Chair of Renewable and Sustainable Energy Systems
TUM School of Engineering and Design
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Optimization and sustainability assessment of energy systems

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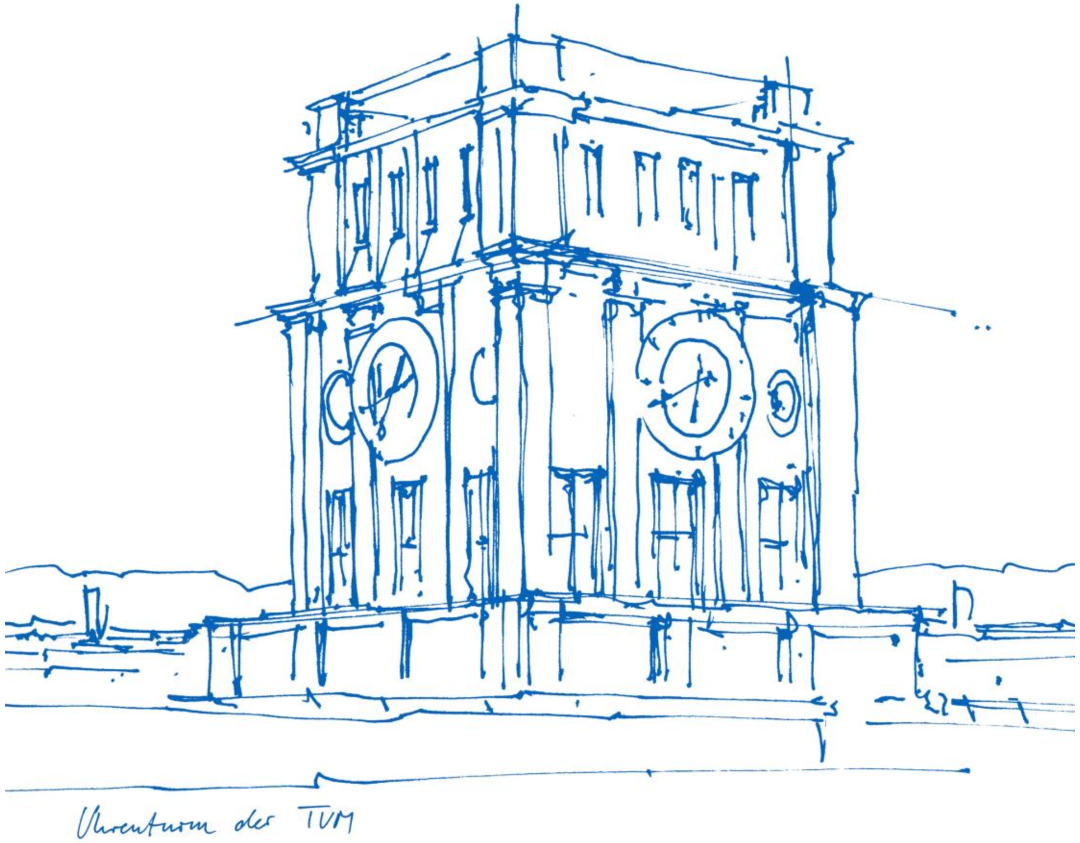
Chair of Renewable and Sustainable Energy Systems

Montevideo, 20 August 2024



Agenda

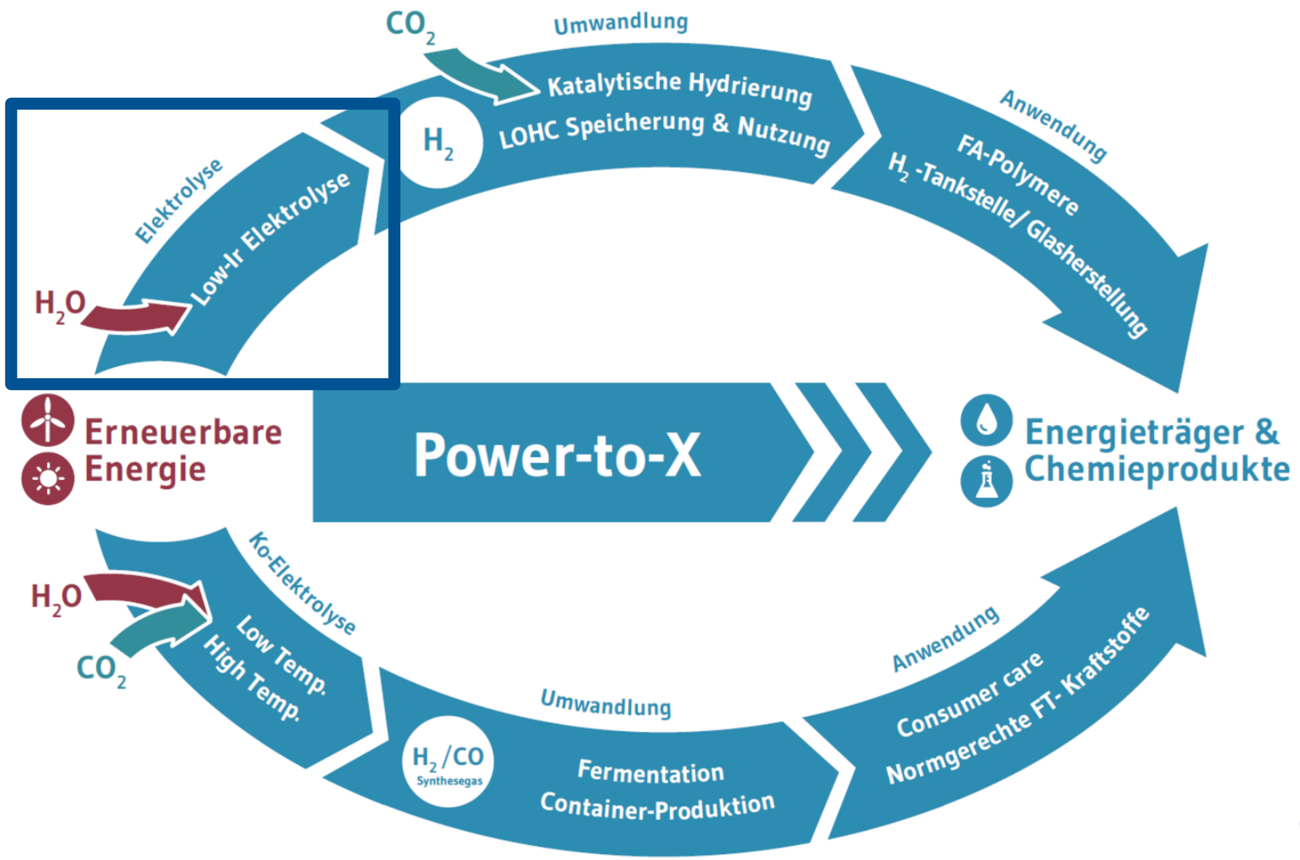
Agenda

Kopernikus Project. P2X

Phase II

2019- 2022

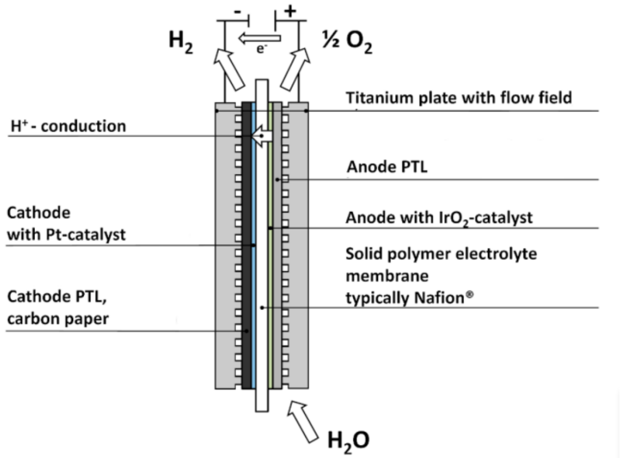
→ best pathways



Source: 4. Roadmap des Kopernikus-Projektes P2X Phase II

Detailing of the PEM-WE model

- PEM Electrolyzer Plant
  - H2 Purification
  - Stack
    - Anode
    - Cathode
    - Membrane
    - Carbon PTL
    - Titanium PTL
    - Bipolar Plates
    - Other Components
  - Balance of Plant



Source: Bareiß et al 2019. Applied Energy

Detailing of the PEM-WE model

Parametrized model

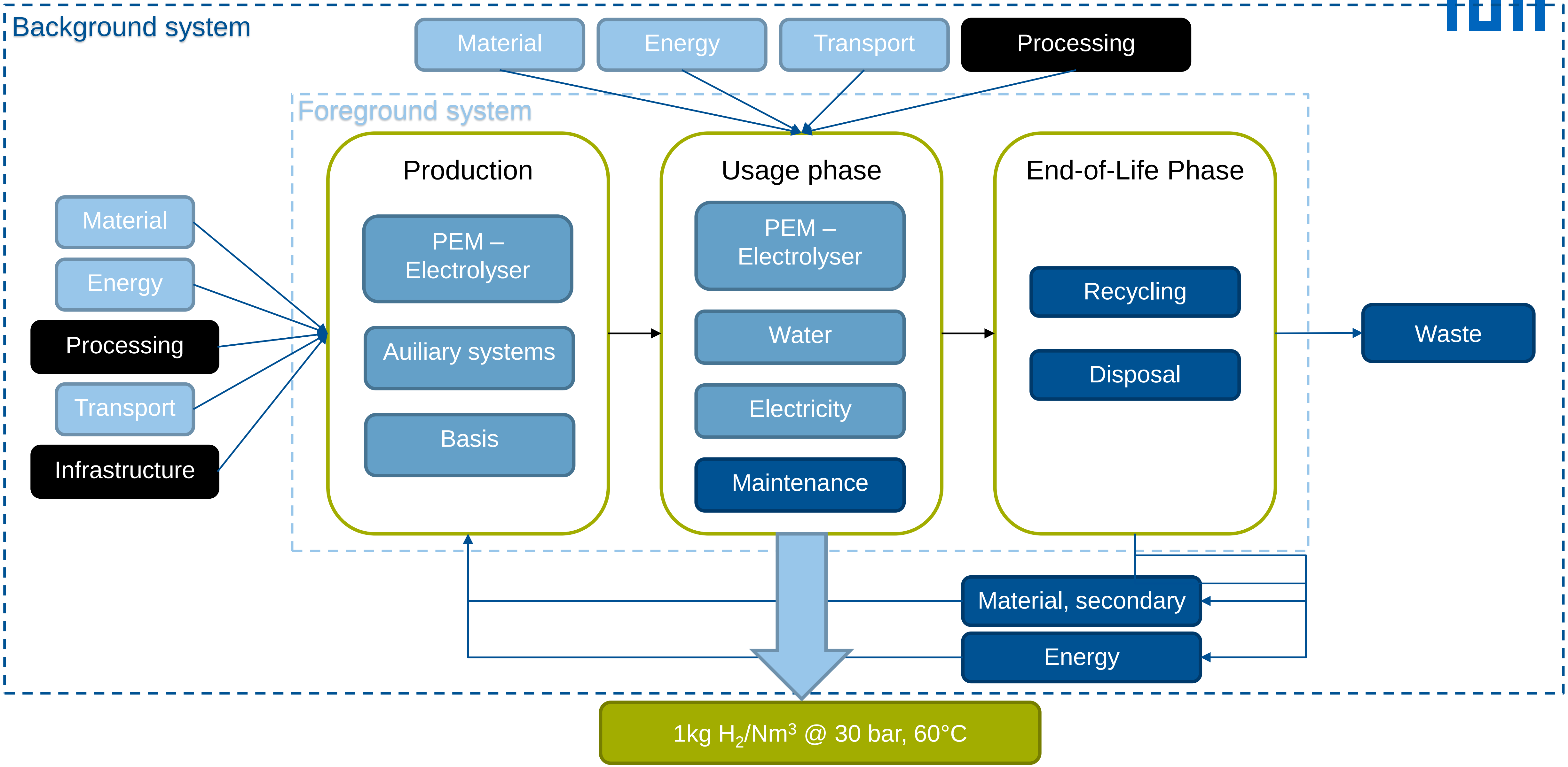
Independent Variables	**Cases**
Technology	Present, 2030, 2050
Plant size	250 kW, 1 MW, 10 MW
Energy Mix	2020, 2030, 2040, 2050
Full load hours / year	8000

Dependent Variables	
Stack efficiency	Active and Total Areas
Specific power	Material and production quantities

Detailing of the PEM-WE model

Key characteristics

Comercialy available in:	Electricity consumption Stack (kWh/kg H2)	Stack-Efficiency (%LHV)	Stack Full load hours	Power density	Auxiliaries consumption (kWh)	Total electricity consumption (kWh/kg H2)
Today	50.53	65.9%	40 000	1,79 V @ 1,5 A/cm2	3.00	53.52
2030	46.37	71.9%	56 000	1,79 V@ 3 A/cm2	3.00	49.36
2050	42.84	77.8%	80 000	1,79 V@ 5 A/cm2	3.00	45.84



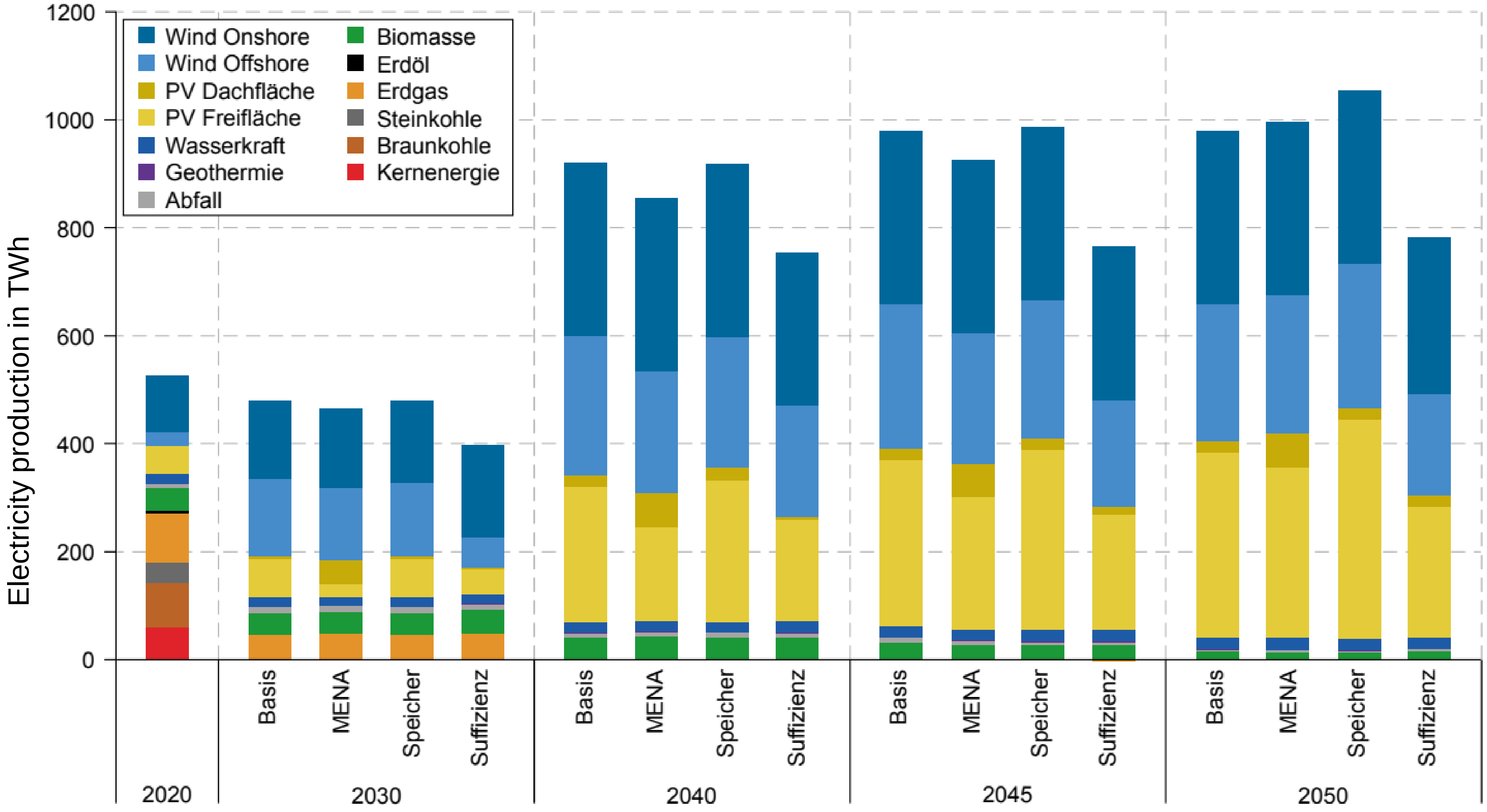
Reference Process: Steam Methane Reforming (from the literature)

Energy Model

- Baseline scenario: reducing GHG emissions to 65%, 88% and clima neutrality in 2030, 2040 and 2045
- MENA scenario: global hydrogen infrastructures that allow imports from MENA
- Storage scenario: no expansion of transmision capacities, but hydrogen transport and energy storage expansion
- Sufficiency scenario: changes in behavior in transport, housing, consumption and food to save energy.

