Friedrich-Alexander-Universität
Fachbereich Wirtschafts- und
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The Industry Transformation from Fossil Fuels to Hydrogen will reorganize Value Chains: Big Picture and Case Studies for Germany

Jonas Egerer, **Nima Farhang-Damghani**, Veronika Grimm and Philipp Runge

Chair of Economic Theory, Friedrich-Alexander-University Erlangen-Nürnberg (FAU)

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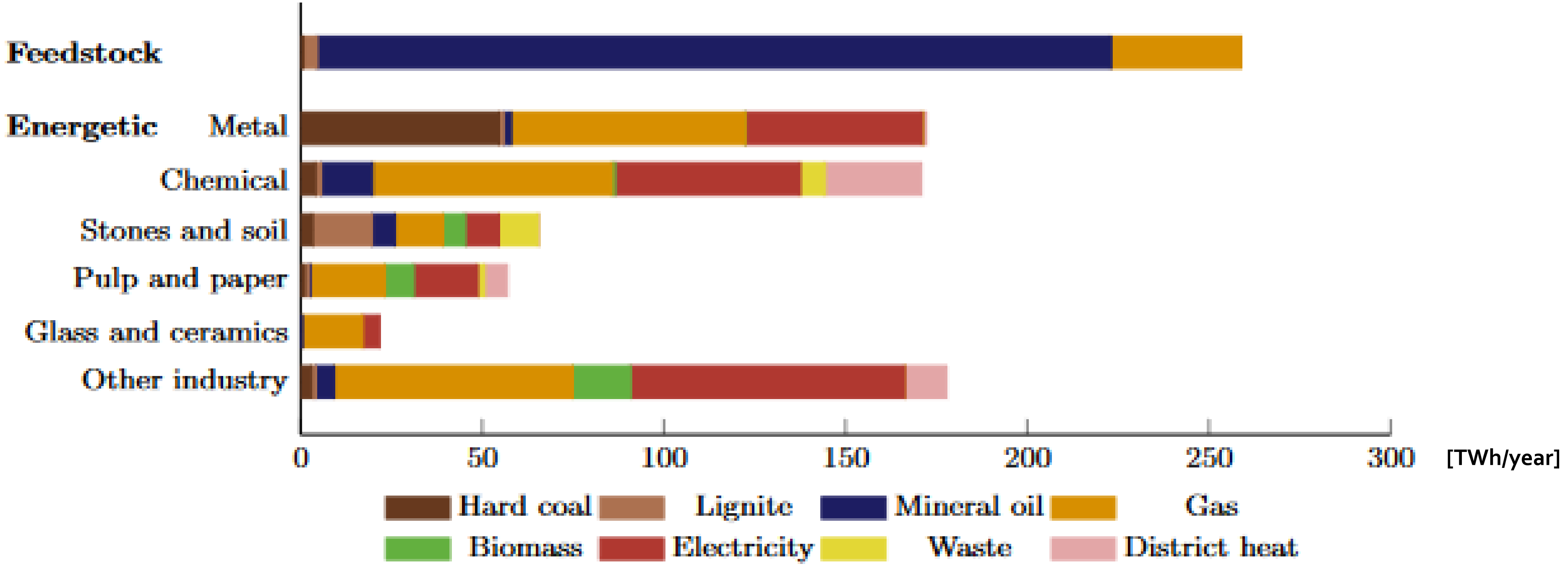
Motivation: 1) What role can hydrogen play in the decarbonization of the German industry?

