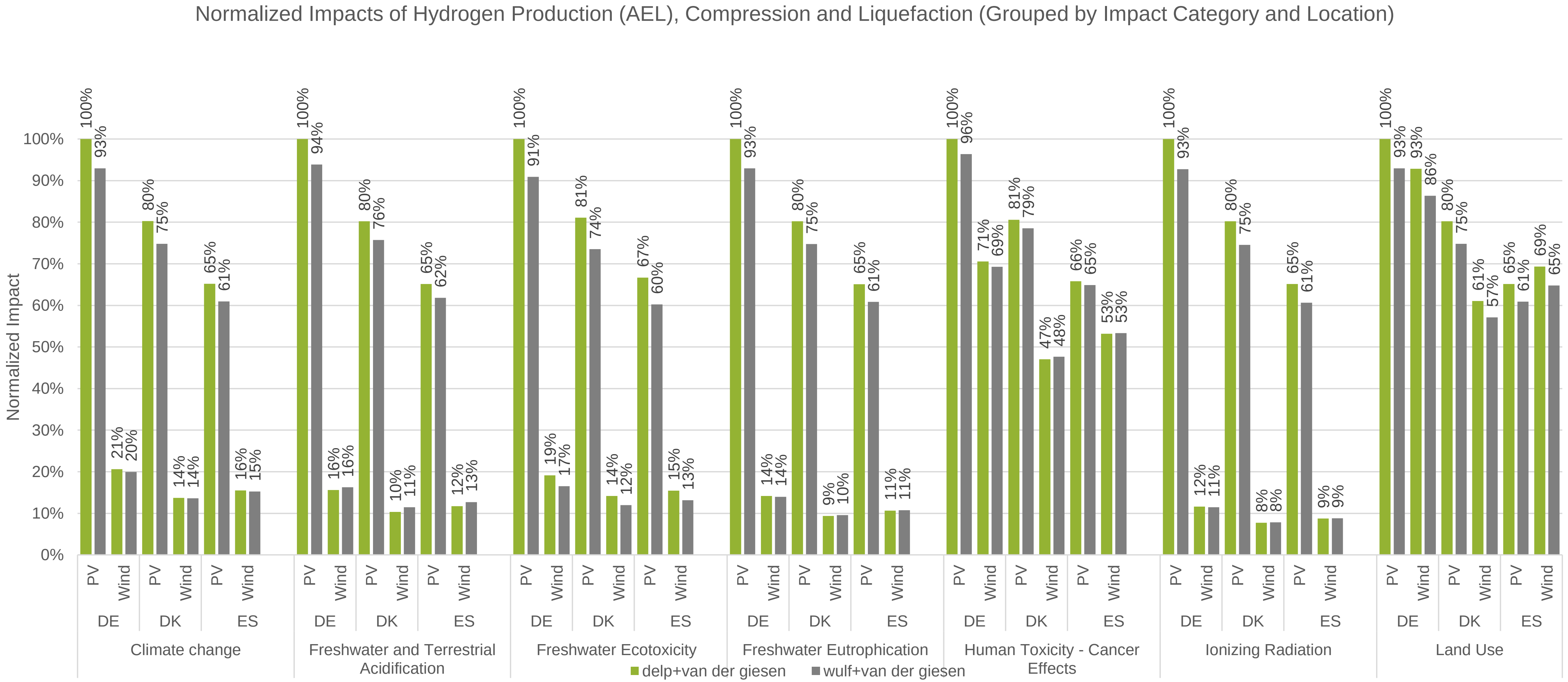


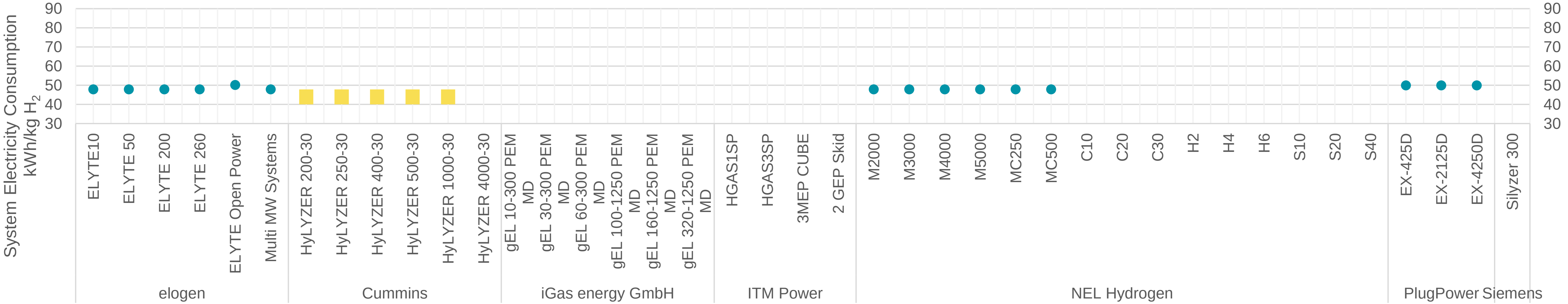
Figure 3: Comparison of the impacts of production the production (PEMEL), compression and liquefaction of hydrogen for different electricity sources, locations and using two different LCI sources for electrolysis. Source: own plot with LCI Data taken from (Delpierre et al 2021) and Wulf et al 2017)

Assumptions

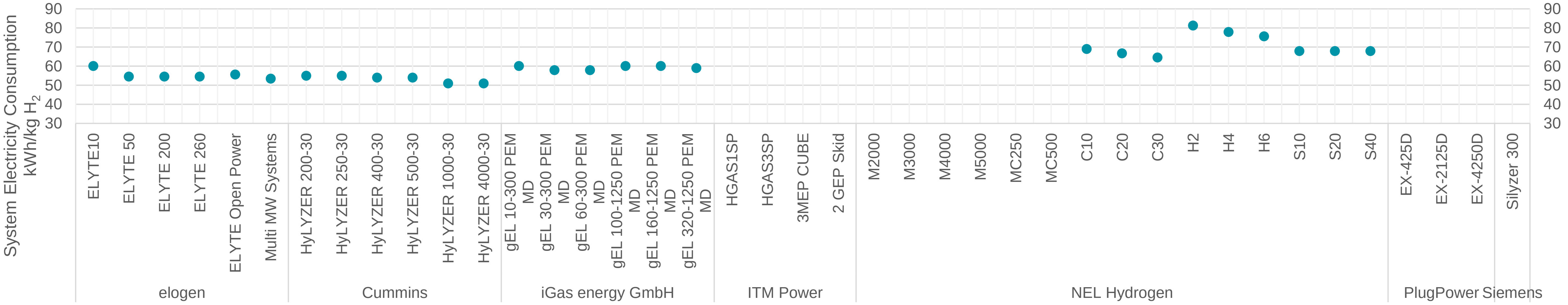
	Alkaline (Van der Giesen)	Alkaline(Koj)	PEM (DELP)	PEM (Wulf)
Efficiency (%)	58	66	60	60
Functional unit	1 MJ of fuel	1 kg of hydrogen	1 kg of hydrogen	1 kg of hydrogen
Size	-	6 MW	1 GW	48 kg/h
Full load of hours	8000	8300	-	4000
Lifetime (years) stack	10	10	30	8
Data age	2014	2017	2021	2018
System boundary	Cradle to gate	Cradle to gate	Cradle to gate	Cradle to gate
software	Cmlca version 5.2	Gabi	openlca	Umberto
Impact assessment method	-	ILCD	ILCD	CML
database	Ecoinvent 2.2	Ecoinvent 3.1	Ecoinvent 3.4	Ecoinvent 3.1

Industry Datasheets - Proton Exchange Membrane Electrolysis (PEMEL)

Reported Electricity Consumption at Stack Level



Reported Electricity Consumption at System Level



Assumption for harmonization: 1 kg H_2 = 11.13 Nm^3 H_2