Urbs: a linear framework for optimal capacity expansion and dispatch planning

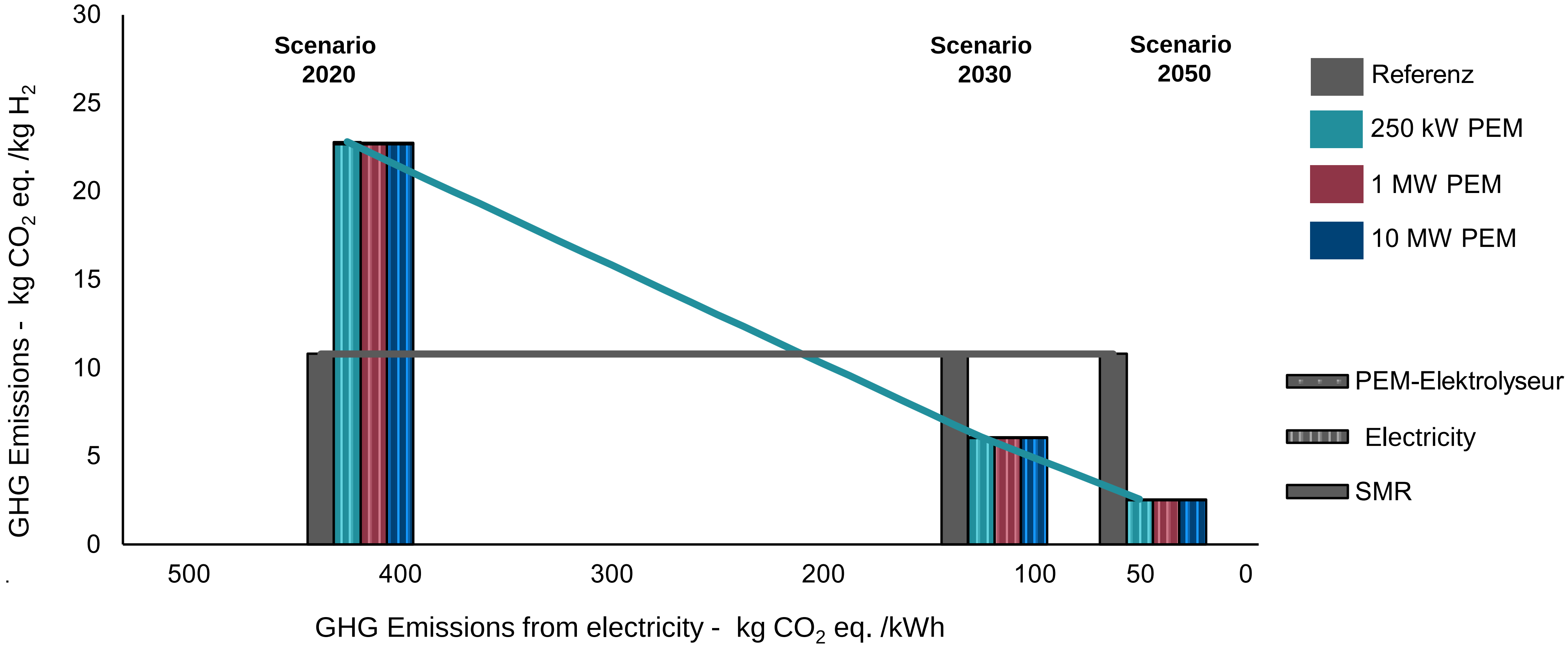
Electricity Production



Source: 4. Roadmap des Kopernikus-Projektes P2X Phase II

GHG Emissions

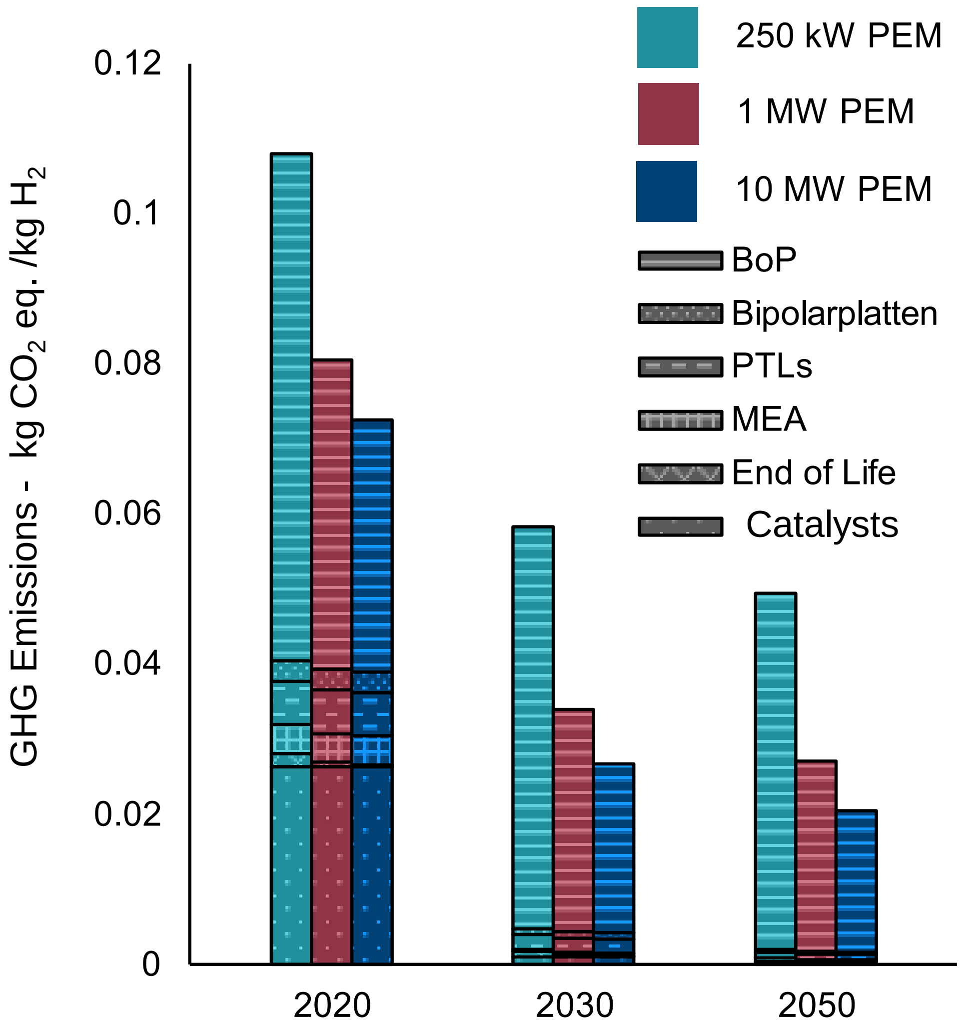
Highly dependent on the electricity mix



Source: 4. Roadmap des Kopernikus-Projektes P2X Phase II

GHG Emissions

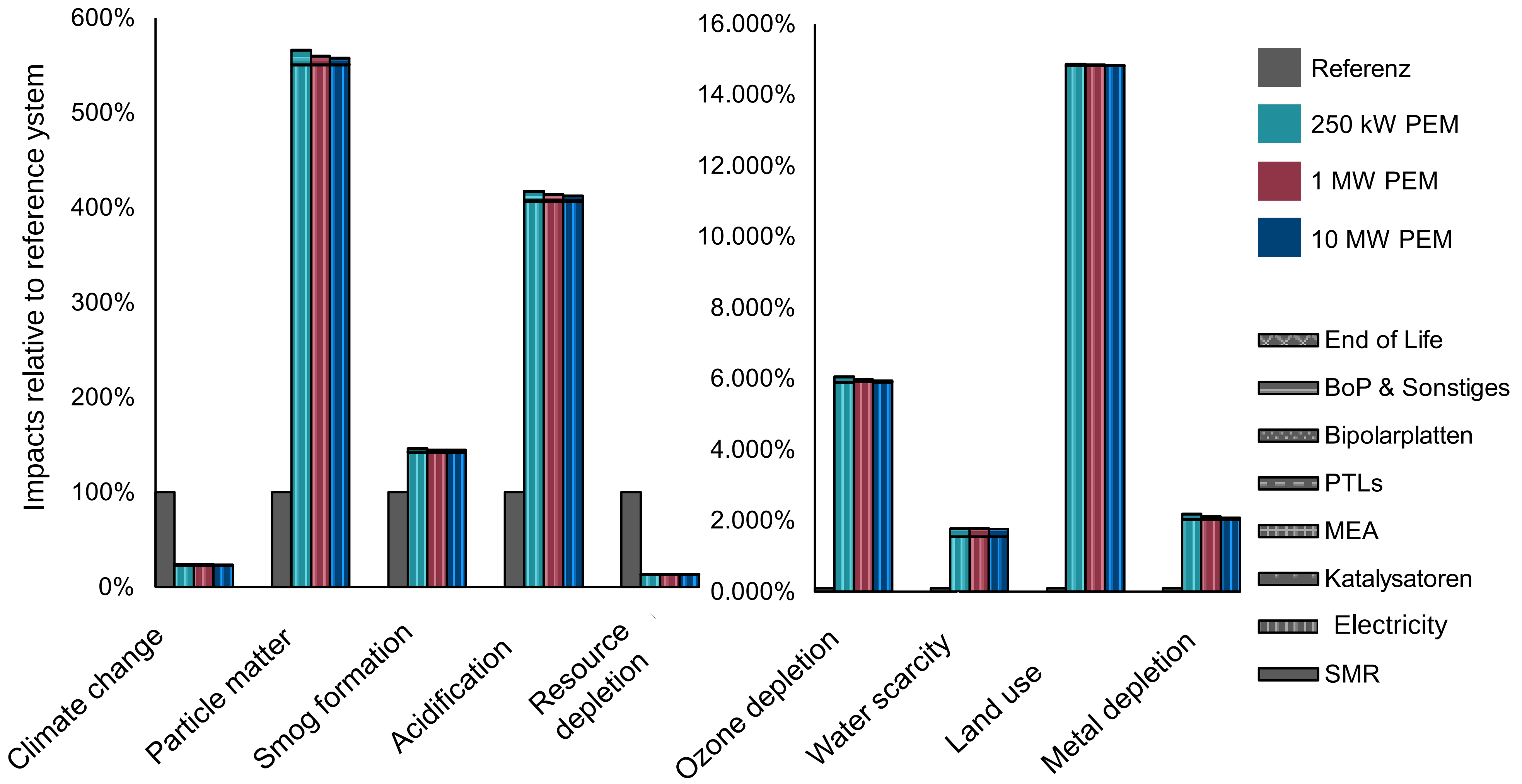
Share of electricity emissions >96%.
No assumptions of BOP improvement and H2 purification.



Source: 4. Roadmap des Kopernikus-Projektes P2X Phase II

Without electricity

Other Impact Categories

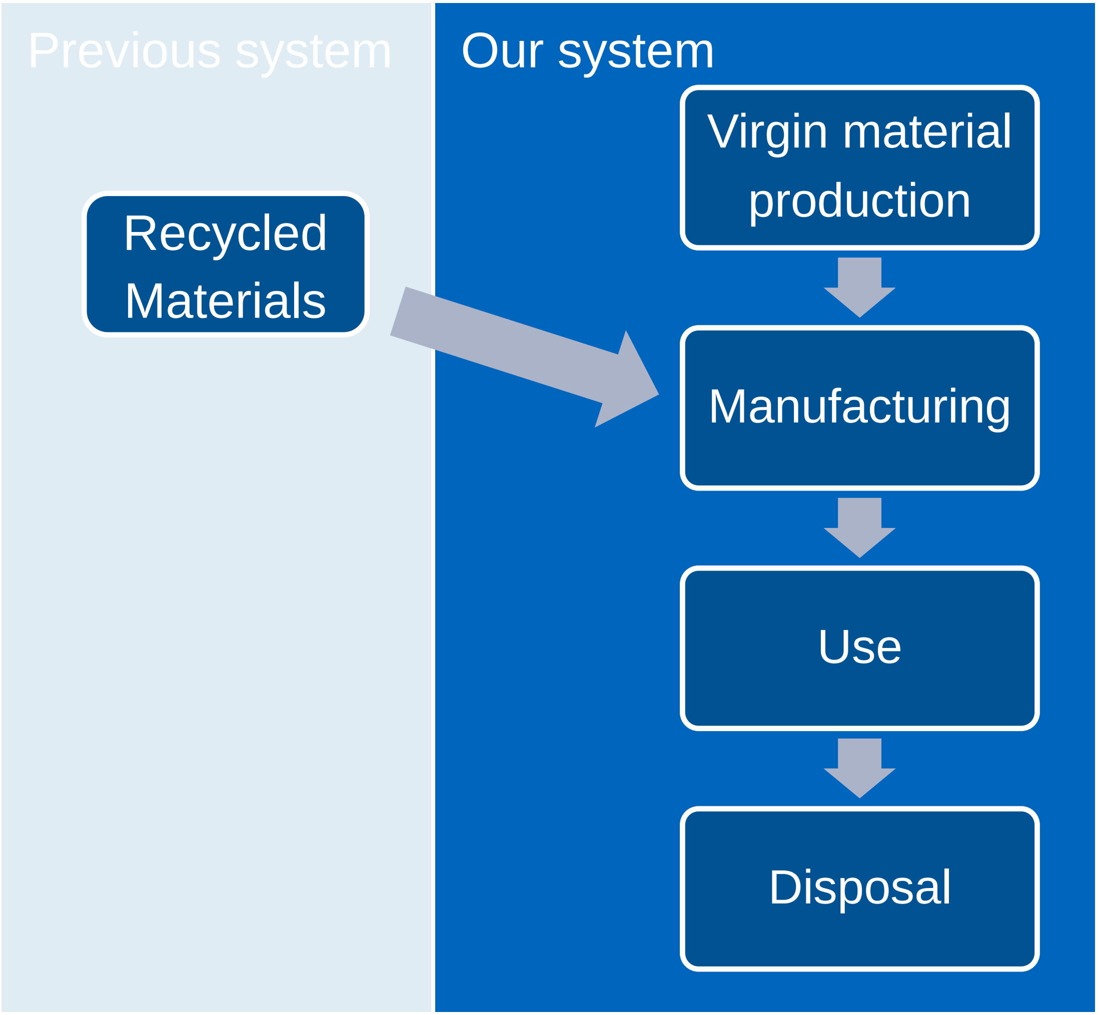


Cause of the trade offs

Impact Category	Power Cluster Process [Main Emission/Resource]
Ozone depletion [kg CFC-11 eq.]	Biomass: Electricity generation from biogas from fermentation[N_2O]
Land use [Annual crop eq.·y]	Solar PV Cluster: PV multi-Si Openfield
Metal Consumption [kg Cu eq.]	Solar PV Cluster: general [Gold]
Water consumption [m3]	Solar PV Cluster: general

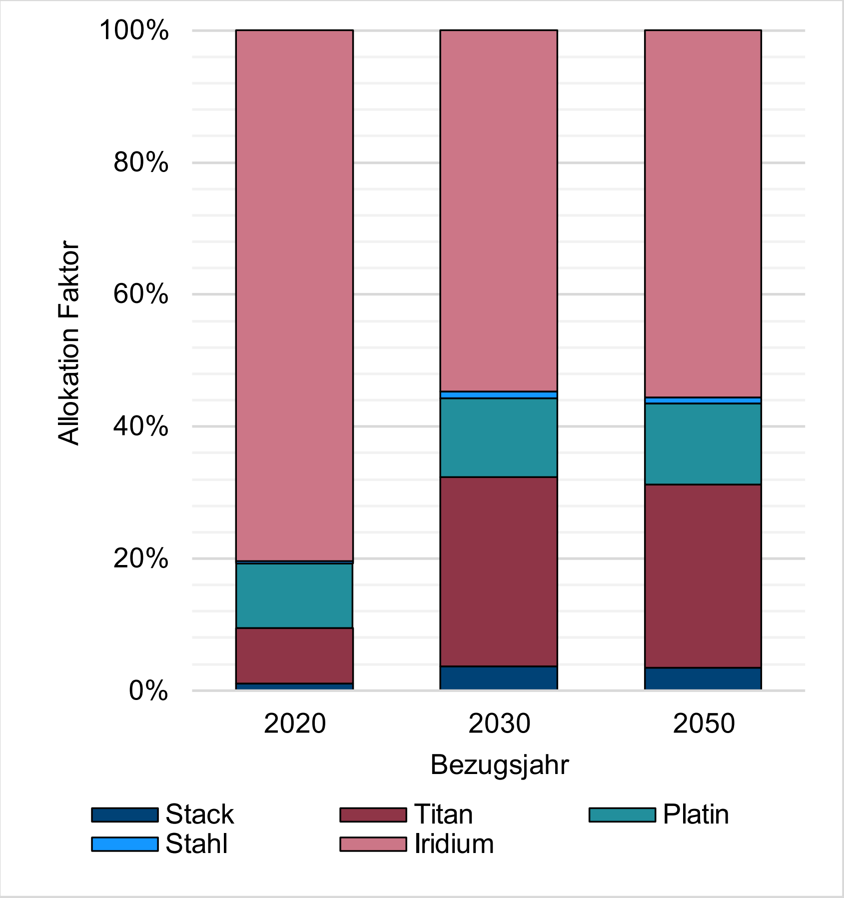
LCA - End of Life

LCA PEM-Electrolyser



Stack End of Life

End-of-Life-Approach

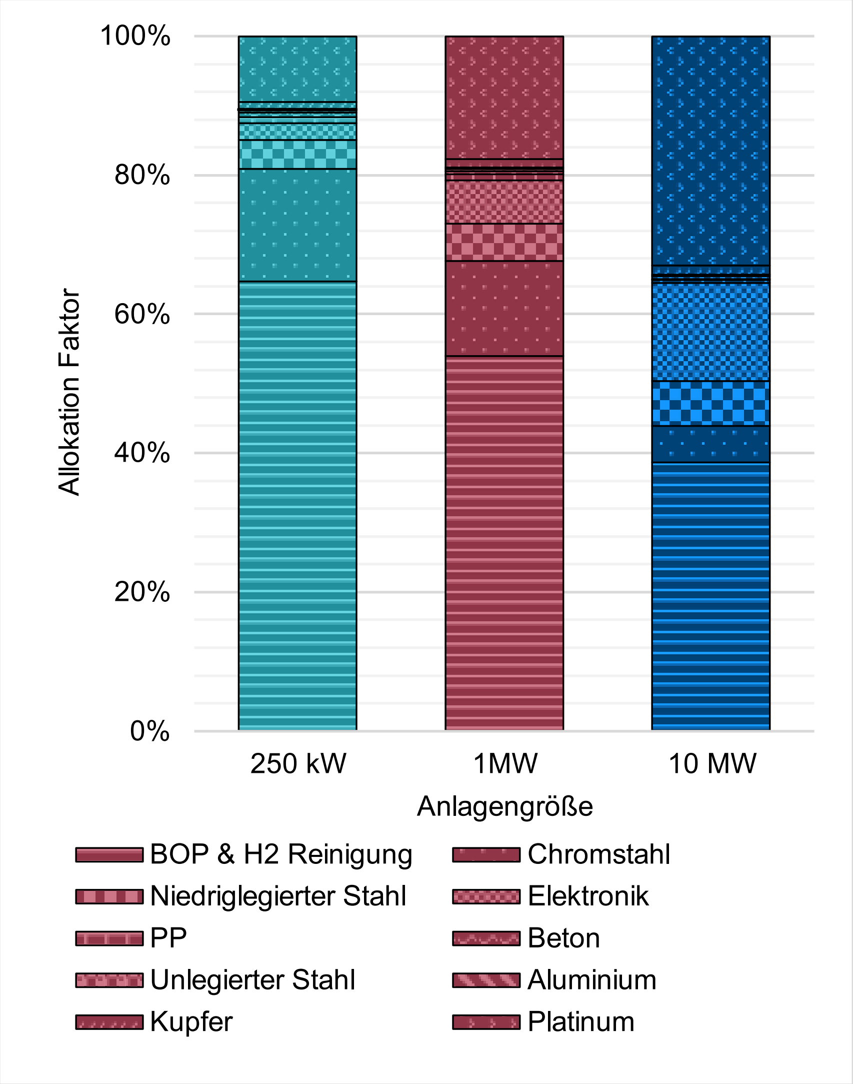


- economic allocation of impacts
- Dismantling the system, disposing of waste and energy requirements by recycling materials
- recycled quantities (year-dependent) and their market value (constant, no assumptions for the future)
- recycled iridium highest AF

BOP End of Life

End-of-Life-Approach

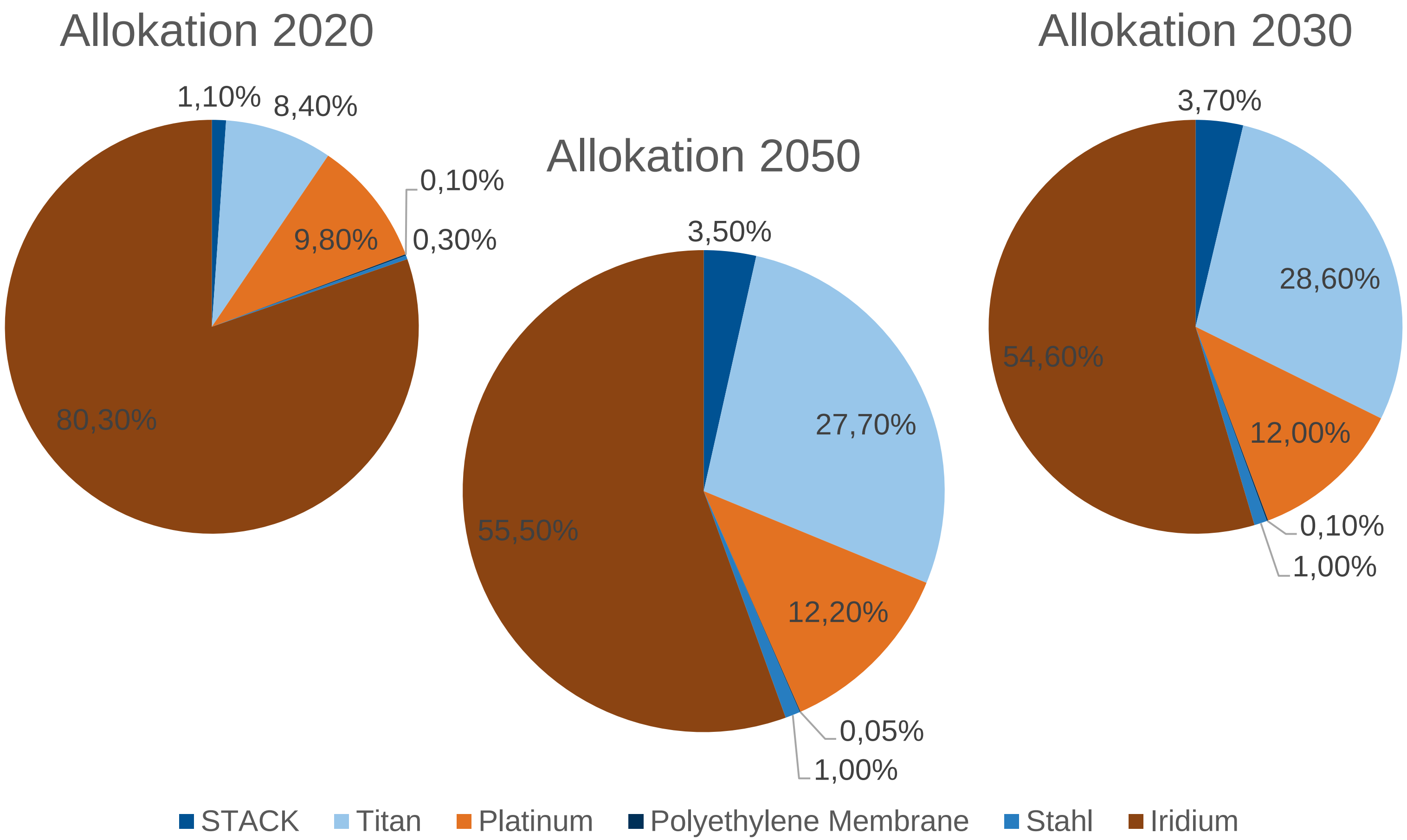
- Recycled % of materials equal for all sizes
- Market value (constant, no assumptions for future)
- Highest AF for BOP and H2 cleaning