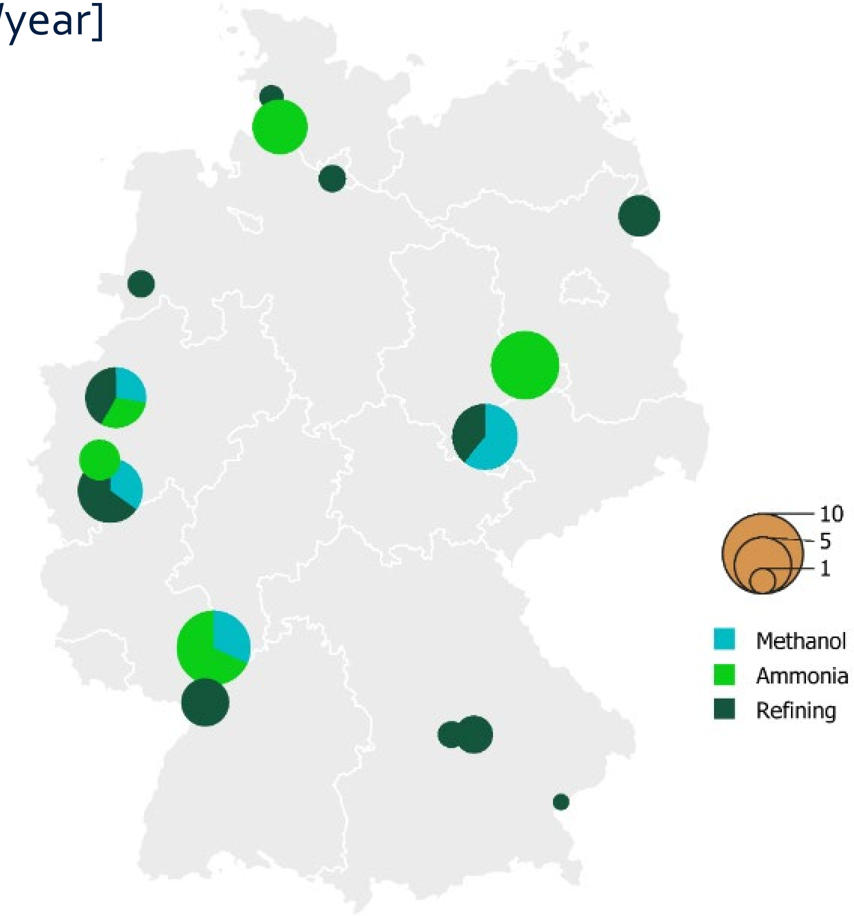
<u>Assumption that current production remains in Germany:</u>

- Demand as **feedstock** for chemical and metal industry (H-atoms)
- Demand for high temperature **heat and steam** in mineral and paper industry (fuel without C-atoms)
- <u>Not</u> topic of paper: Fossil fuel/feedstock conversion (refineries / coke ovens), i.e., future source of C-atoms?



Motivation: 1) What role can hydrogen play in the decarbonization of the German industry?

Today's (fossil) hydrogen demand in Germany in [TWh/year]

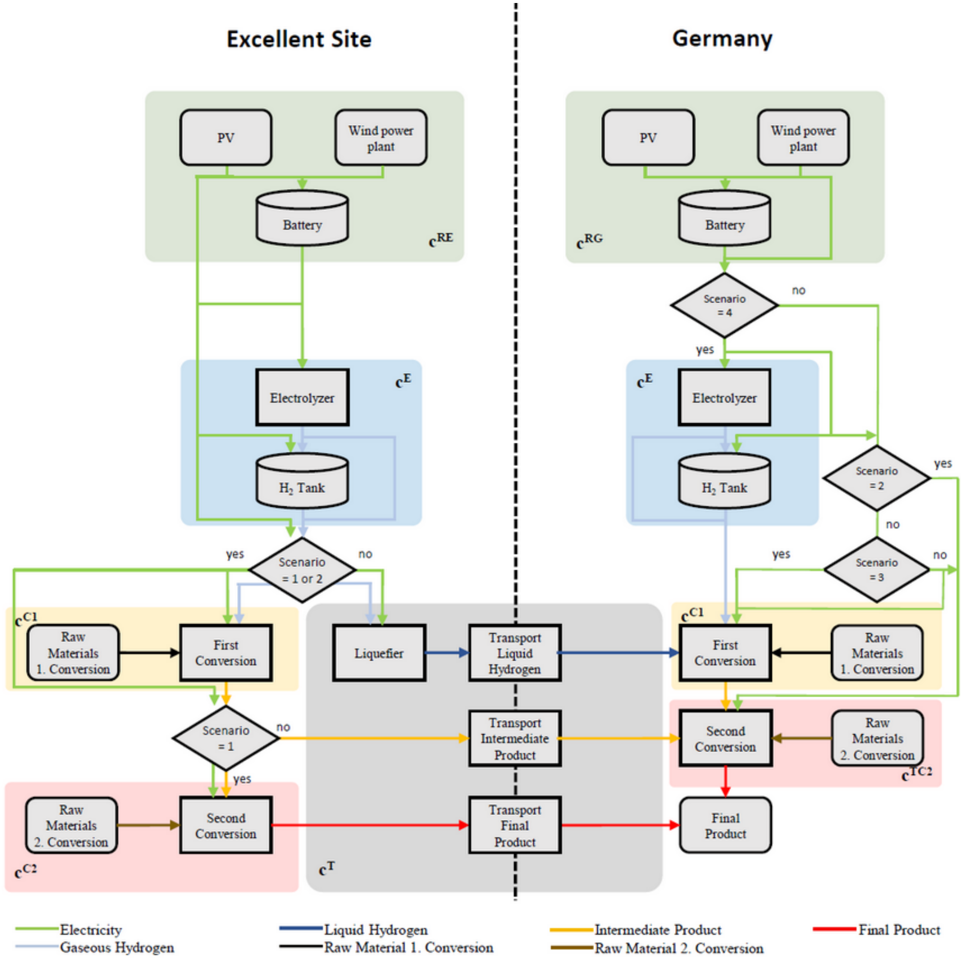


Ammonia	19.4 TWh
Refineries	22.4 TWh
Methanol	9.5 TWh
Total	55 TWh

Mainly produced onsite (steam reforming of natural gas) and in refineries as by-product