Stack End of Life

End-of-Life-Approach

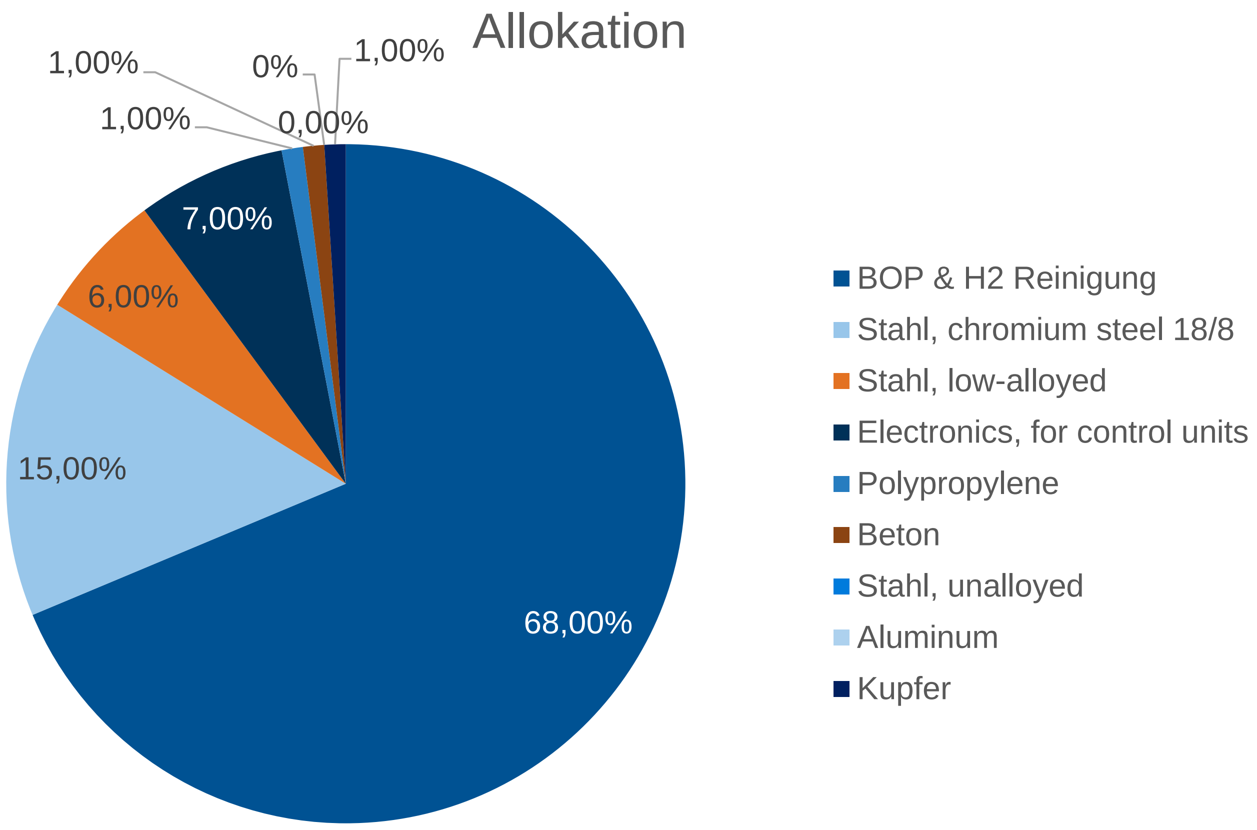
	Recovery Rate	Sources
STACK		[2]
Titan (titanium)	90%	[3]
Platinum	97%	[4],[5],[6]
Polyethylene Membrane	84%	[7]
Stahl (Steel)	88%	[7]
Iridium	50% Today 90% Future	[5],[6],[8]



BOP End of Life

End-of-Life-Approach

	Recovery Rate	Source
BOP & H2 Purification		[2]
Stahl, Chromium Steel 18/8	88%	[7]
Stahl, low-alloyed	88%	[7]
Electronics, for control units	90%	[7]
Polypropylen	84%	[7]
Beton	100%	[7]
Stahl, unalloyed	88%	[7]
Aluminum	96%	[7]
Kupfer (Copper)	100%	[7]



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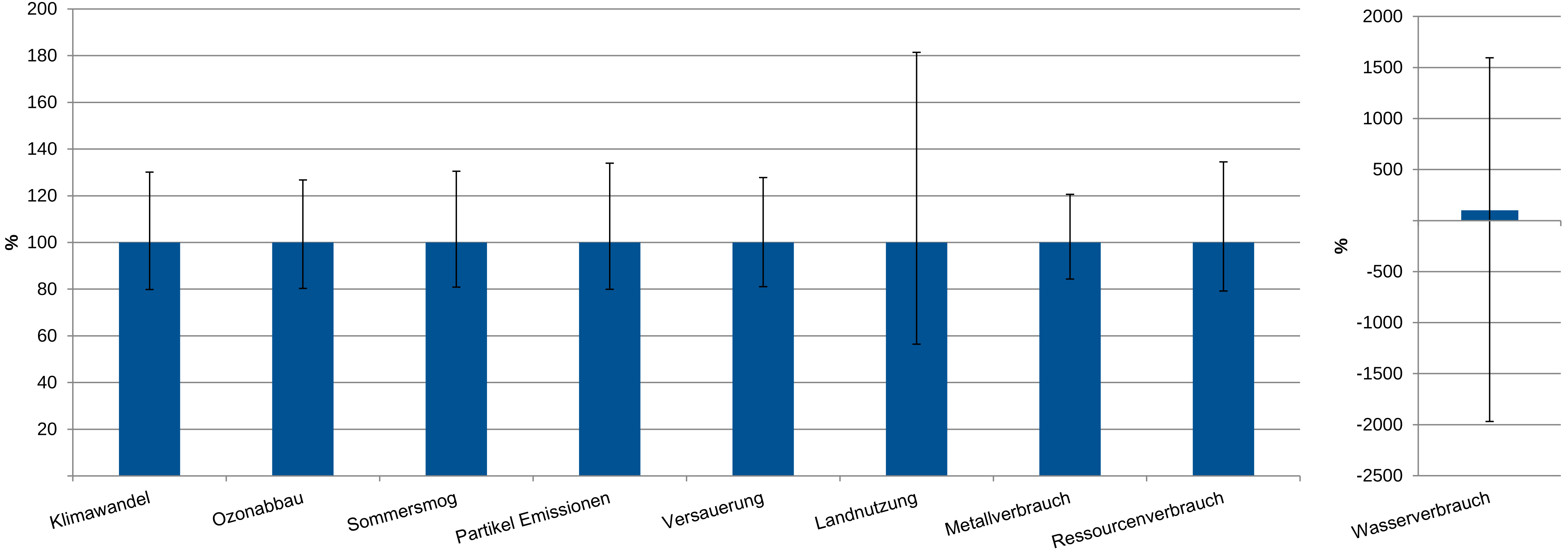
Agenda

Monte Carlo - Absolute Uncertainties 2050

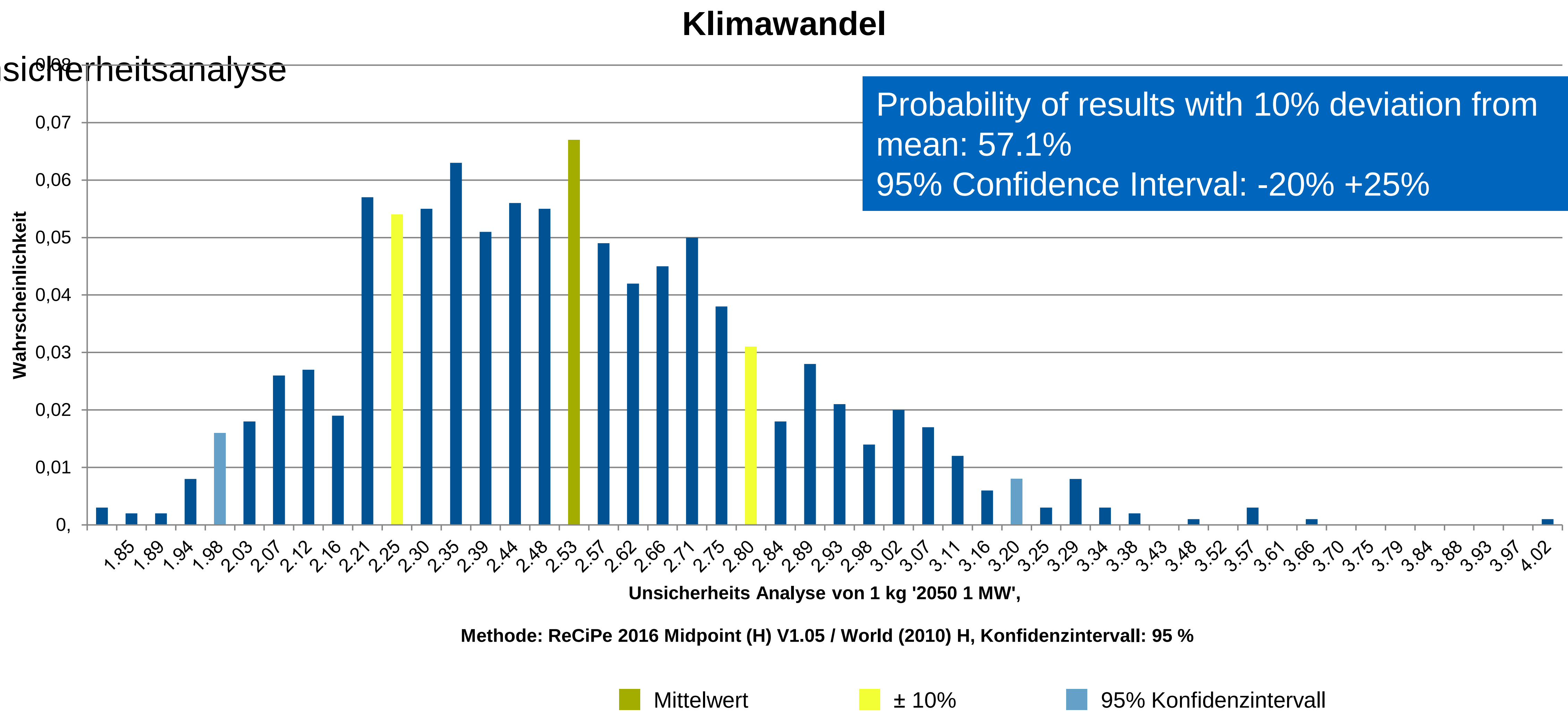
LCA PEM-Elektrolyseur



Unsicherheit Analyse von 1 kg H2 im 2050

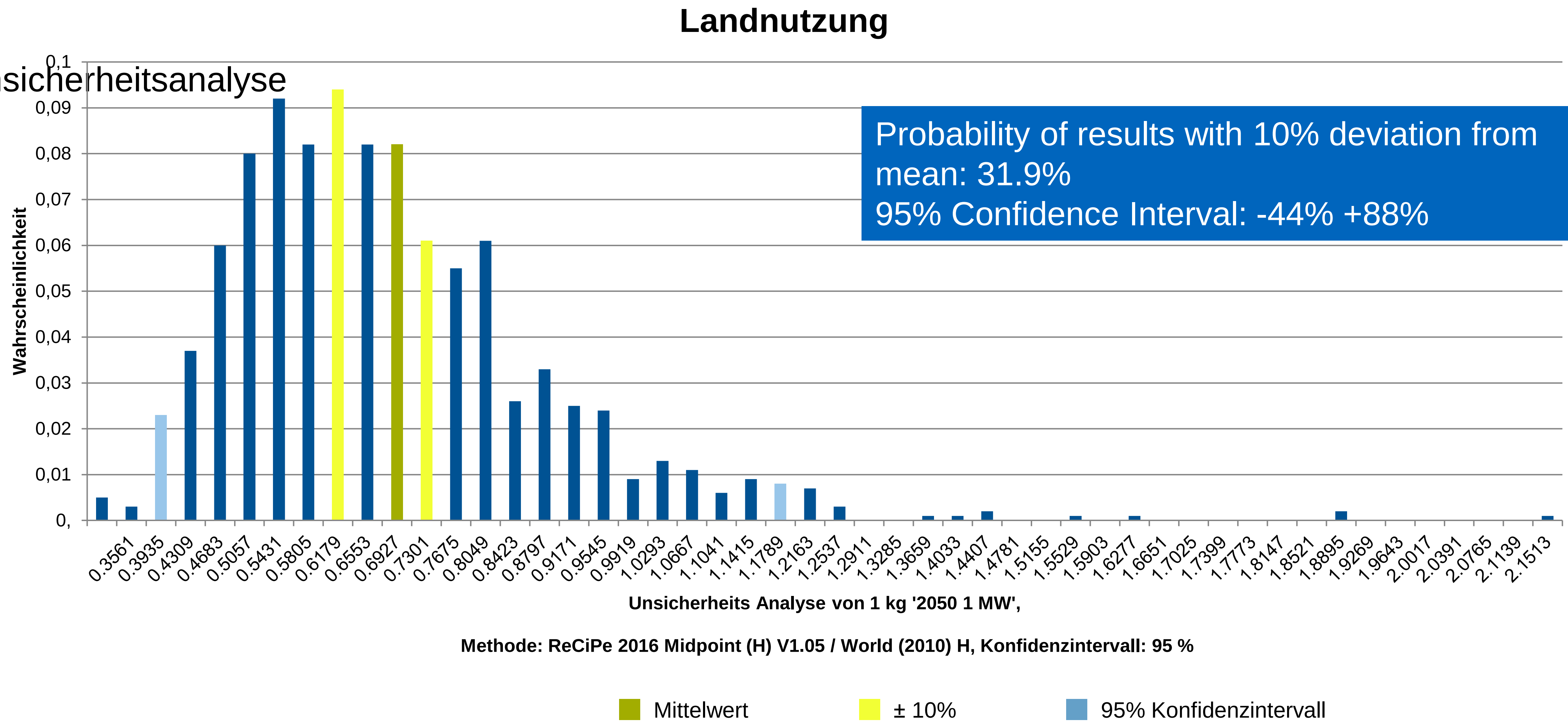
Methode: ReCiPe 2016 Midpoint (H) V1.05 / World (2010) H, Konfidenzintervall: 95 %

Monte Carlo - Uncertainty analysis



Probability of results with 10% deviation from mean: 57.1%
95% Confidence Interval: -20% +25%

Unsicherheitsanalyse



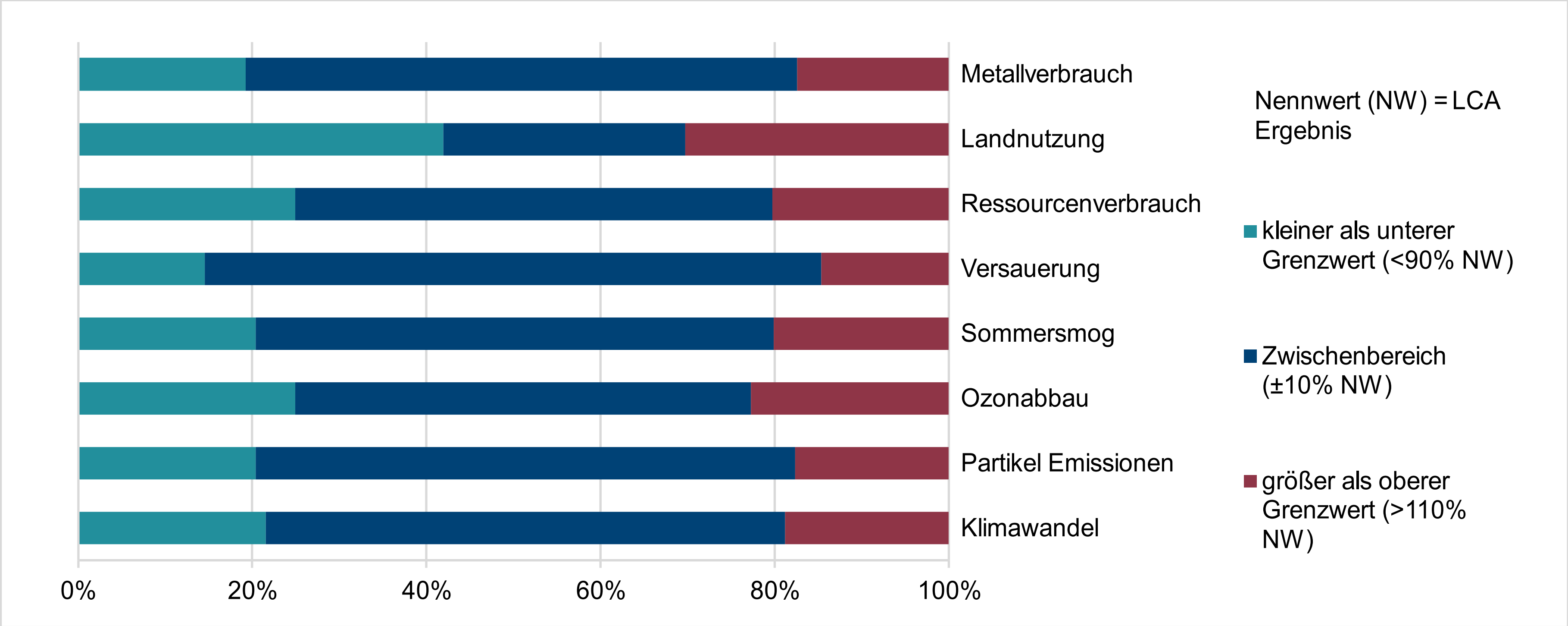
Probability of results with 10% deviation from mean: 31.9%
95% Confidence Interval: -44% +88%

Uncertainty analysis

Uncertainty analysis

>75% probability of being less than or close to (+-10%) the nominal value.

Land use exception: High uncertainty for the required industrial area for the global production of the mounting systems of ground-mounted PV systems.



Agenda

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Project Studies:

Comparing the Global Warming Potential of Different Hydrogen Import Routes to Germany:

Cases of Egypt and Chile

TUM School of Engineering and Design

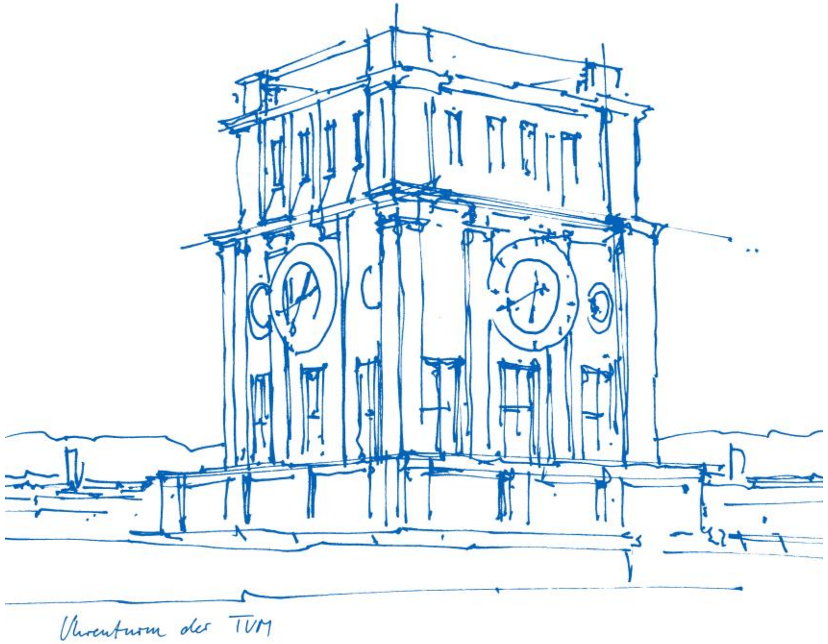
Chair of Renewable and Sustainable Energy Systems

Munich, 15 May 2024

Haas, Jonas

Wiesheu, Stefan

Lang, Christoph Alexander



Team

Haas, Jonas
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Lang, Christoph
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Wiesheu, Stefan
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The relevance of partnerships in the green hydrogen economy

COP27

“Climate neutrality is not just a goal of some but of all of us. Green hydrogen is essential to reach it.”
- Olaf Scholz

- Stay below 2°C ↑ in temperature
- Especially for industrial use

Domestic Production

H_2

“Even if domestic H_2 production should be prioritized, […] the EU can’t rely solely on domestic production to meet its growing demand.”
- REpowerEU

- Demand > Total generation potential
- Higher production costs

Partnerships
SDG 17

“Revitalize the Global Partnership for Sustainable Development”
- SDG 17

Chile

Egypt

Chile and Egypt as possible green hydrogen export Countries for Germany

Export Nations

Import Nation

	Chile	Egypt	Germany
Geography	Abundant water access	Close to European mainland	Energy-intensive industry is demanding high quantities of hydrogen
Economic target	- 1.5 USD/kg H_2 - 5 Mt/year by 2040	- 1.7 USD/kg H_2 - 5.6 Mt/year by 2040	
Energy system	Excellent solar and wind potential in North and South	Africa's largest ammonia producer	3.5 Mt/year by 2030 (50% to 70% hydrogen imports)
Government commitment	National Green Hydrogen Strategy already in 2020	Numerous H_2 projects and various partnerships	Infrastructure that can be transformed to H_2-ready
Existing infrastructure	Desalination plants + extensive desert areas	Suez canal already main line for LNG trade to Europe	

How does the Global Warming Potential of hydrogen supply chains differ when comparing Egypt and Chile?

Life Cycle Analysis

Goal and Scope Definition

Inventory Analysis

Impact Assessement

Interpretation & Conclusion

Goal and Scope Definition

Objectives

- Comparing the GWP of a green hydrogen supply chain …
  … from Chile to Germany and Egypt to Germany
  … based on electricity scenarios for Germany in 2023 and 2050
- Highlighting GWP reductions by incorporating a German electricity mix in 2050

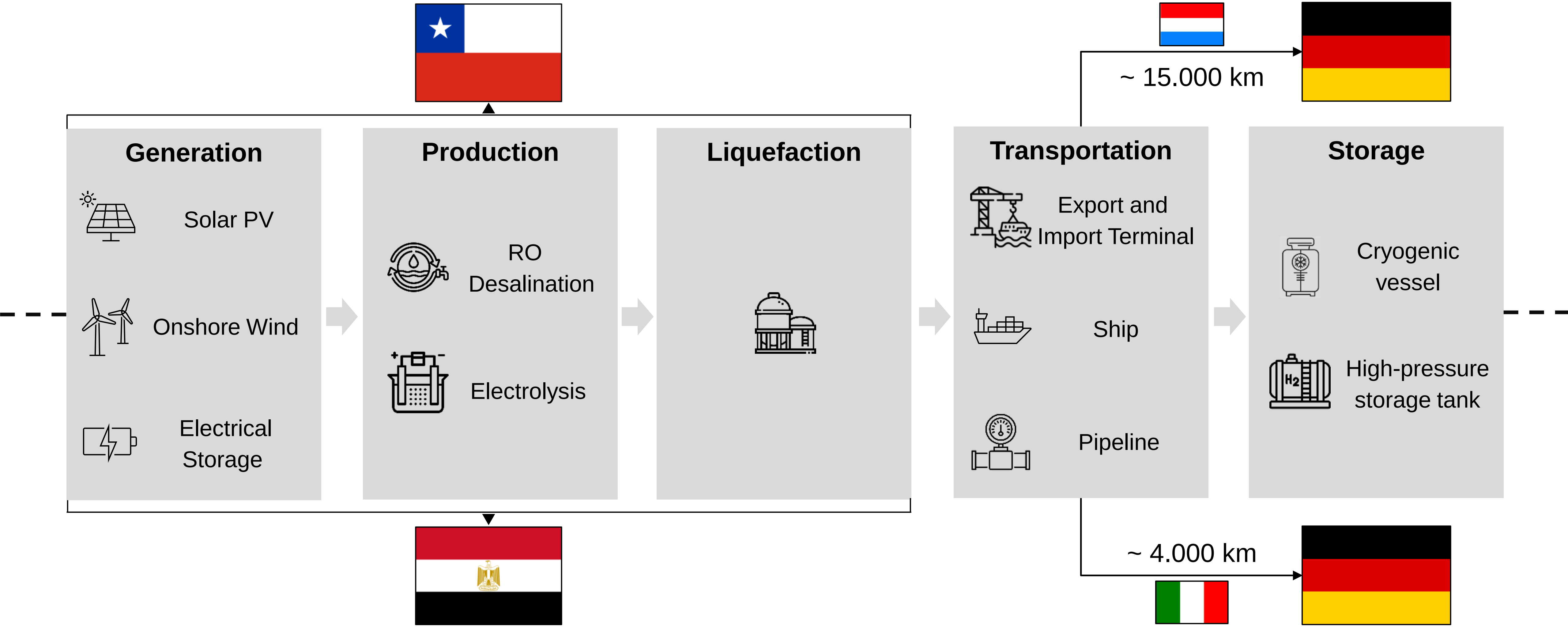
Functional Unit

1 kg of green hydrogen supplied from a production and processing facility in Chile vs. Egypt imported to a demand site in Germany

Impact Category

Global Warming Potential (in kg CO_2e/kg H_2)

System Boundaries



Life Cycle Analysis

Goal and Scope Definition

Inventory Analysis

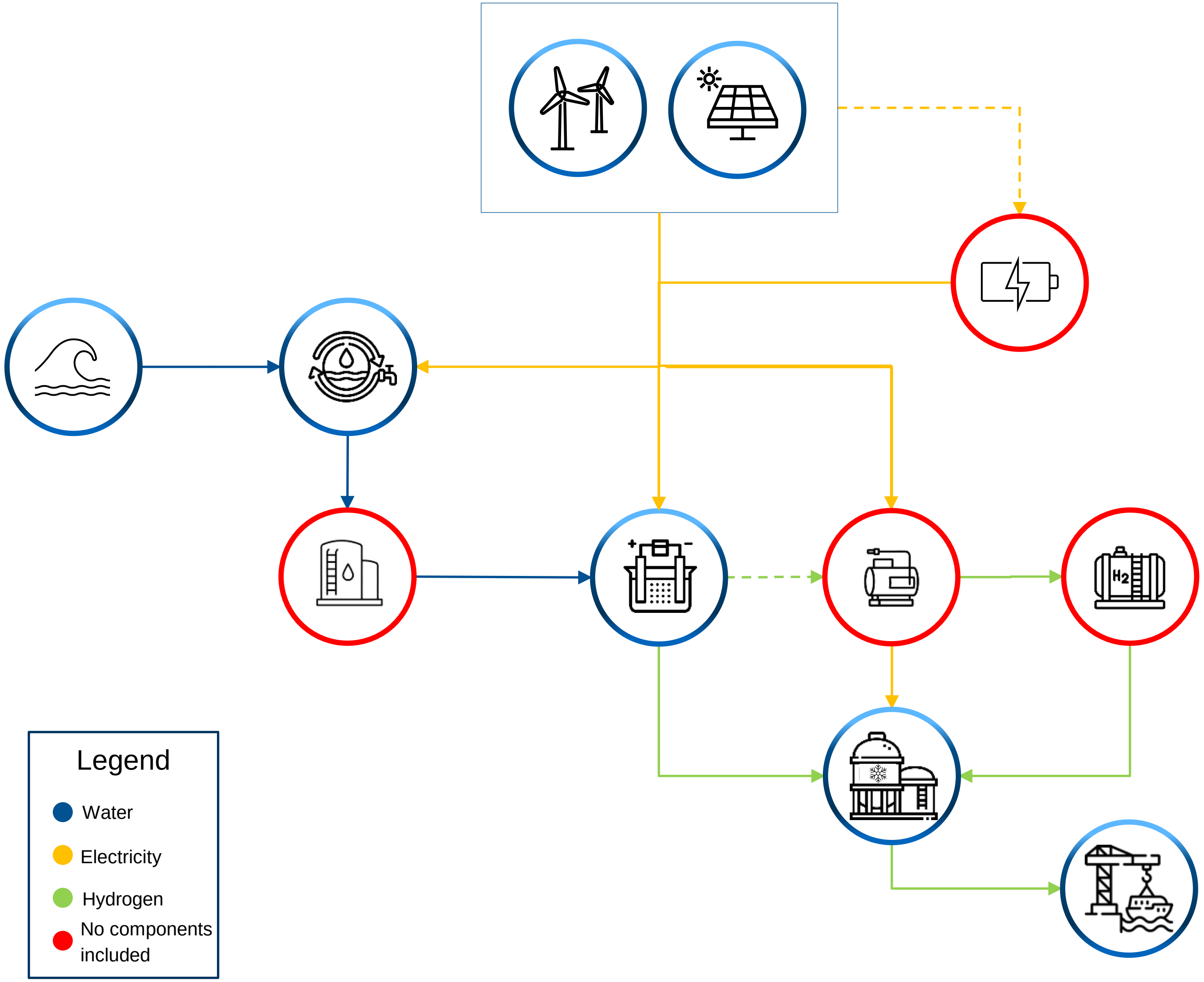
Impact Assesseement

Interpretation & Conclusion

Hydrogen Production Scenarios

	Chile 	Egypt 
Scenario	Onshore wind power and solar PV	Onshore wind power and solar PV
RE gen.	3909 FLH onshore wind and 690 FLH solar PV 97.4% installed capacity onshore wind	3841 FLH onshore wind and 2147 FLH solar PV 95.5% installed capacity solar PV
Techno-logy	Renewable energy, Alkaline - electrolyser, liquefaction and storage systems	
Notes	Alkaline electrolyser and liquefaction on part-load	Alkaline electrolyser and liquefaction on base load

Generation and Conversion

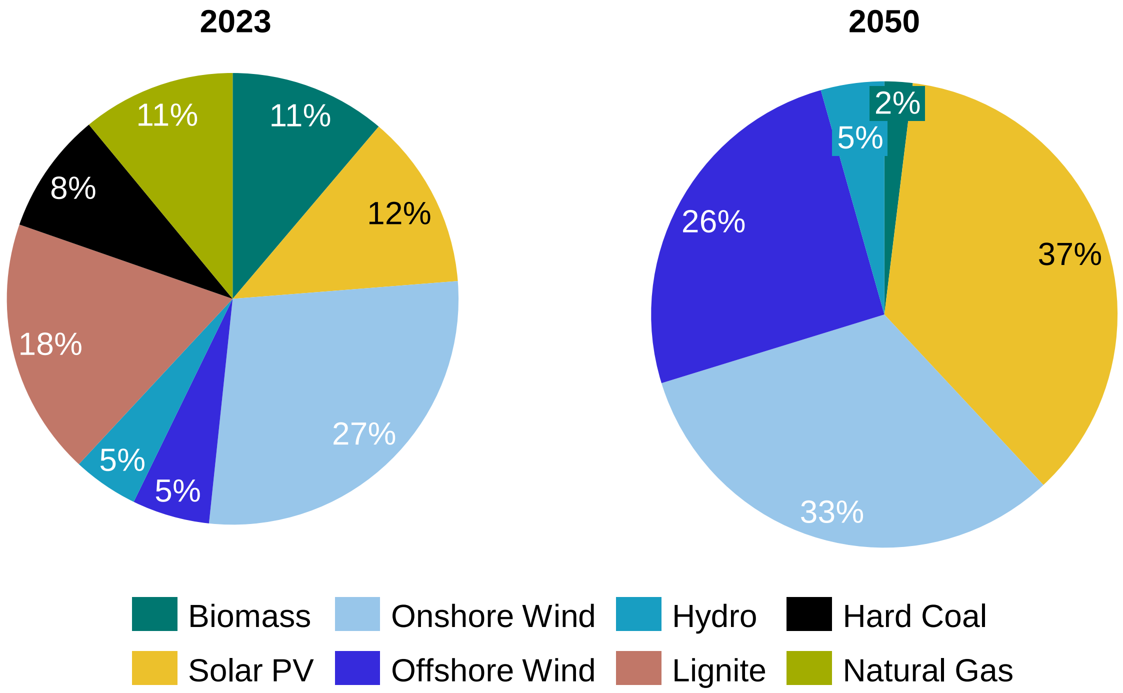


	Input	Output	orig. Size
Desalination	- 3.66 kWh/m^3 - 2.5 m^3 sea water	- 1 m^3 water - 1.5 m^3 salt brine	10,000 m^3 water/day (~1.5 MW)
Electrolyser	50 kWh/kg 10 kg Water	1 kg H_2	6 MW
Liquefaction	6.76 kWh/kg 1.0165 kg H_2	1kg liquefied H_2	14 MW

Transportation, Transmission & Distribution

		
Export Terminal	San Antonio, CL	Cairo, EG
Ship	Heavy Fuel Oil	Heavy Fuel Oil
Import Terminal	Rotterdam, NL	Naples, IT
Transmission Pipeline	Rotterdam, NL	Naples, IT
Distribution Pipeline	Germany	Germany
Compressor	Piston Compressor	Piston Compressor

Energy Mix Germany

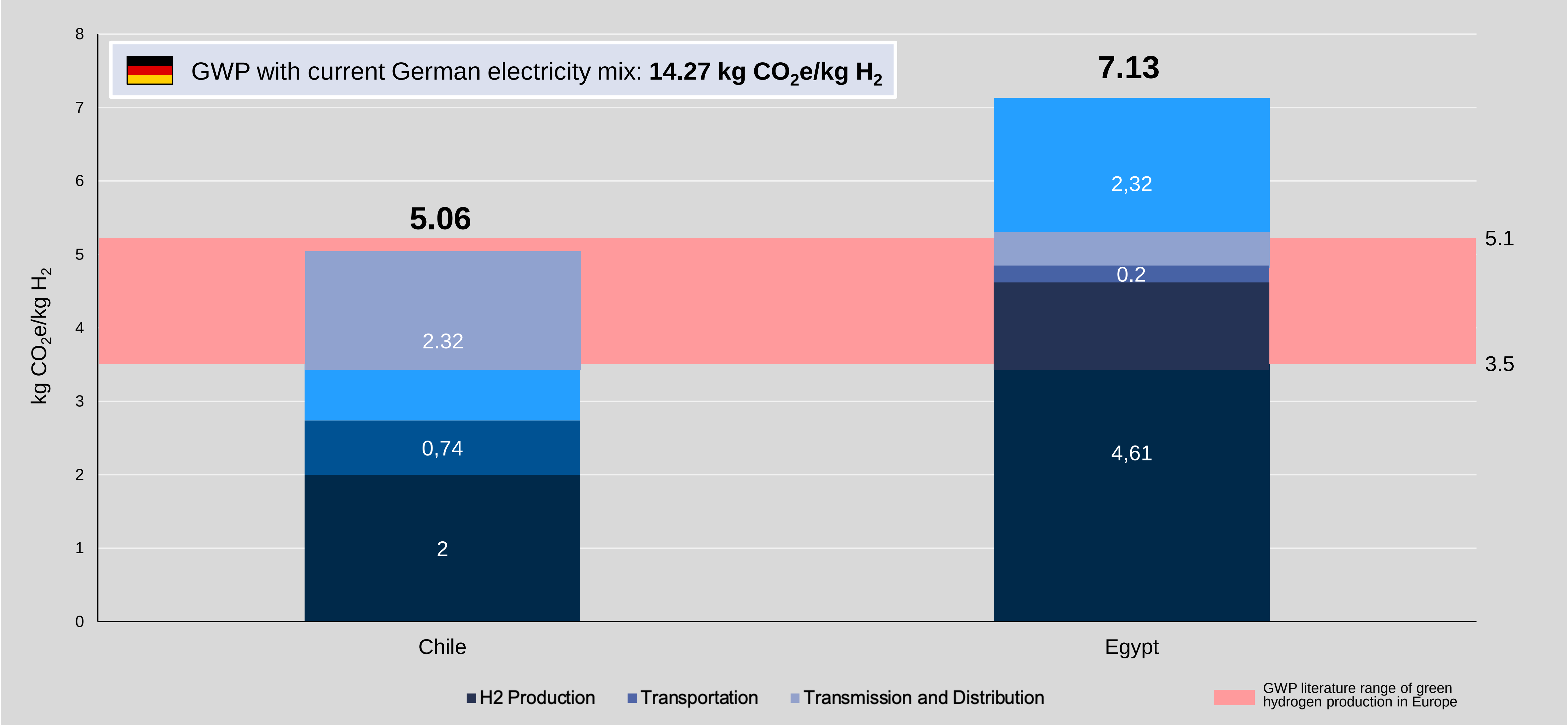


2023: 0.377 kg CO2e/kWh
2050: 0.070 kg CO2e/kWh

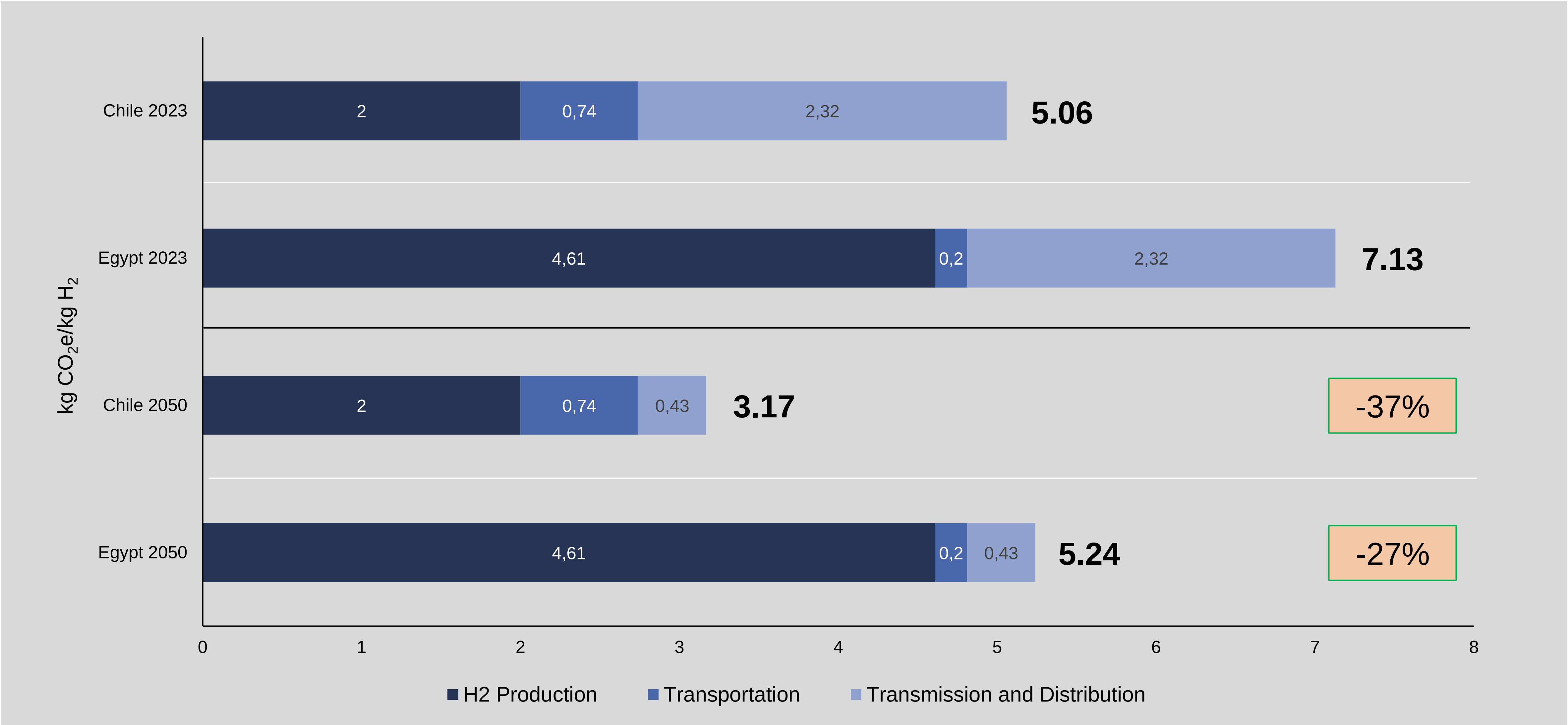
Life Cycle Analysis

- Goal and Scope Definition
- Inventory Analysis
- Impact Assessement
- Interpretation & Conclusion