- Potential to replace hydrogen produced from fossil sources
- Demand as feedstock and energy carrier increases if industrial value chains switch to carbon-neutral production
- Annual demand of ~100 TWh in 2030 (NHS)
- What is the future demand for hydrogen in industry?

Motivation: 2) Case study on value chains of downstream products



Focus on:

- **Steel by H2-DRI**
- **Urea by Ammonia**
- **Ethylene by Methanol**

1) Hydrogen in the German industry: **Approach – Demand calculation**

Sources	Inputs	Result
▪ EU Emission Trading Scheme ▪ Sector-specific studies, reports and papers ▪ Association websites/databases ▪ Company reports	▪ 2021 production / capacity data ▪ Specific energy consumption ▪ Total energy demand per sector ▪ Fuel share forecasts and studies ▪ Current fuel mix shares for each process ▪ ETS plant emission data ▪ ETS plant locations ▪ Stoichiometry ▪ Efficiencies	Total hydrogen demand for each sector/process and each plant

Further underlying assumptions:

- Production data of 2021 stays constant in the future
- No specific reference year for climate-neutrality

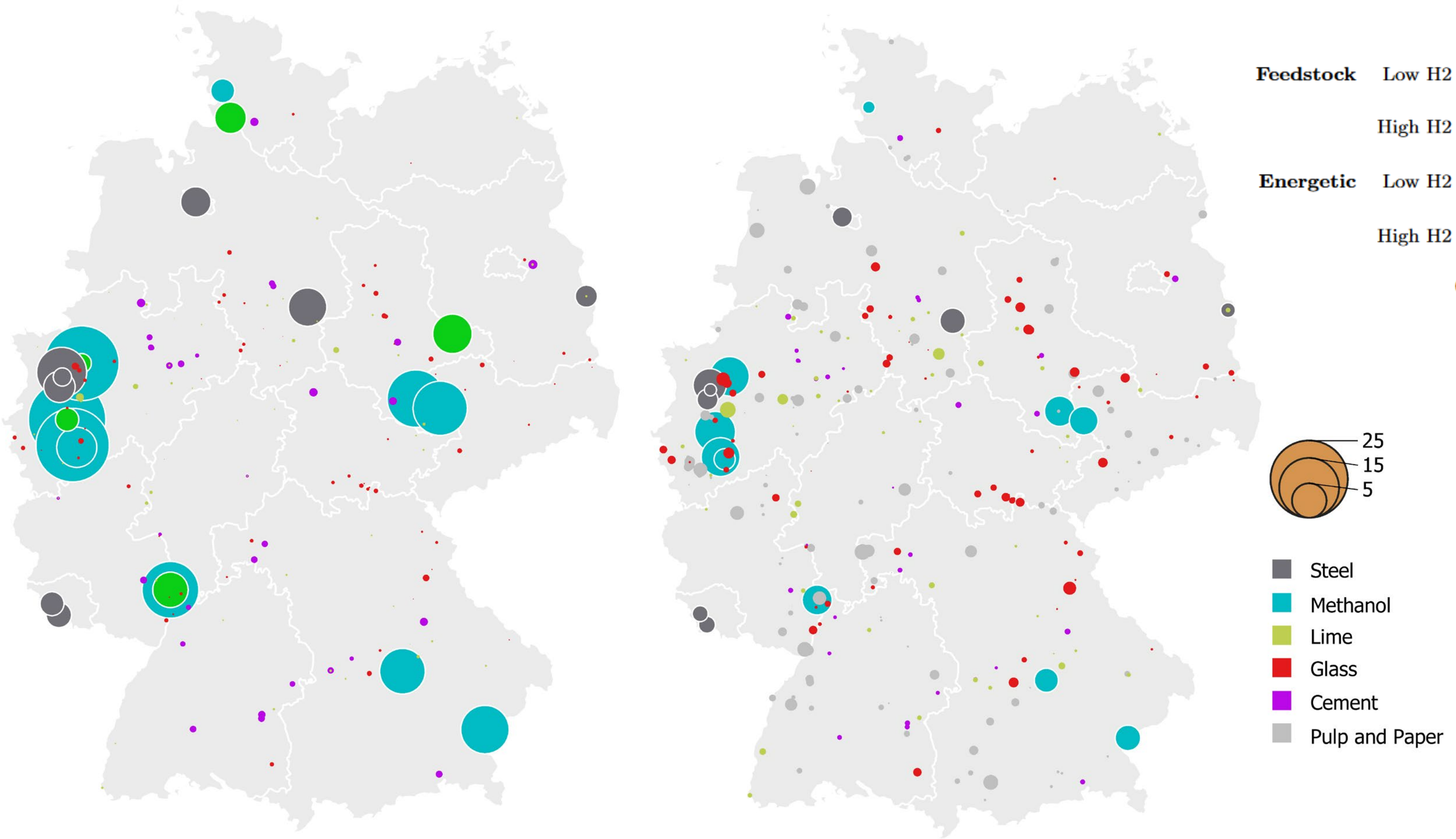
1) Hydrogen in the German industry: **Approach – Scenarios**