Comparison of the GWP of the two green hydrogen supply chains in 2023



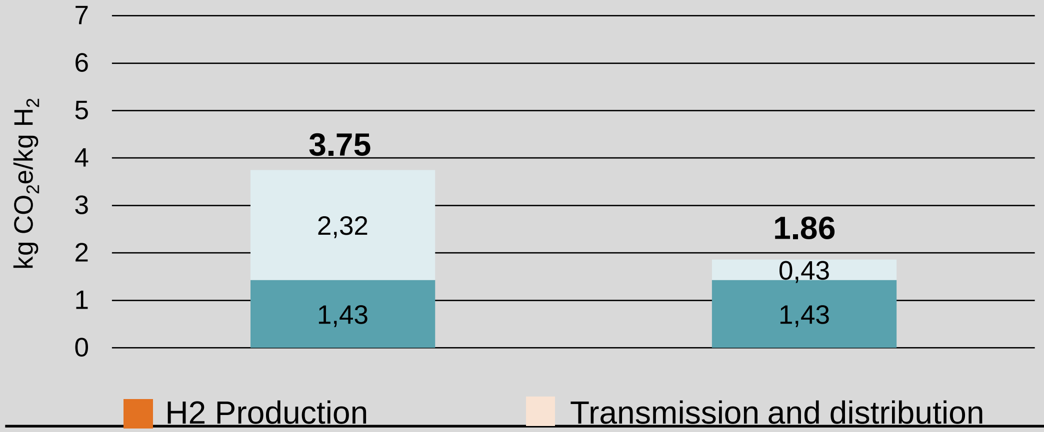
GWP of the two green hydrogen supply chains in 2023 and 2050



Contribution of electrictiy to GWP in each scenario

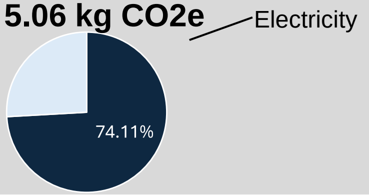
2023	2050

GWP from electricity generation

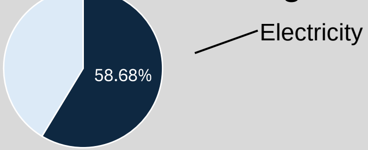


Portion of GWP attributable to electricity

Total GWP = 5.06 kg CO2e

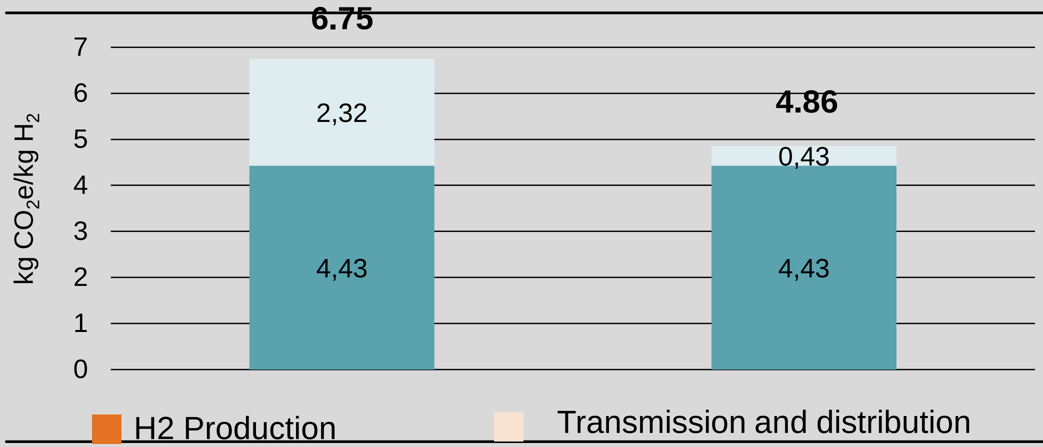


Total GWP = 3.17 kg CO2e



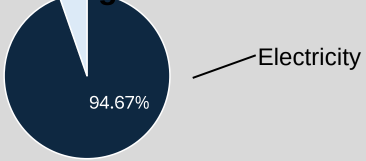
2023	2050

GWP from electricity generation

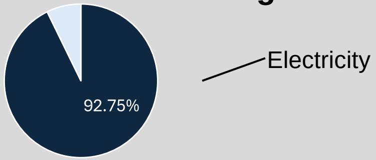


Portion of GWP attributable to electricity

Total GWP = 7.13 kg CO2e



Total GWP = 5.24 kg CO2e



Life Cycle Analysis

Goal and Scope Definition

Inventory Analysis

Impact Assessement

Interpretation & Conclusion

Interpretation & Conclusion

Interpretation

Although Egypt shows extraordinary solar PV potentials, influence on GWP of the green hydrogen production process from solar PV is tripled compared to onshore wind in Chile

Distance between countries currently plays a minor role

Comparing the GWP, only one import scenario is competitive with domestic green hydrogen production in Germany in 2023

The decarbonization of the electricity mix in Germany is an important cornerstone for the whole green hydrogen supply chain

Interpretation & Conclusion

Conclusion

The terminology “green hydrogen” should be treated carefully.

Substituting other energy carriers with green hydrogen must be evaluated carefully

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Agenda

Chair of Renewable and Sustainable Energy Systems
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Technical University of Munich

Integration of Hydrogen Production in Brazil’s Electricity System: An Energy System Model and a Life Cycle Assessment Approach

Master’s Thesis

Final Presentation

Christoph Alexander Lang

Munich, 05th of June 2024

Content

1. Theoretical Background
2. Research Questions
3. Methodology
4. Results and Interpretation
    - 4.1 Energy System Model
    - 4.2 Life Cycle Assessment
5. Conclusion

Global collaborations vital for a successful energy transition

Climate Goal According to Article 2 Paris Agreement

Global average temperature increase < 2°C above industrial levels

"Green hydrogen can play a key role in the [energy] transition" (United Nations, 2021)

Need for green hydrogen imports in Germany

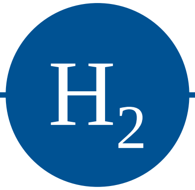
- Demand > Total generation potential
- Higher production costs

Brazil as potential export country

Resources	*Political Status*	*Knowledge*
- Renewable sources in electricity mix > 80 % - Huge potential for wind and PV - Huge coastline with major ports	- NDC to carbon neutrality by 2050 - No dedicated hydrogen strategy, but multiple support reports	- "H2 Brasil" with Germany - US-Brazil Energy Forum - Energy Program for Brazil with GB

The three research questions this thesis aims to answer

Research Question 1	Research Question 2	Research Question 3
Changing Energy Mix	**Hydrogen Integration**	**Global Warming Potential**
“How will the Brazilian energy system need to expand and adapt to effectively manage a - potential significant increase in intermittent power production and - a surge in electricity demand due to green hydrogen production?”	“How can the integration of hydrogen production into Brazil's energy system be optimized to effectively facilitate the transition towards a decarbonized domestic and potentially global energy supply?”	“How high is the Global Warming Potential associated with - the local production of hydrogen in Brazil, - compared to potential hydrogen export scenarios, such as exportation to Germany?”



Twofold methodological approach

Research Questions 1 and 2

Energy System Modeling

Research Question 3

Life Cycle Assessment

Introduction to energy system modeling

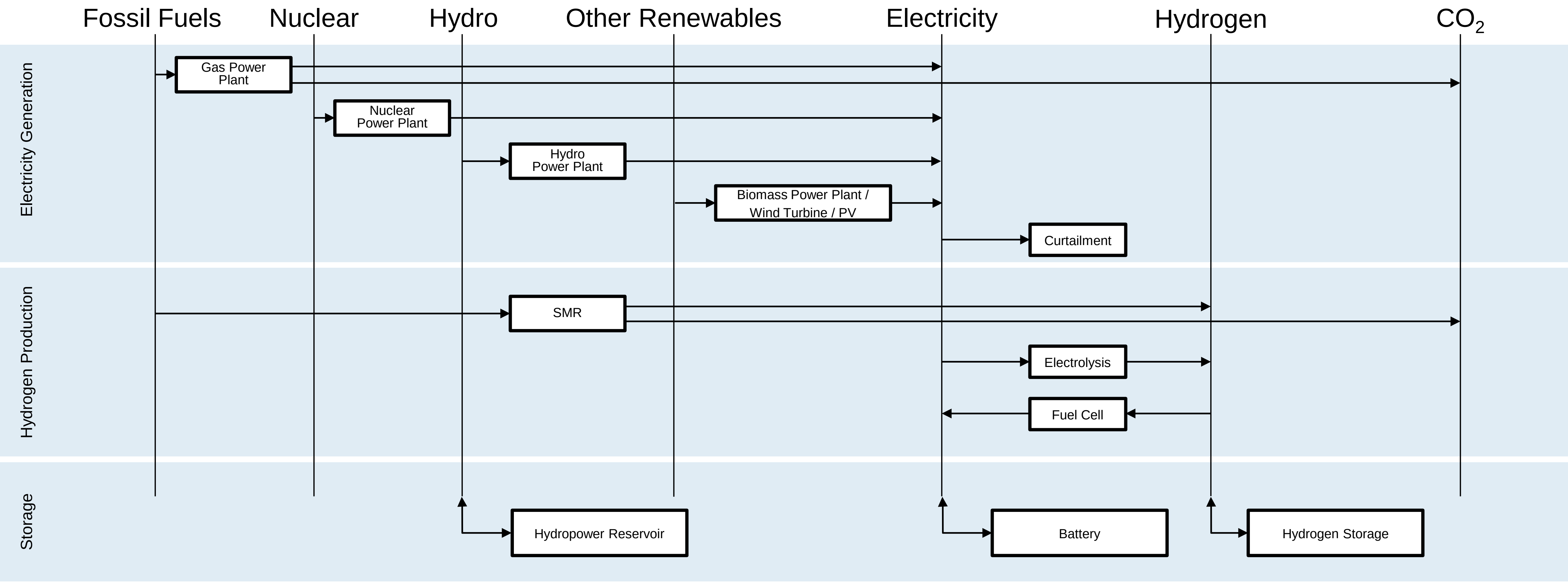
Research Questions 1 and 2

Energy System Modeling

Research Question 3

Life Cycle Assessment

Reference energy system



Scenarios and sensitivity analysis

Base

Cost-minimization for an intertemporal model (2021 – 2030 – 2040 – 2050)

Scenarios

Scenario 1	Scenario 2
"Carbon neutrality" by 2050 - 100 % emission reduction by 2050 - CO_2 price from 2030 onward	**"Business-as-usual"** - No emission reduction targets - No CO_2 price

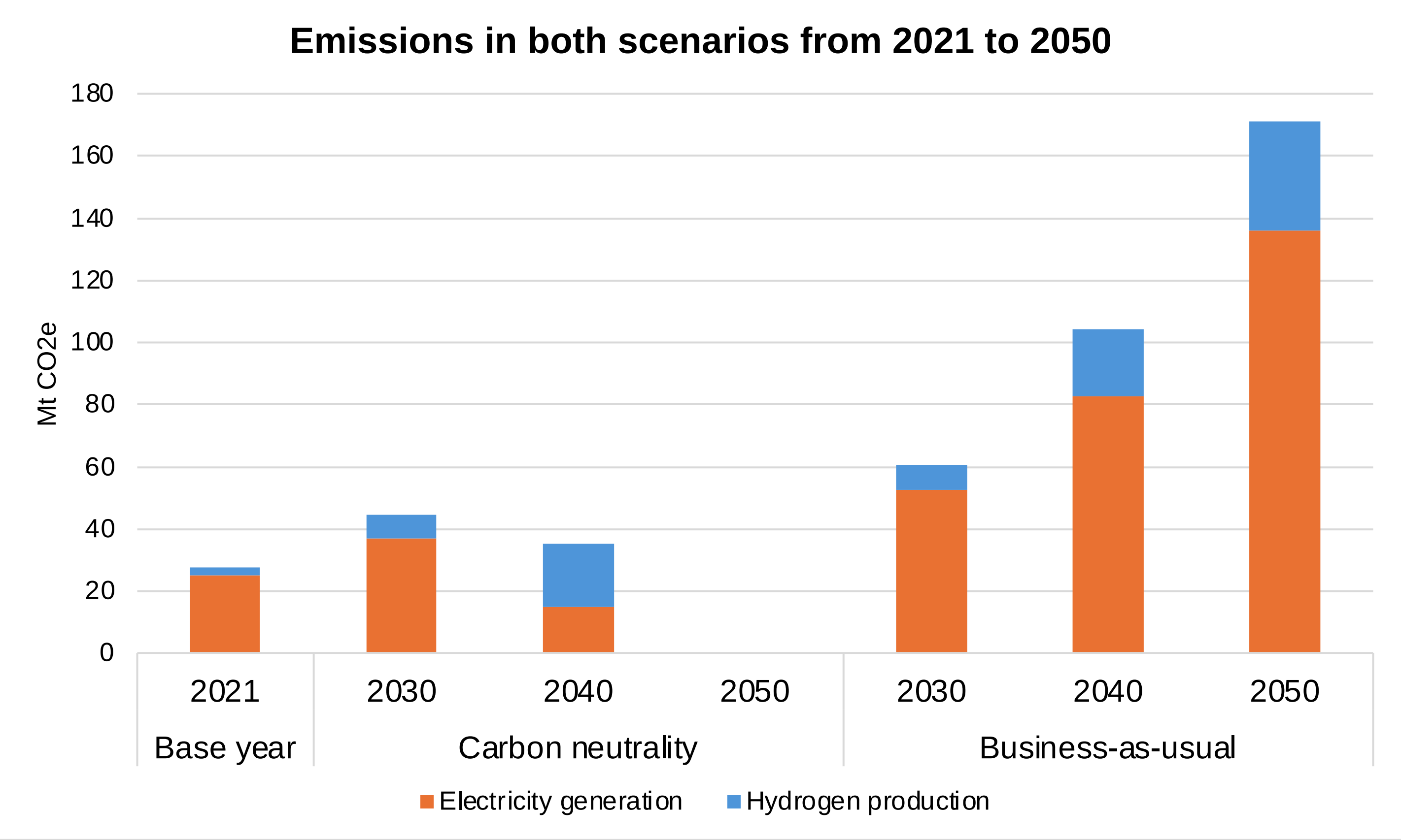
Sensitivities

Sensitivity 1	Sensitivity 2	Sensitivity 3
Hydrogen demand follows industry demand	Hydro supply distribution from 2021	Best-case alternative for green hydrogen production
instead of	*instead of*	*instead of*
Equal distribution throughout the year	10-year average supply distribution	Average CAPEX and OPEX for electrolysis and RE

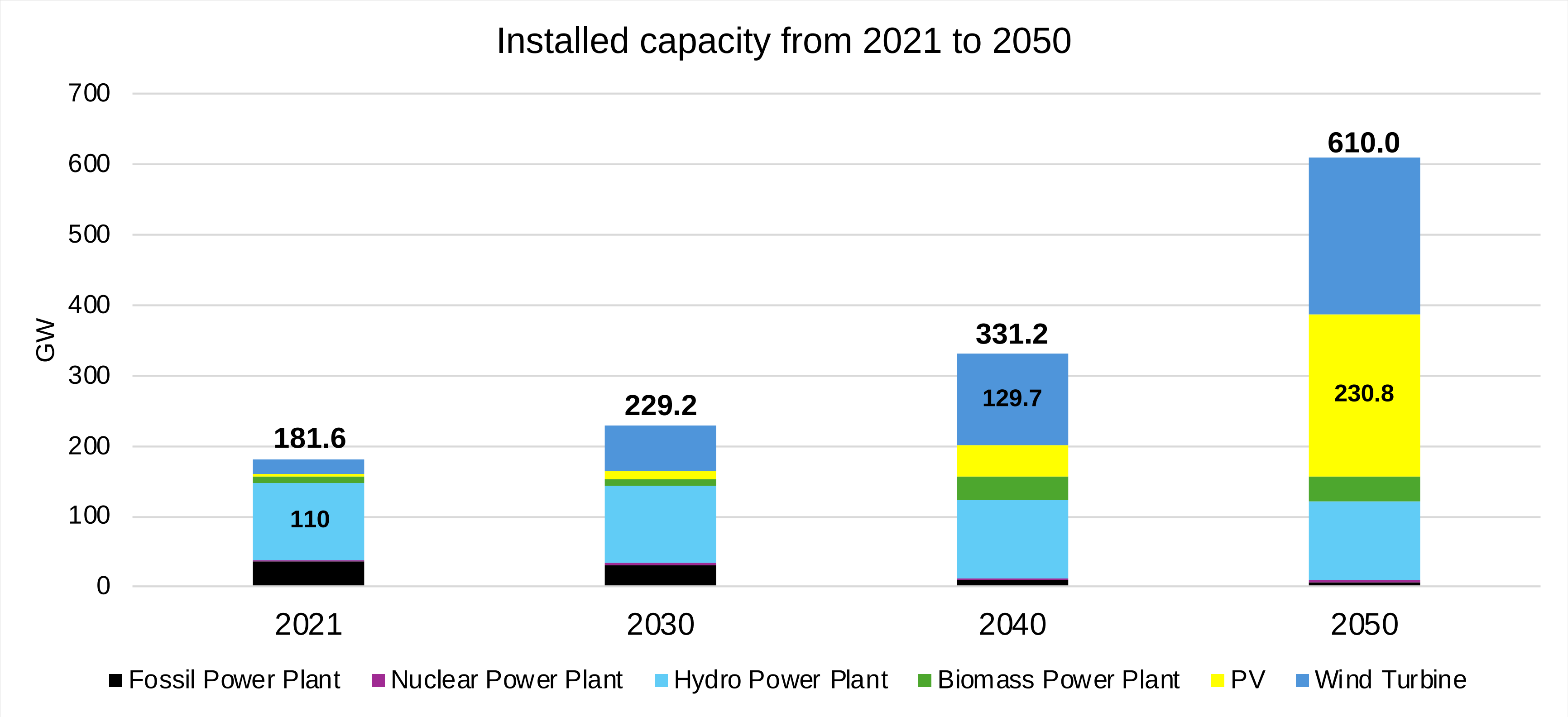
Costs and emissions of the two scenarios

Costs in both scenarios over the model period

[billion $]	"Carbon neutrality"		"Business-as-usual"
CAPEX	86.4	↘	58.3
OPEX	110.8	↘	102.8
Fuel	105.9	↗	115.8
Evironment	15.9	↘	0
Total	**319.0**	↘	**276.9**

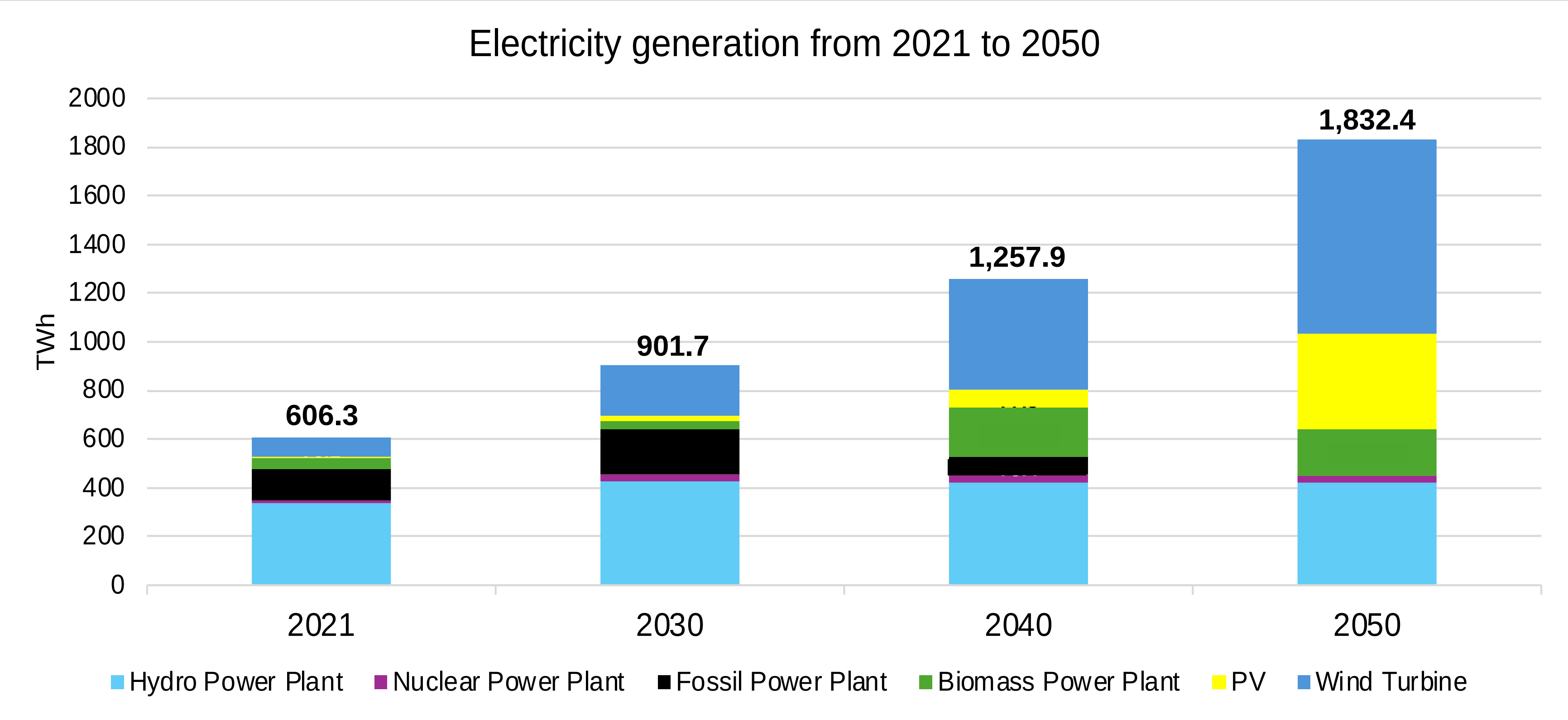


Detailed results of the “carbon neutrality” scenario



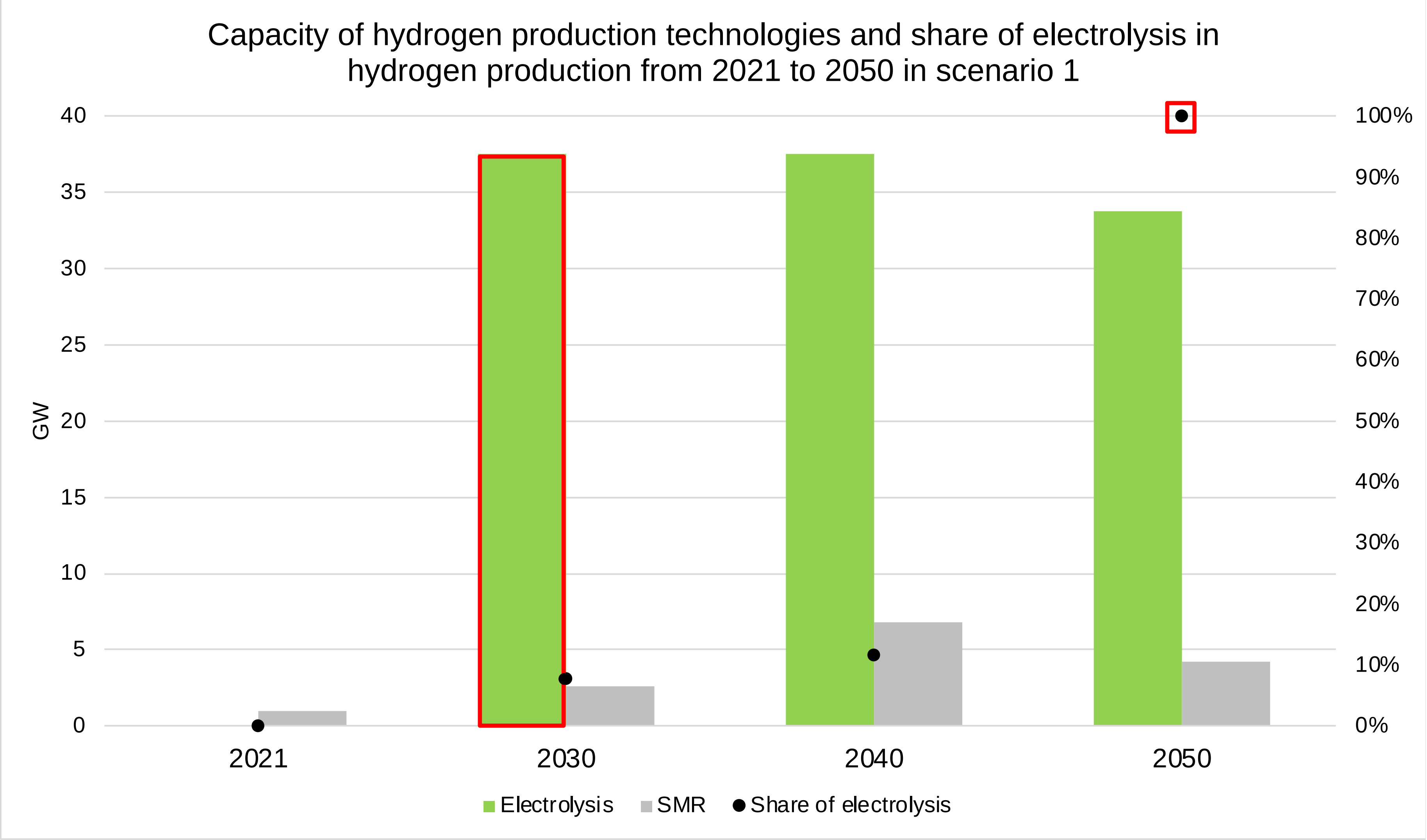
Δ from 2021 to 2050	Fossil	Nuclear	Hydro	Biomass	PV	Wind
	- 80 %	+ 71 %	+ 1 %	+ 310 %	+ 4900 %	+ 973 %

Detailed results of the “carbon neutrality” scenario

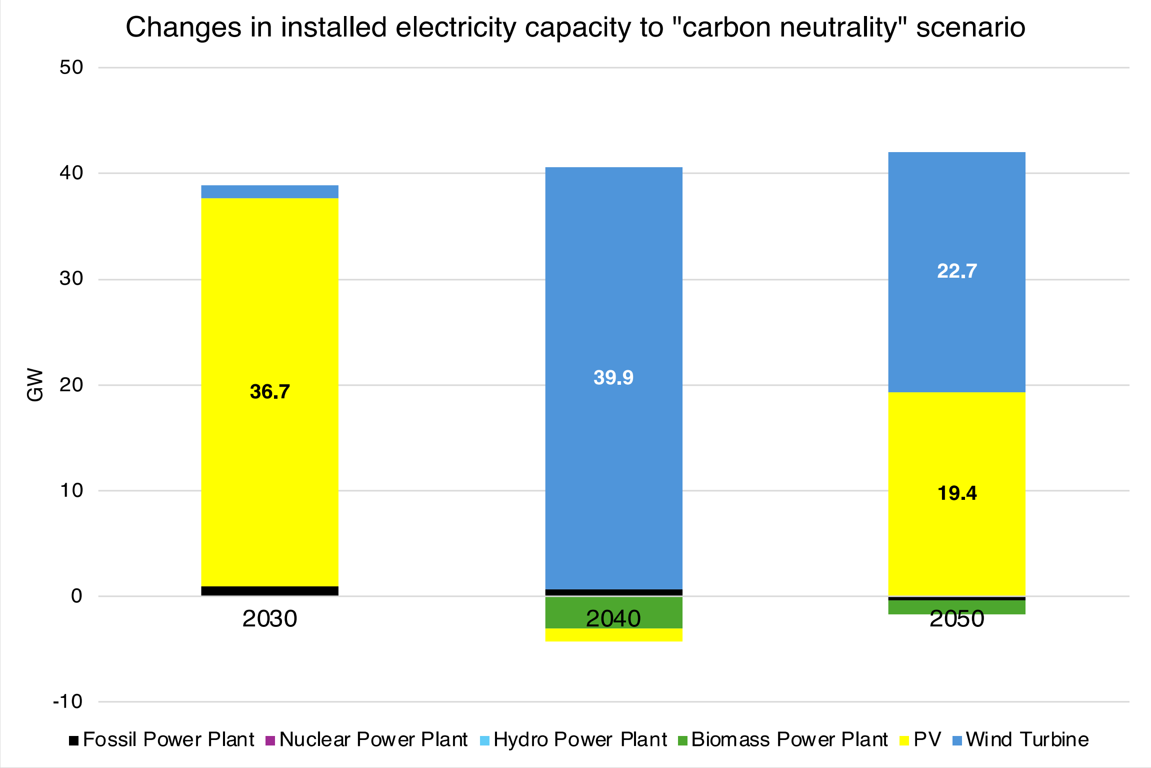


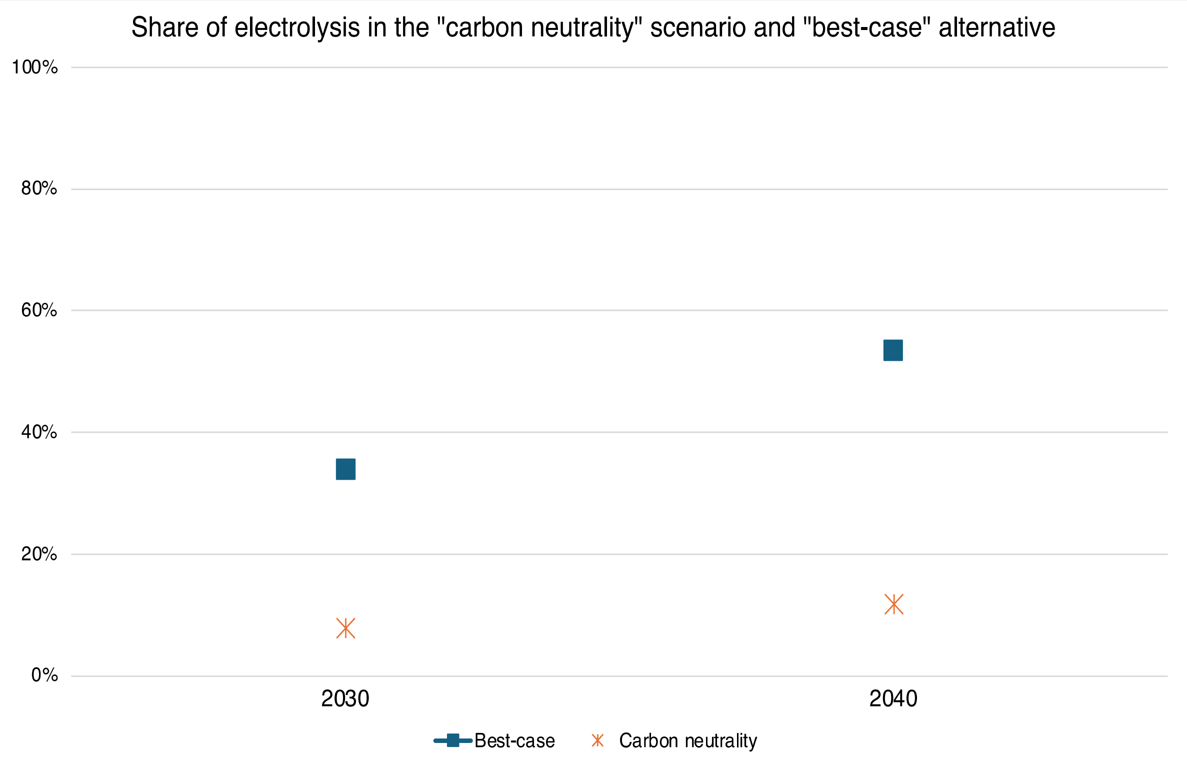
Flexibility options *[GWh]*	Electricity			Hydrogen storage tank
	Transmission	Battery	Hydro reservoir	
2050	↑ 275 %	148.3	→ 0 %	21.0

Detailed results of the “carbon neutrality” scenario

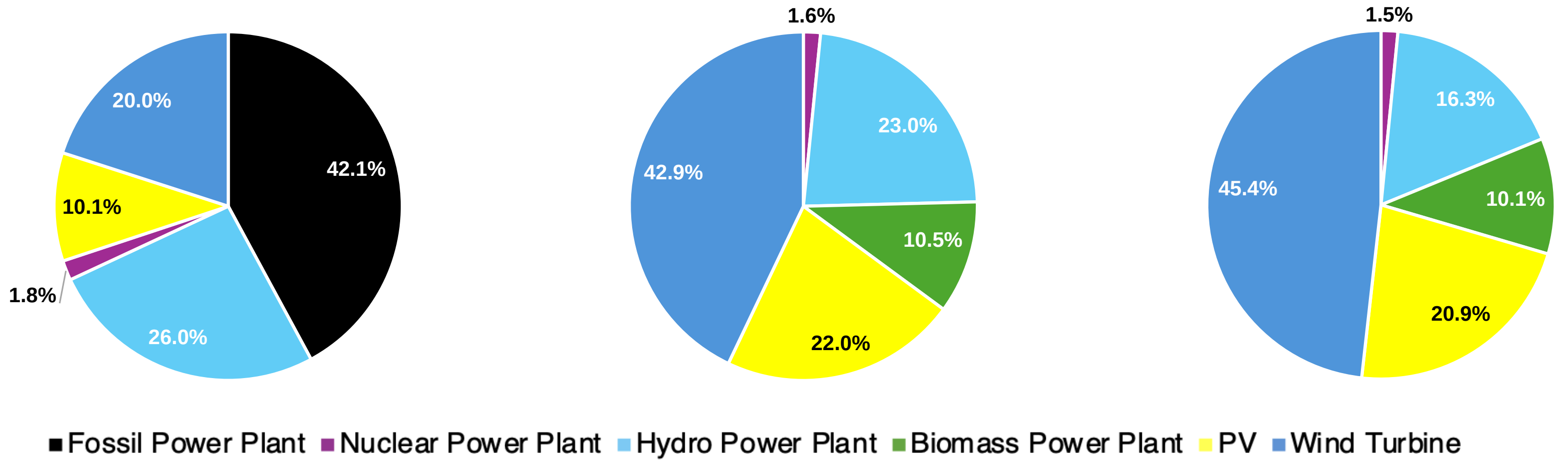


Comparison to the “best-case” sensitivity





Result overview of the remaining scenarios and sensitivities

	Unit	Scenario 2 ”Business-as-usual”	Sensitivity 1 Hydrogen demand	Sensitivity 2 Hydro supply
Installed capacity in 2050	*GW*	413.1	613.6	651.3
Electricity mix in 2050	*%*			
Share of electrolysis in 2040	*%*	3.3 %	36.7 %	18.2 %

Introduction to Life Cycle Assessment

Research Questions 1 and 2

Energy System Modeling

Research Question 3

Life Cycle Assessment

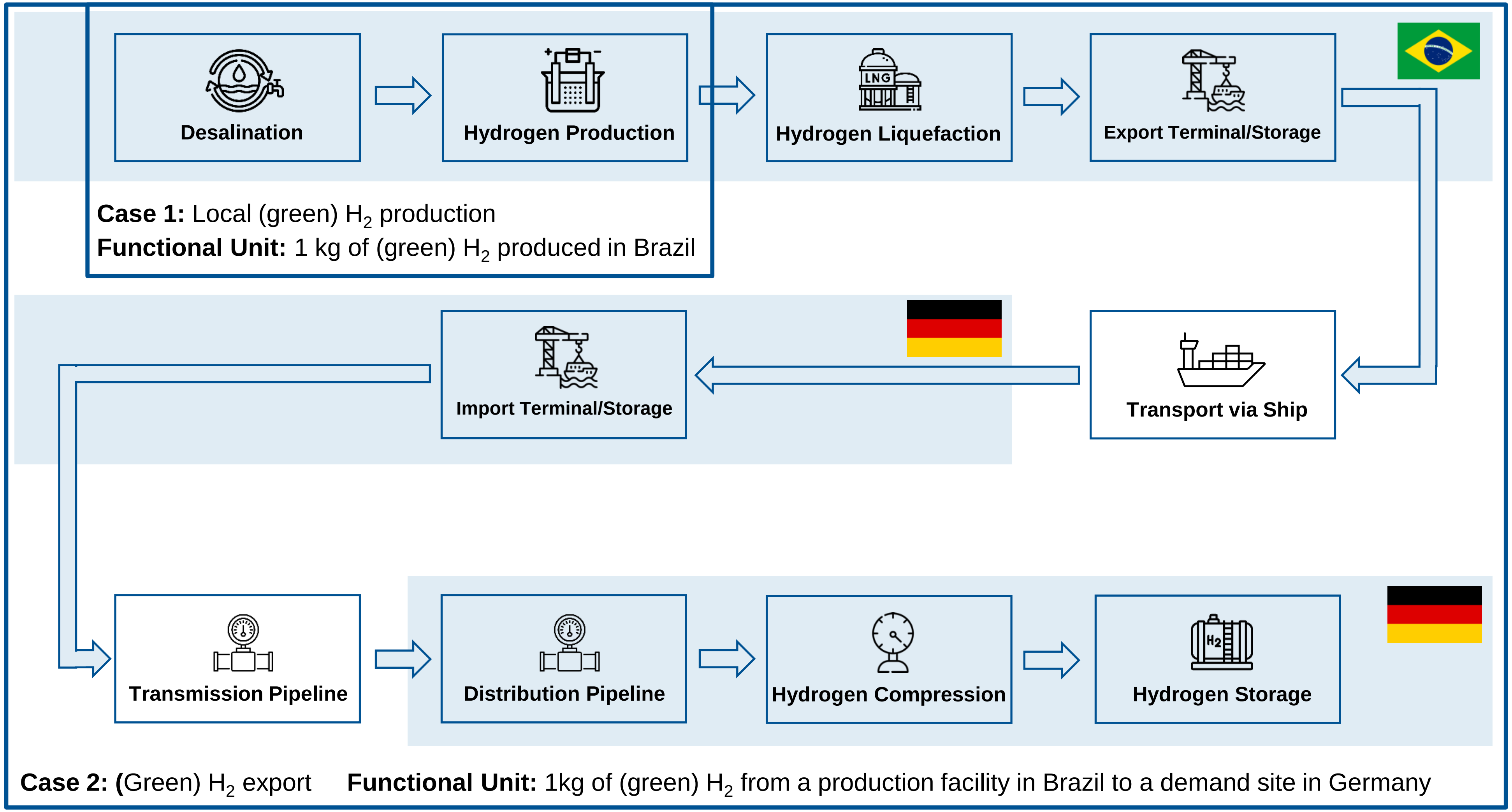
Goal and Scope Definition

Objective
Assessment of environmental viability of importing (green) hydrogen from Brazil to Germany

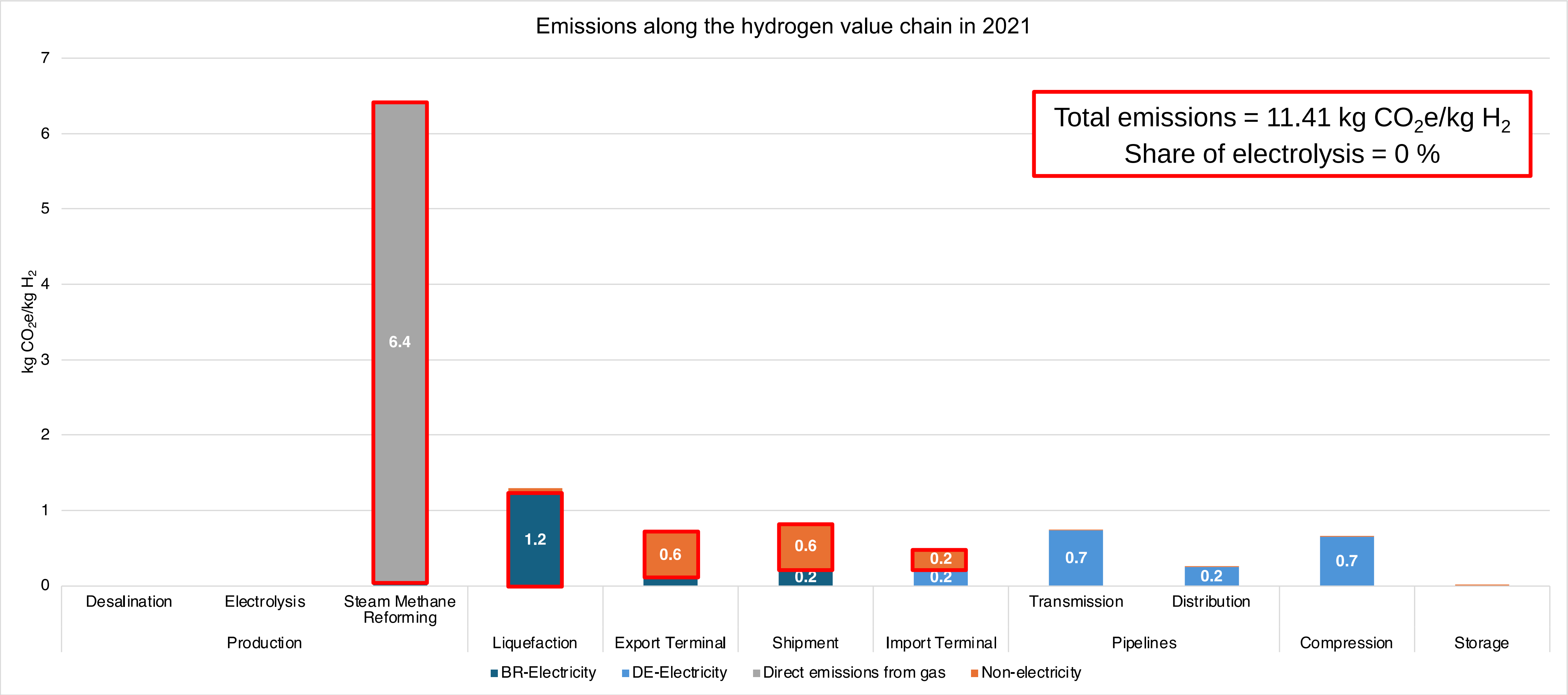
Method		
Comparative analysis of GWP for …		
… producing (green) hydrogen in Brazil and utilizing it locally	vs.	… producing (green) hydrogen in Brazil and exporting it to Germany

Definitions	
Functional unit	**Impact category**
1 kg of (green) hydrogen produced and liquefied in Brazil and imported to a demand site in Germany	Global Warming Potential *[kg CO_2e/kg H_2]*

Goal and **Scope** Definition



Impact Assessment



Impact Assessment

kg CO_2e/kg H_2	"Carbon neutrality"	"Business-as-usual"	"Best-case" alternative
2021	11.41		
2050			
Local production	2.1	6.6	1.9
Rest of the value chain	2.3	4.0	2.3
Total	**4.4**	**10.6**	**4.2**

Interpretation

56 %

of the emissions in 2021 stem from **SMR** along the entire hydrogen value chain

63 %

Emission reduction potential from 2021 to 2050 in the “best-case” alternative

5 %

Difference in 2050 between the emissions of the “carbon neutrality” and the “best-case” scenario only

55 %

Share in emissions in 2050 in the „best-case“ scenario from the **processes after the production**

45 %

of the emissions in 2050 in the “best-case” stem from **infrastructure processes** alone

Answers to the research questions

Research Question 1

Changing Electricity Mix

"How will the Brazilian energy system need to expand and adapt to effectively manage a

- potential significant increase in intermittent power production and
- a surge in electricity demand due to green hydrogen production?"