Assumptions on hydrogen shares:

- Lower and higher scenario for hydrogen utilization in each process
- Lowest and highest hydrogen utilization share considered after careful literature review for different possible fuel and technology shares for each analyzed production process

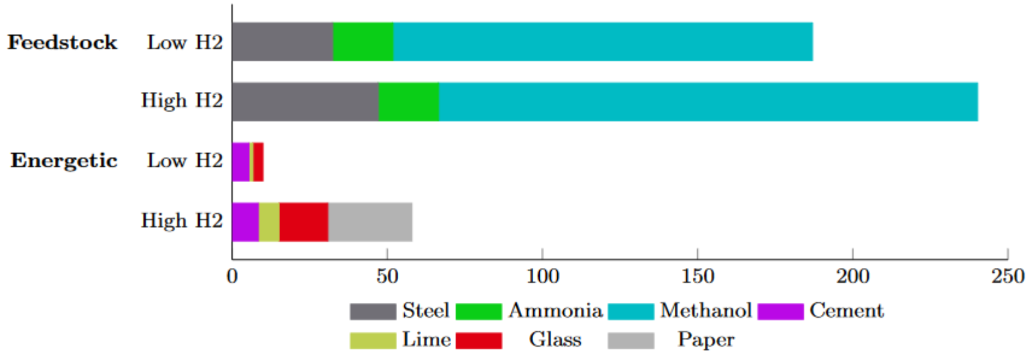
Sector	# of plants	Low H_2 share, %	High H_2 share, %	
Crude steel	8	40.6	59.0	Recycling quota
Ammonia	5	100.0	100.0	No alternative
Methanol	10	60.0	85.0	Bio-MeOH, FTS
Cement clinker	33	20.0	30.8	Ideal vs. fossil sub
Lime	57	20.0	100.0	Cf. cement, no bio
Glass	75	20.0	100.0	Low ideal vs High
Paper	141	0.0	71.5	None vs. Replace fossil

1) Hydrogen in the German industry: **Resulting hydrogen demand and distribution**, in [TWh/year]



Lower bound scenario

Δ between higher and lower H_2 demand scenarios



Sector	Low H_2	High H_2
Steel	32.4	47.1
Ammonia	19.4	19.4
Methanol	135.2	173.7
Total feedstock	187.0	240.2
Cement	5.4	8.4
Lime	1.3	6.7
Glass	3.2	15.7
Pulp and Paper	—	27.1
Total energetic	9.9	57.9
Total	**196.9**	**298.1**

2) Case study on value chains: **Cost perspective for the transformation of value chains**

Model

Optimization model:

Obj: Minimize total costs of each value chain incl. transport (green hydrogen, intermediate or final products)