Research Question 2

Hydrogen Integration

"How can the integration of hydrogen production into Brazil's energy system be optimized to effectively facilitate the transition towards a decarbonized domestic and potentially global energy supply?"

Research Question 3

Global Warming Potential

"How high is the Global Warming Potential associated with

- the local production of hydrogen in Brazil,
- compared to potential hydrogen export scenarios, such as exportation to Germany?"

Agenda

Final Presentation

A Life Cycle Assessment of Green Hydrogen Production and Ammonia-Based Transportation

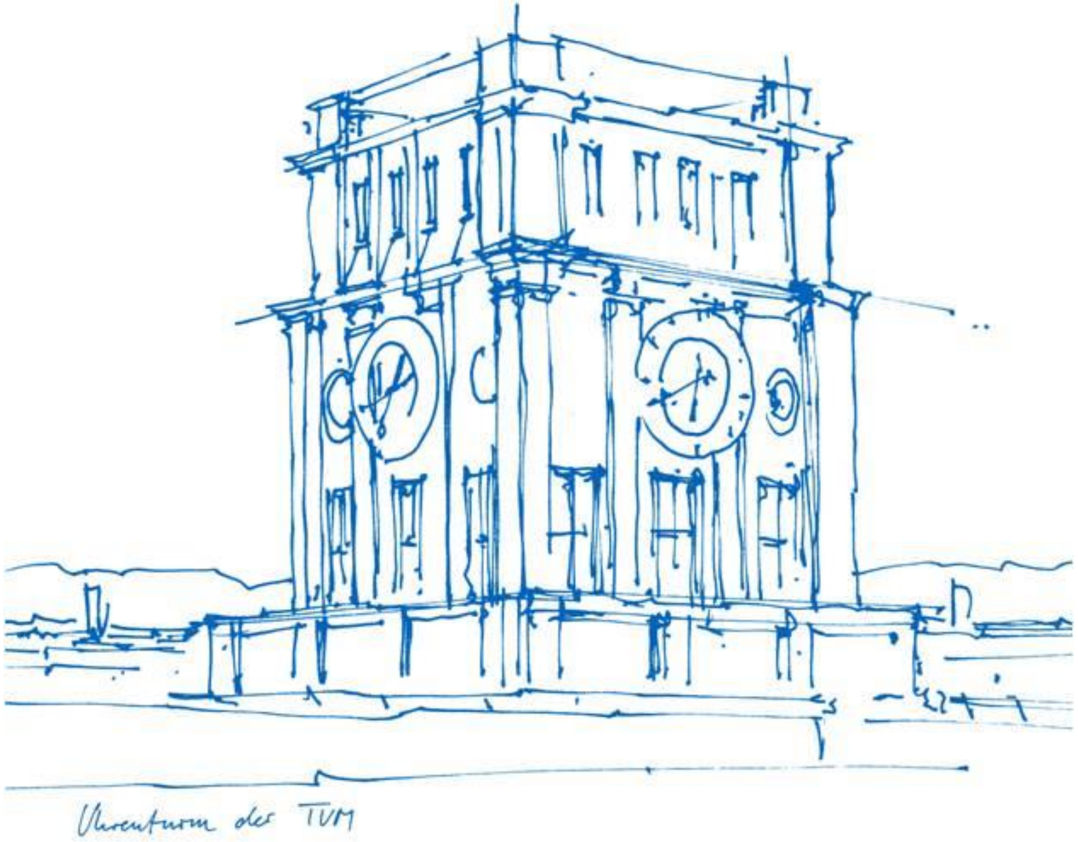
Michael Sonntag

Technical University of Munich

TUM School of Engineering and Design

Chair of Renewable and Sustainable Energy Systems

Munich, 22. January 2024



Introduction

Broader Context

Climate Change

Sustainable & Efficient Energy

Hydrogen

Green Hydrogen

Energy Storage

Energy Source

Feedstock

National Hydrogen Strategy of Germany

Carbon Neutrality → 2050

Market Ramp-Up

New Technology

Ammonia

Hydrogen Carrier

Mature Infrastructure

Export Countries

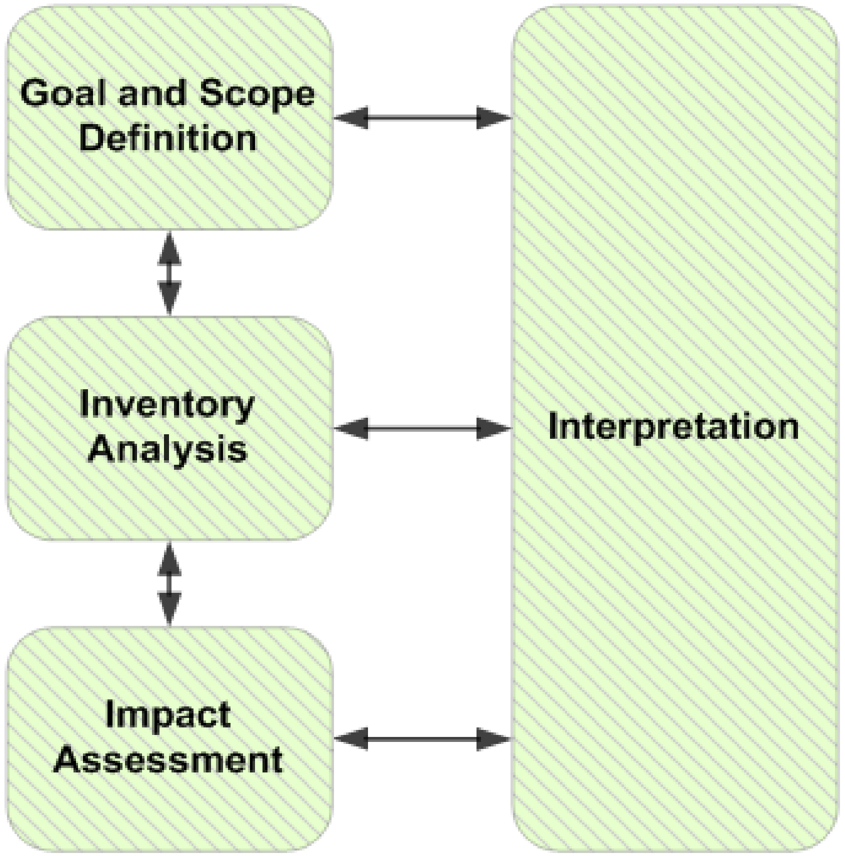
Energy Partnerships

High Potential for Renewables

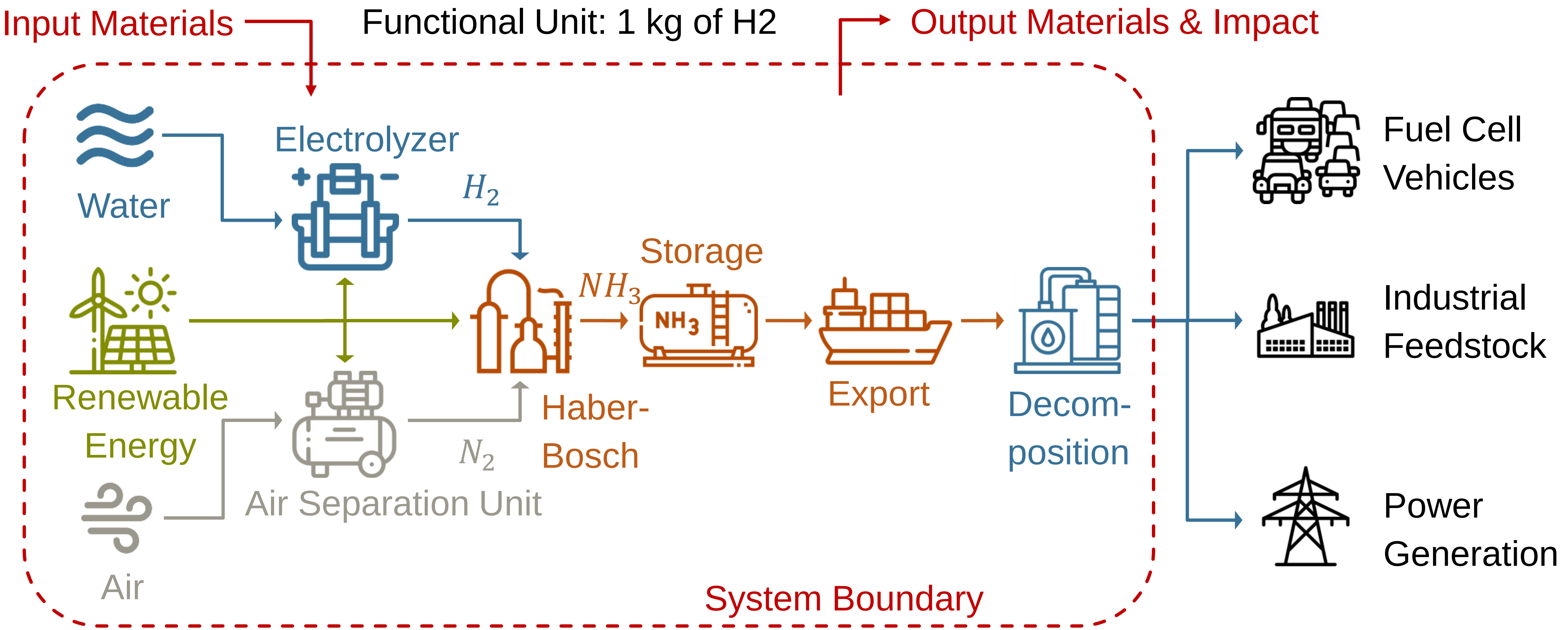
Methodology of the Life Cycle Assessment

- **Goal and Scope Definition**
  - Product System, Functional Unit, System Boundary
- **Inventory Analysis**
  - Create Inventory Flow, Quantify Raw Materials and Energy, Relating Data to Functional Unit, Detail in Charts
- **Impact Assessment**
  - Impact Categories, Characterization, Grouping

→ Interpretation of Results

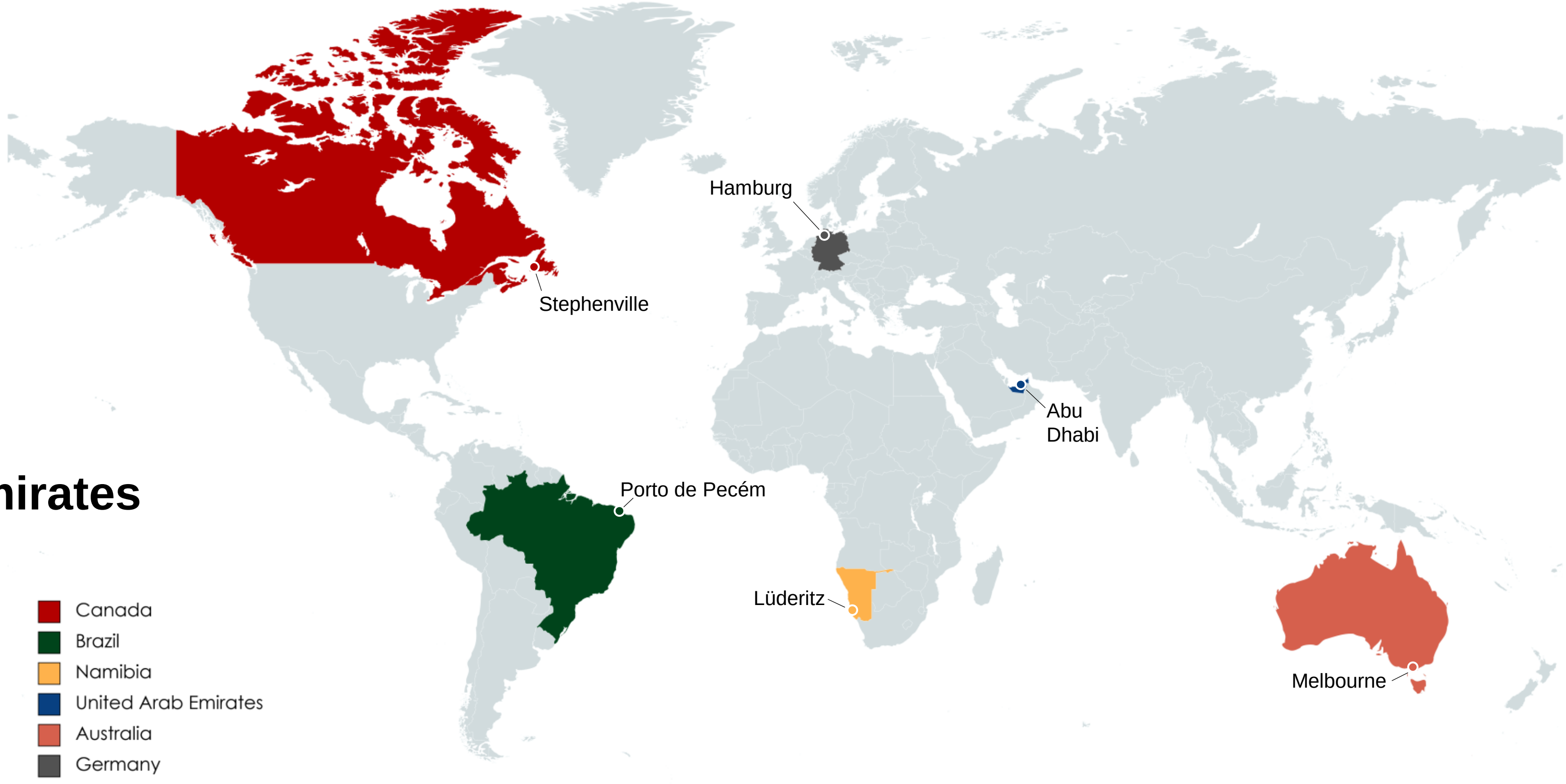


Energy System Description and Boundaries

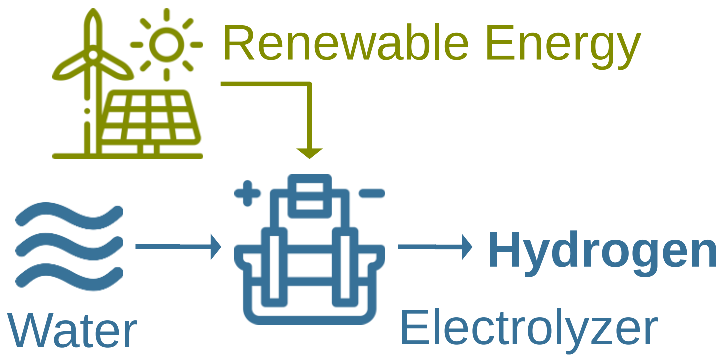


Export Countries

- **Stephenville, Canada**
  - Wind Power
- **Porto de Pecém, Brazil**
  - Solar & Wind Power
- **Lüderitz, Namibia**
  - Solar & Wind Power
- **Abu Dhabi, United Arab Emirates**
  - Solar Power
- **Melbourne, Australia**
  - Solar Power

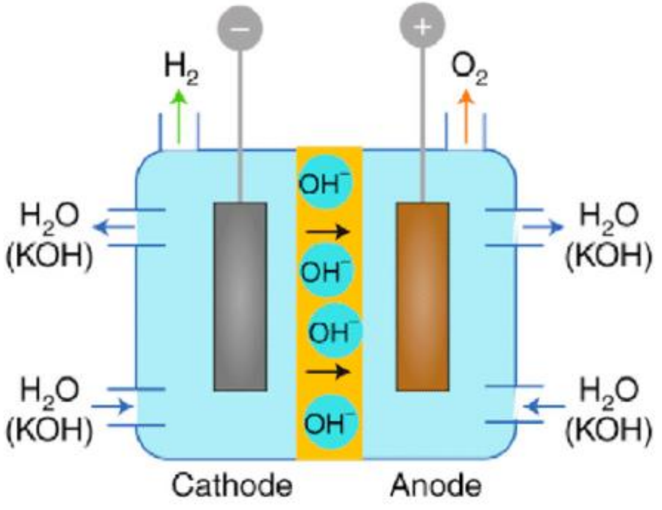


Water Electrolysis Technology



- Electricity is used to split water into hydrogen and oxgen
  - $2H_2O \rightarrow 2H_2 + O_2$
- Output: 1 kg Hydrogen
- Input: 10 kg Water + 180 MJ Electricity

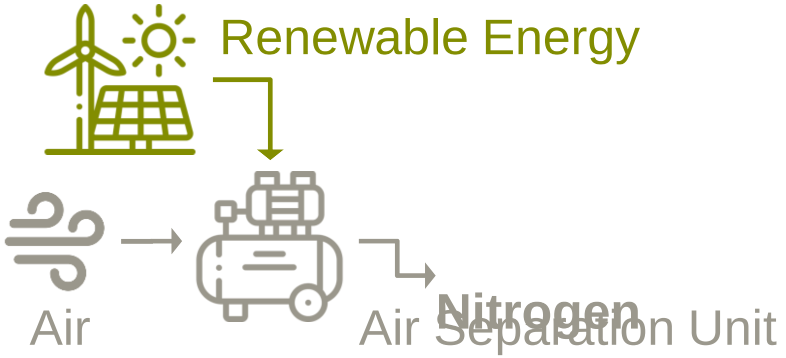
	Alkaline	PEM	Solid Oxide
Technology	Mature	Semi-Mature	Development
Flexibility	Low	High	Low
Efficiency	Low	High	High
Cost	Low	High	High