Objective Function

$$\min c = c^{RE} + c^{RG} + c^{E} + c^{C1} + c^{C2} + c^{T}$$

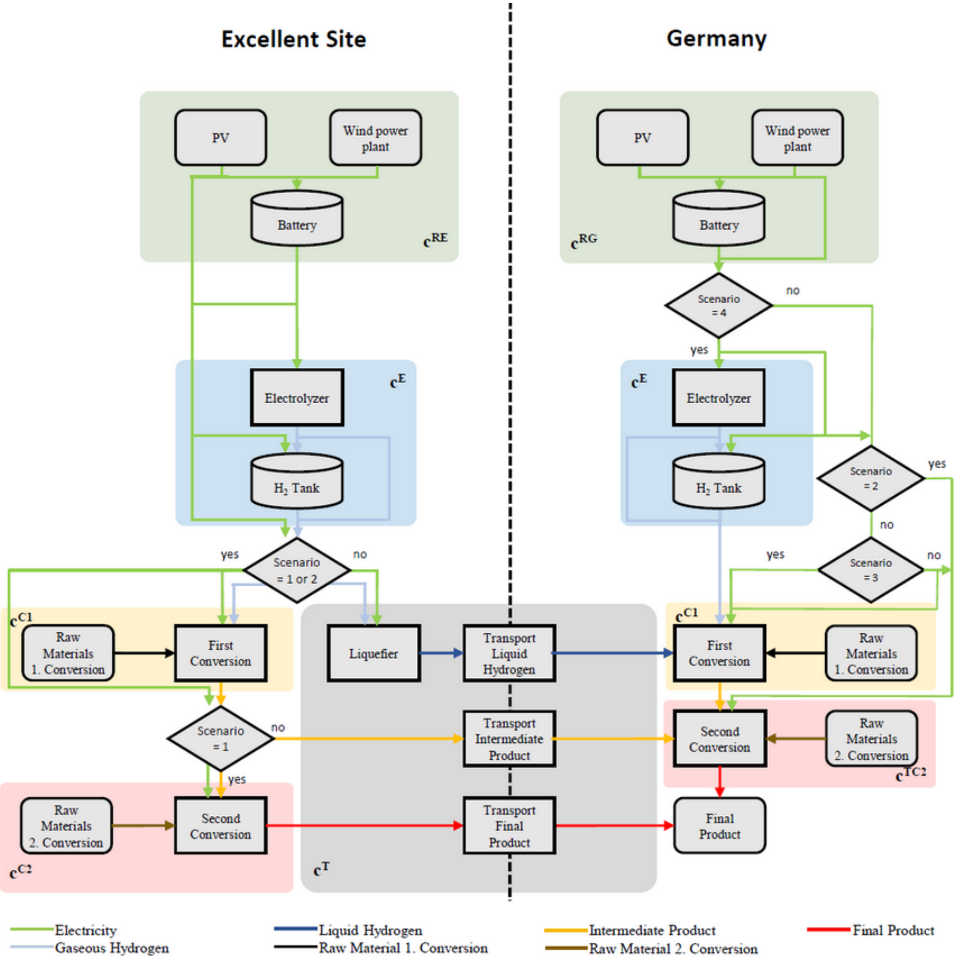
Parameters

CAPEX/OPEX, Renewable energy vectors, storage, transport distance, raw materials, …

Decision Variables

Levelized Costs of final product in €/t

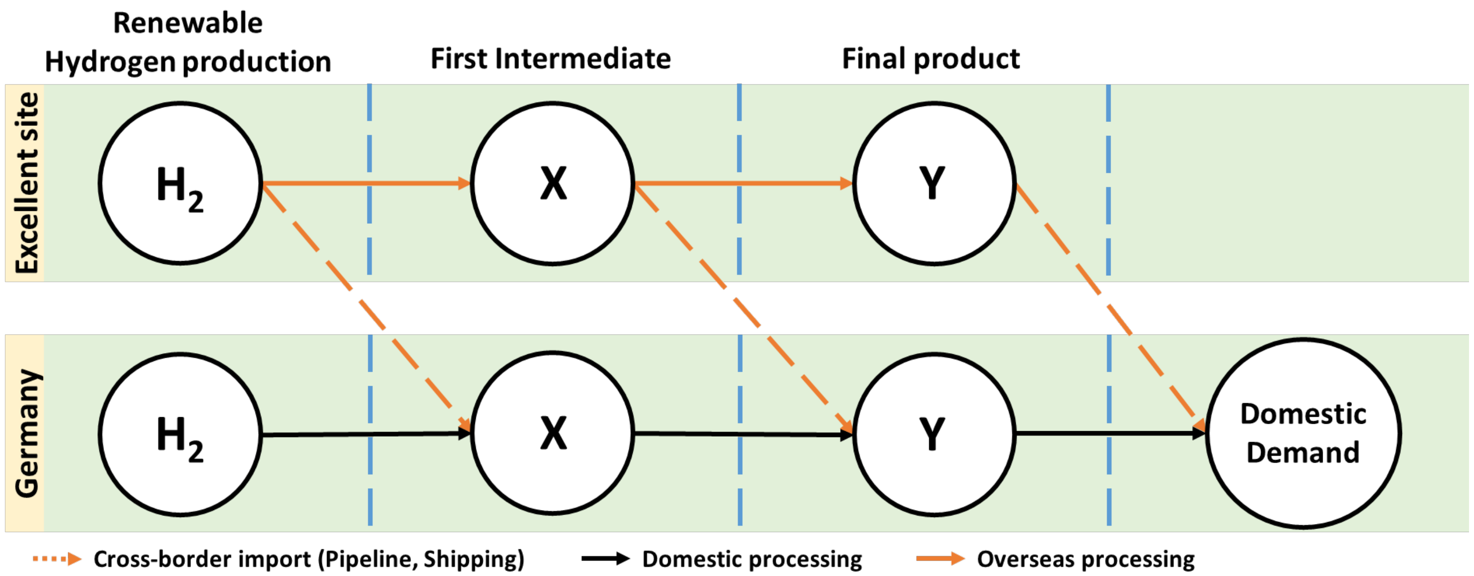
Capacities of conversion and production plants



2) Case study on value chains: **Steel, Ethylene, and Urea**

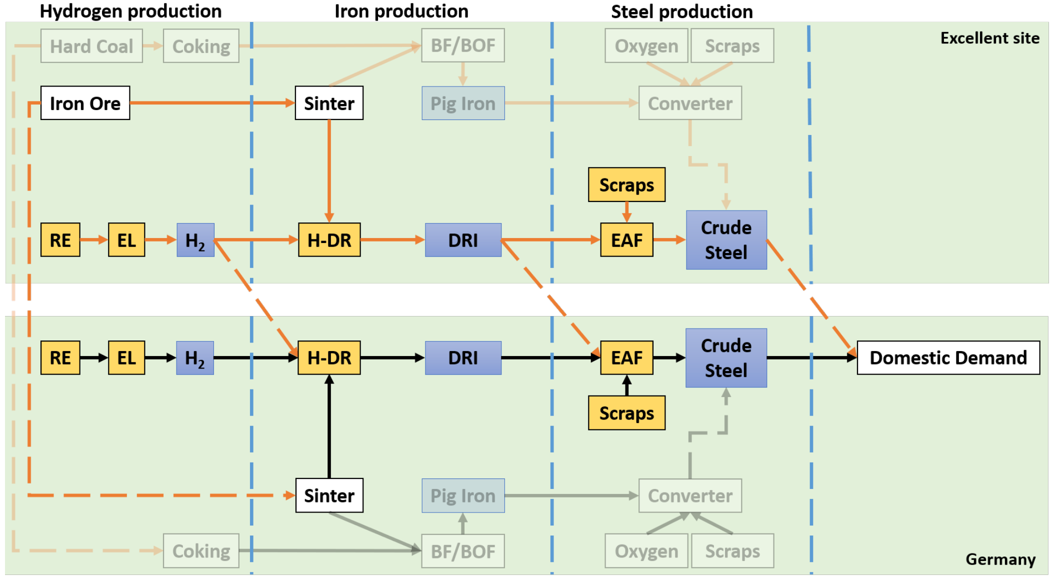
Different levels of relocation from Germany to "excellent site":

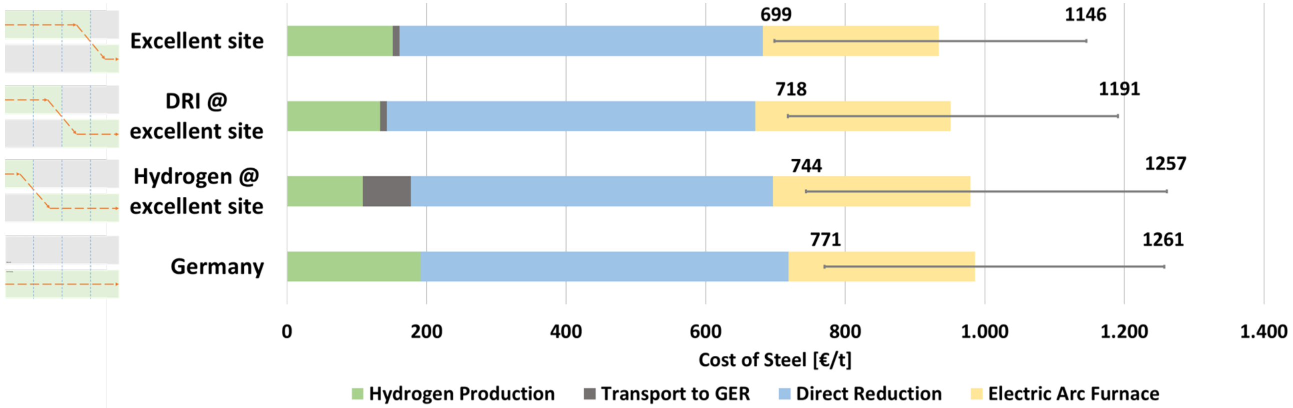
- Full domestic production in Germany
- Relocation of hydrogen production + import
- Relocation including first intermediate product + import
- Complete relocation of value chain + import