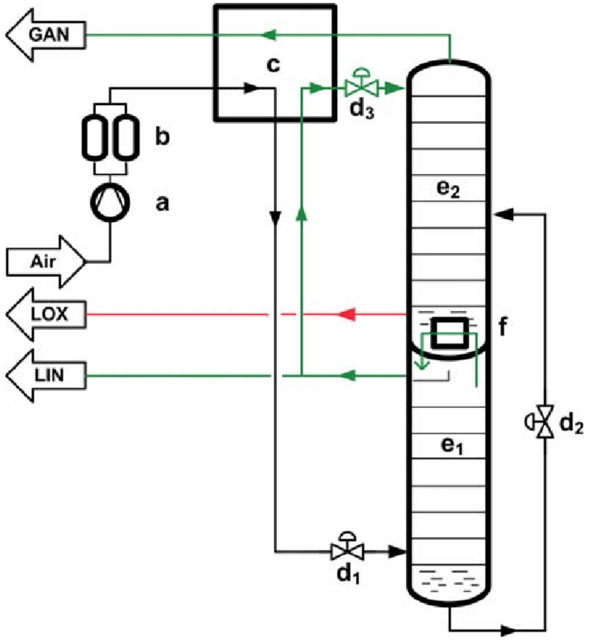


Air Separation Technology

- Difference in boiling points is used to separate gases
  - Nitrogen: 77.4 K, Oxygen: 90.2 K, Argon 87.3 K
- Ouput: 1 kg Nitrogen
- Input: 1.31 kg Air + 2.88 MJ Electricity

	Cryogenic	Pressure Swing	Membrane
Technology	Mature	Semi-Mature	Semi-Mature
Flexibility	Low	High	High
Efficiency	High	Low	Low
Purity	High	High	Low

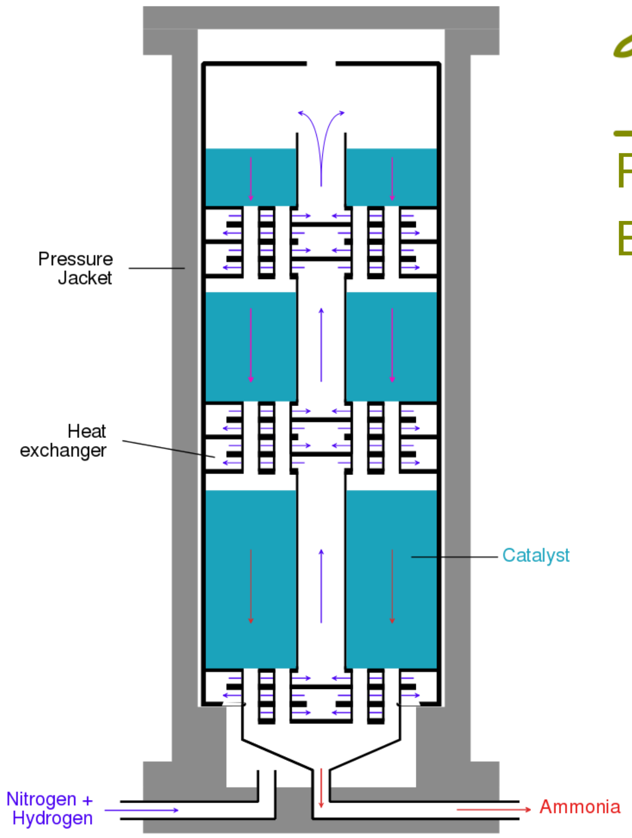


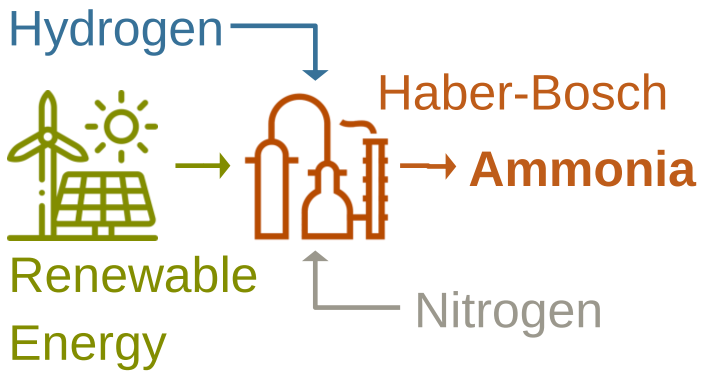


Ammonia Synthesis

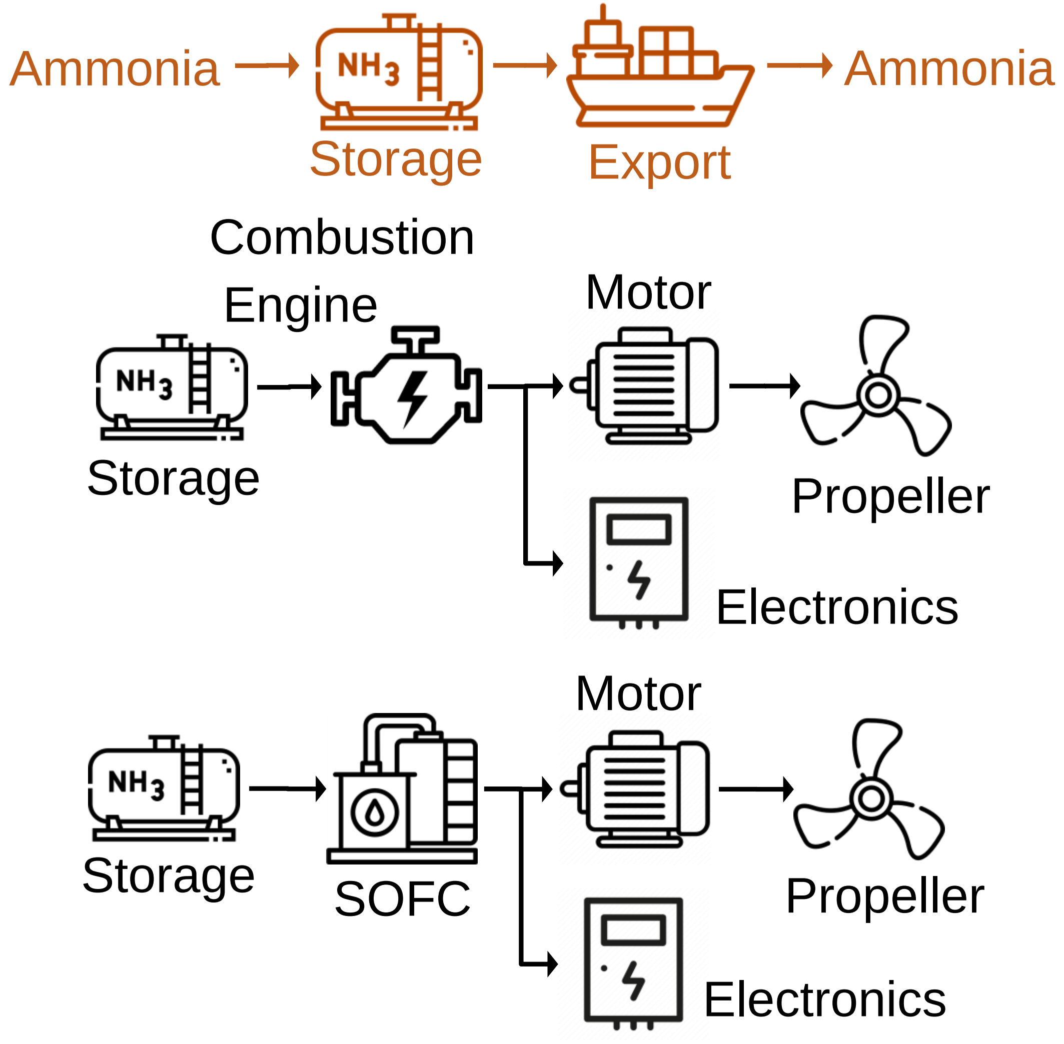
- Heat, pressure and the catalyst start reaction
  - $3H_2 + N_2 \rightarrow 2NH_3$
- Output: 1 kg Ammonia
- Input: 0.82 kg Nitrogen + 0.18 kg Hydrogen + 1.7 MJ Electricity

- Mature technology (used for 100 years)
- Need for constant stream of electricity





Transportation

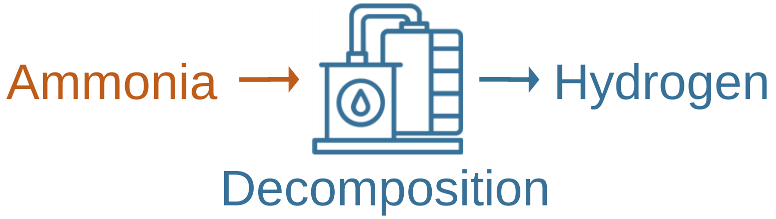


- Liquid Carrier: 173.6 mio. liter of liquids
- Storage in cryogenic tanks
  - Boil-Off Gas

- Using ammonia as fuel
  - Internal Combustion Engine → NO_x $Emissions$
  - Solid Oxide Fuel Cell + Electric Motor

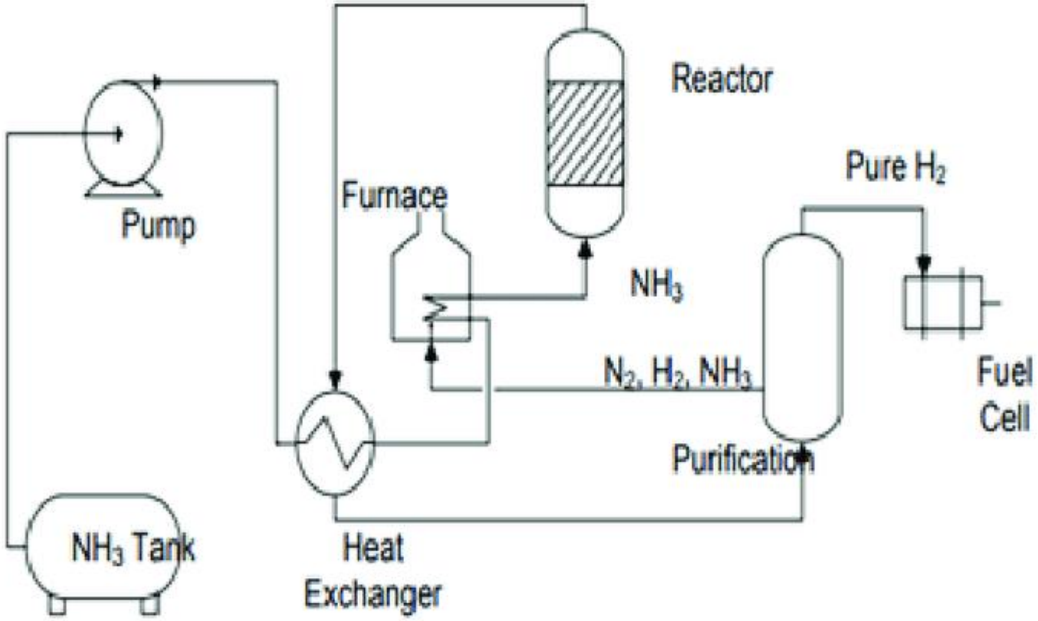
- Average Speed of the ship is at 10 kn
- Boil-Off Gas can be used (avg. 1.91 kg/s)
- Fuel consumption: 2.35 kg/s

Ammonia Decomposition



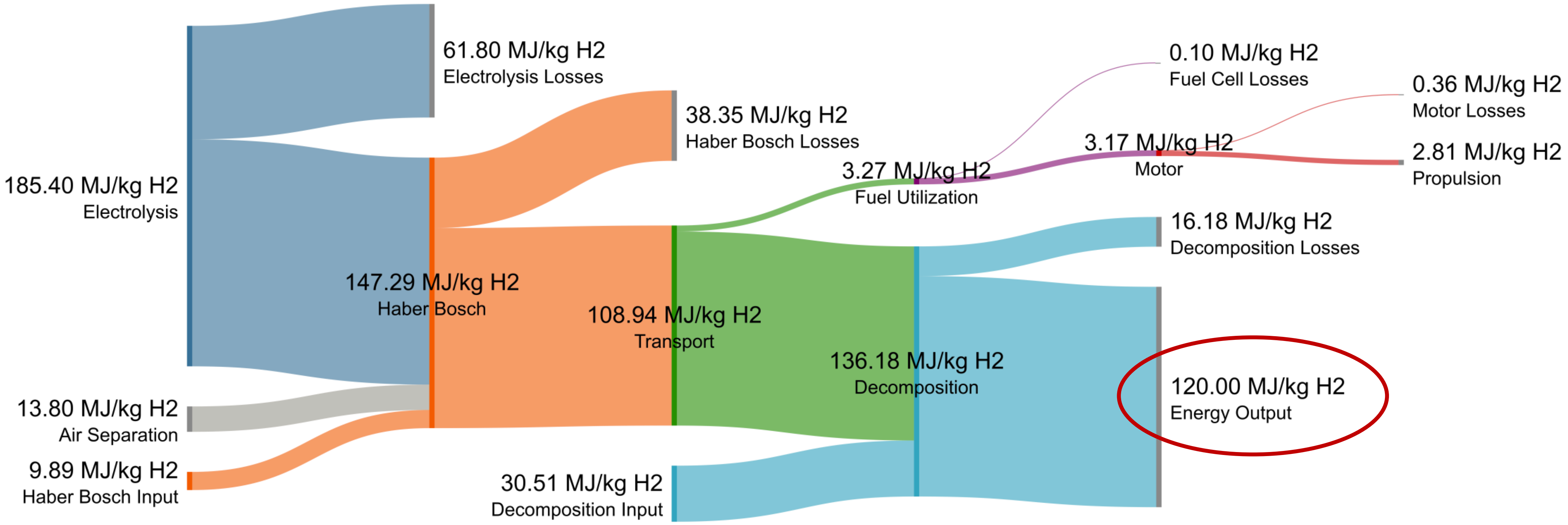
- Utilized heat to „crack“ ammmonia into hydrogen and oxygen
- $2NH_3 \rightarrow N_2 + 3H_2$
- Output: 1 kg Hydrogen
- Input: 5.65 kg Ammonia + 30.51 MJ Electricity

- Most challenging technical aspect
- No large scale units
- Thermal Decomposition most promising

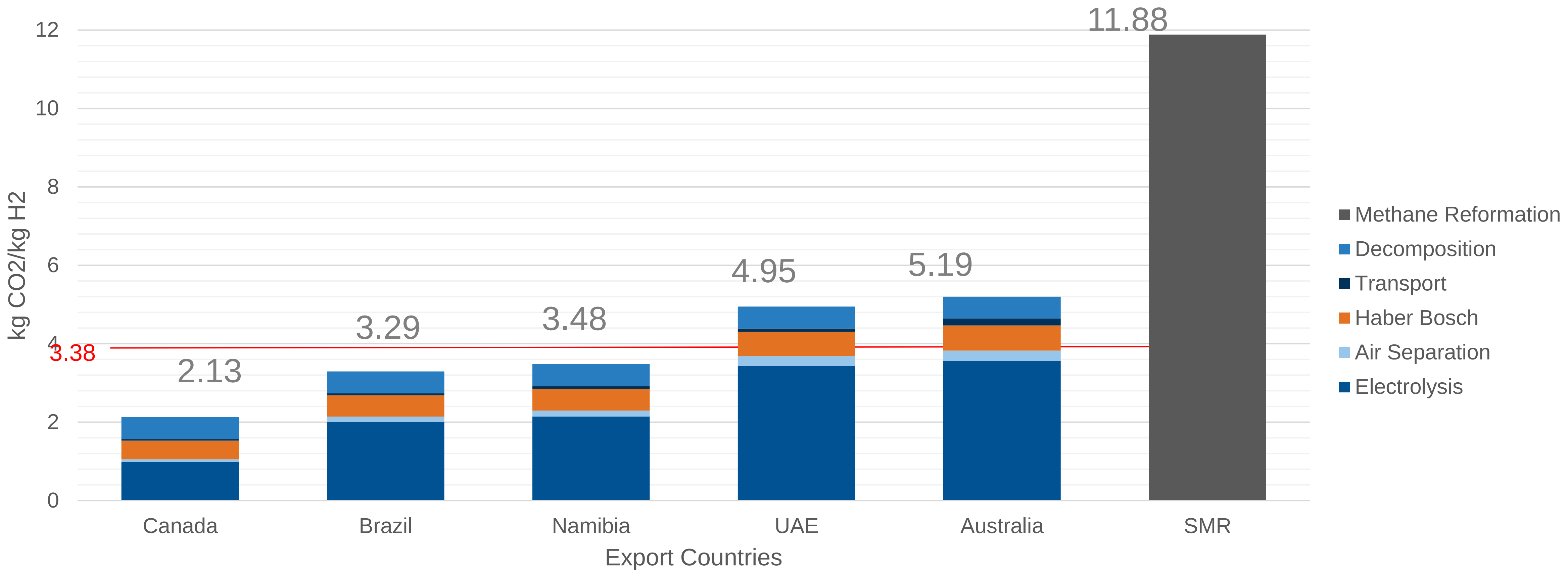


Energy Efficiency of the System

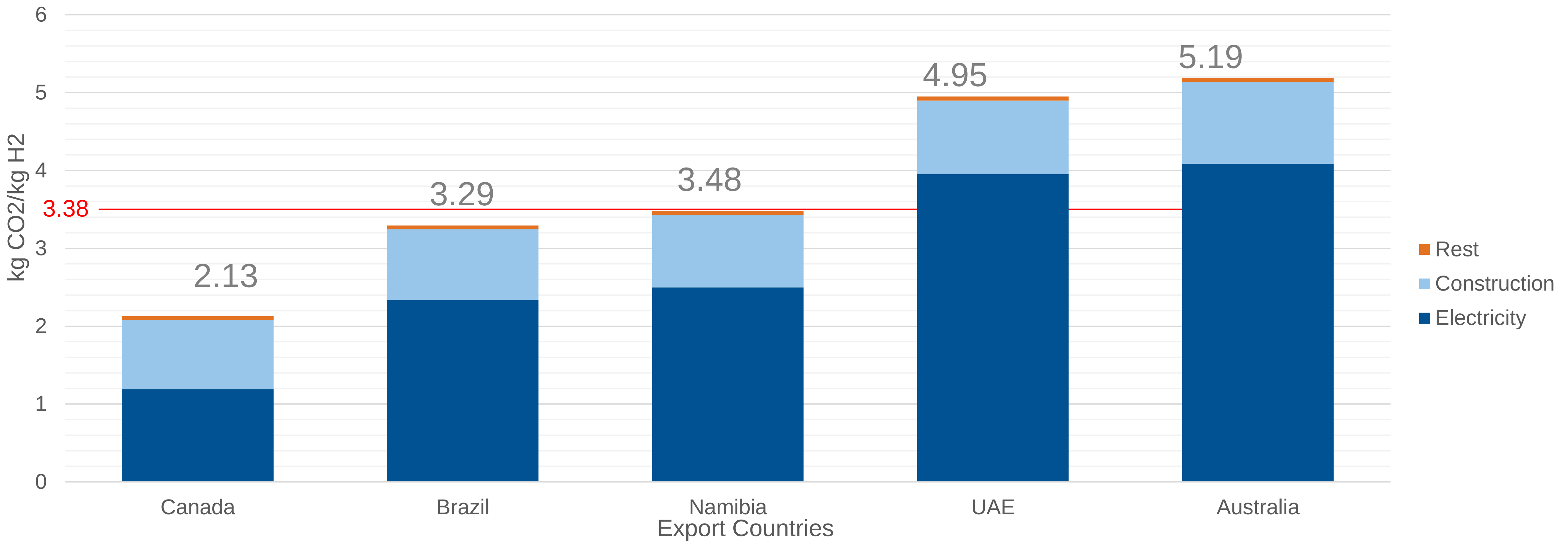
Total Input: 239.60 MJ/kg H2 Total Output: 120 MJ = LHV of 1 kg H2 Efficiency: ~50%



Impact on the Global Warming Potential



Share of the Global Warming Potential



Conclusion and Further Research

Conclusion

- 50% efficiency for energy input
- Climate impact: ${}^{1}/_{2} - {}^{1}/_{6}$ of SMR
- Impact of transportation is small
  → Diversification possible
- Biggest impact from power generation
- Wind power > solar power

Further Research

- Compare different technologies
- Compare different power sources
- In-depth look at the existing technologies
- Improving the models
- Waste treatment