2) Case study on value chains: **Steel**

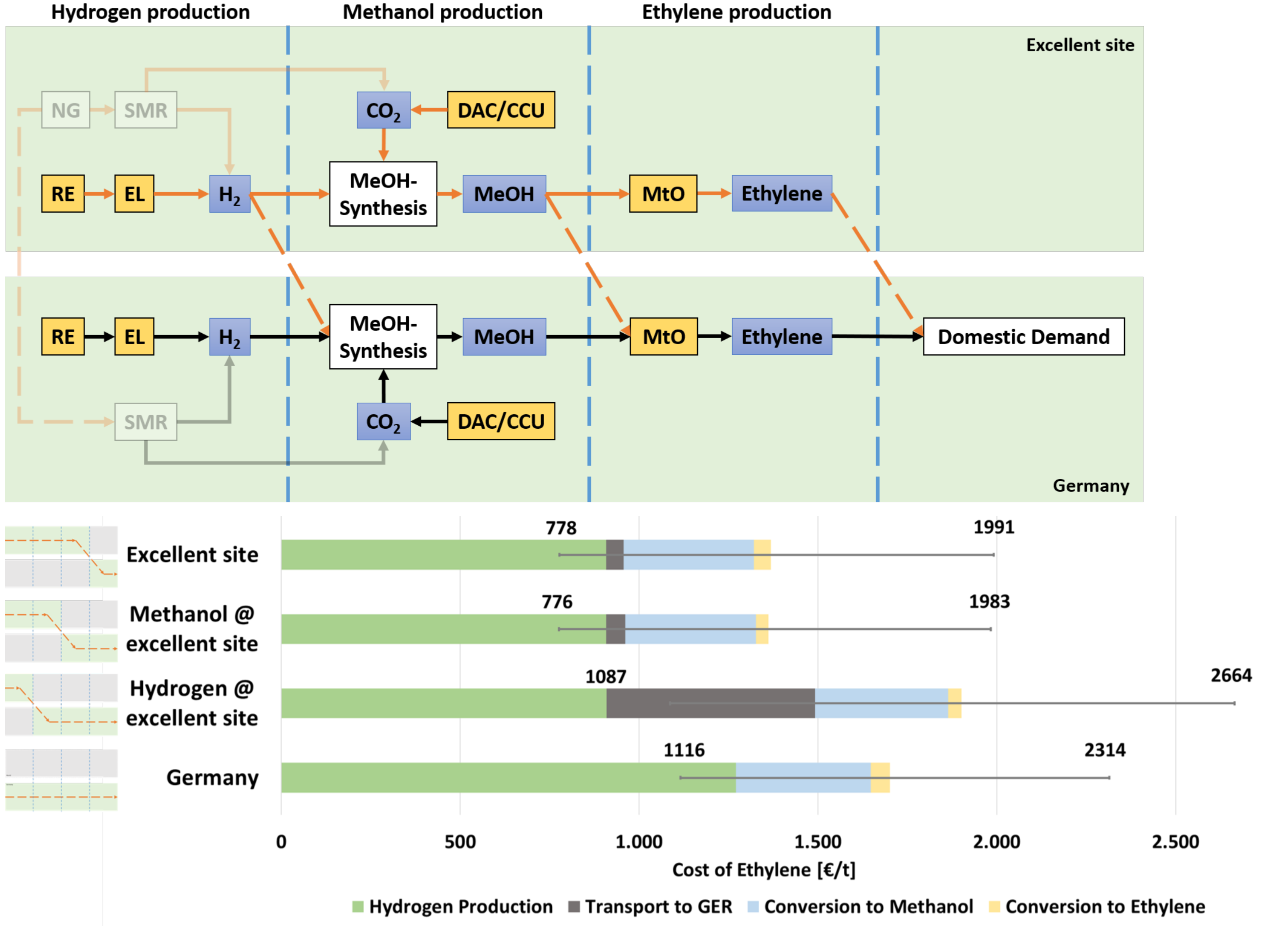
- Hydrogen has a rather small share of 11-19% of the total levelized costs of steel
- Relocation may be less a matter of cost but more of location advantages such as workforce and customer proximity
- Overall small cost advantages when steel value chain is relocated to favorable sites





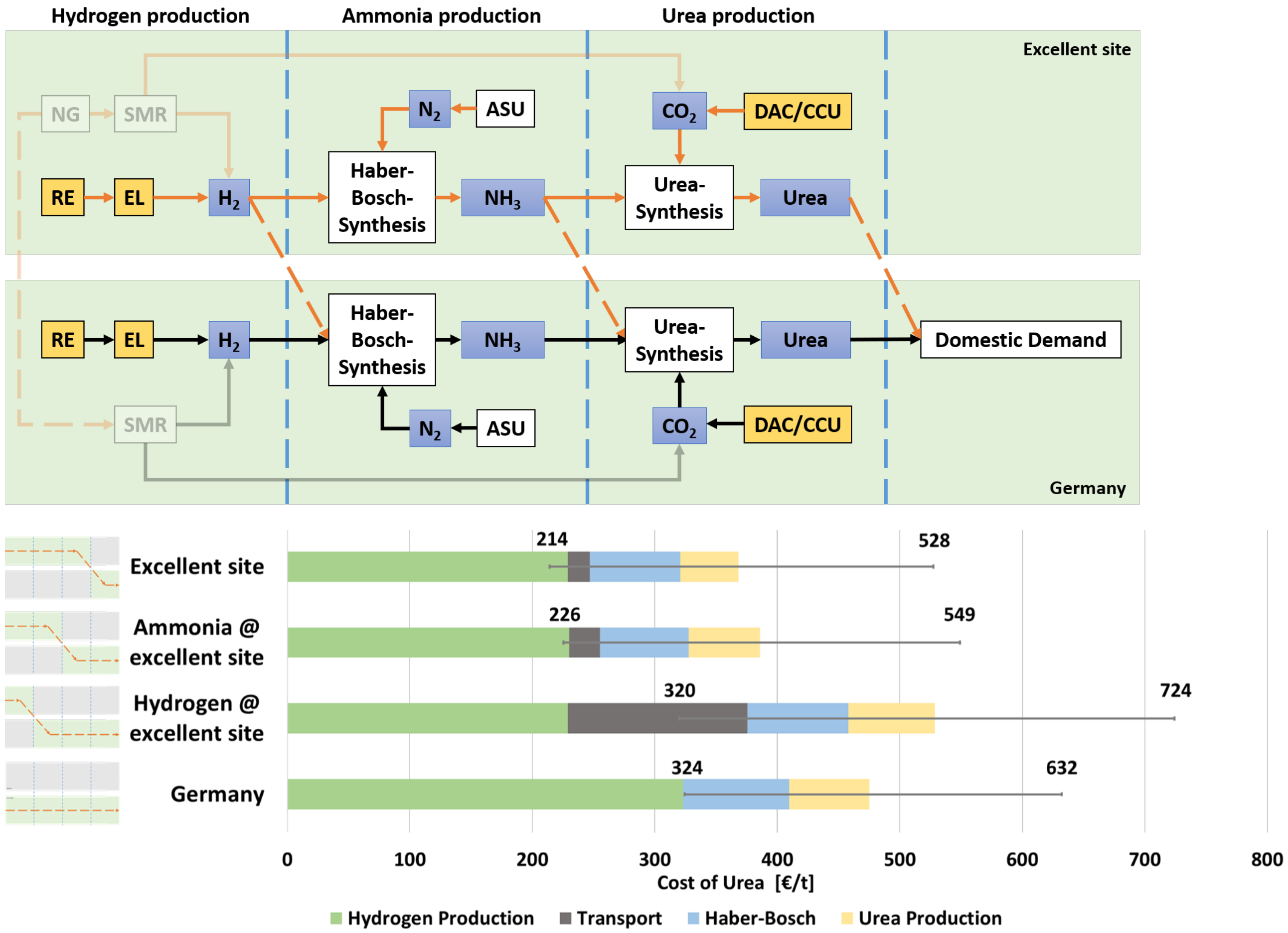
2) Case study on value chains: **Ethylene**

- Levelized costs are second-highest when the entire process chain takes place in Germany.
- Transport of methanol or ethylene over long distances is much easier and cheaper than the transport of elemental hydrogen
- Relocation of further process steps including hydrogen production is significantly cheaper than domestic production



2) Case study on value chains: **Urea**

- Levelized costs are second-highest when the entire process chain takes place in Germany.
- Transport of ammonia or urea over long distances is much easier and cheaper than the transport of elemental hydrogen
- Relocation of further process steps including hydrogen production is significantly cheaper than domestic production



Take-aways for the transformation of global and German industrial value chains?

- Industrial hydrogen demand for status-quo in Germany will rise significantly (domestic production?), but:
  - Uncertainty on demand for specific products with changes in relative prices
  - Relocation of processes to sites with better access to H- (and C-) Atoms possible

- Potential for relocation ("green leakage"):
  - \+ Differences in regional hydrogen prices for products with high hydrogen cost share (NH_3, MeOH)
  - \+ Defossilization requires new processes with large investments (H-DR)
  - \- Integration of value chains (chemical industry?)

- Possibly results in increasing global trade of intermediate products (e.g. ammonia, olefins, MeOH)

- Perspective for Germany and the EU
  - Which are the important processes in value chains for value creation
  - Industrial policy in terms of future chances instead of protection of current system

Thank you for your attention!

Nima Farhang-Damghani – nima.farhang-damghani@fau.de

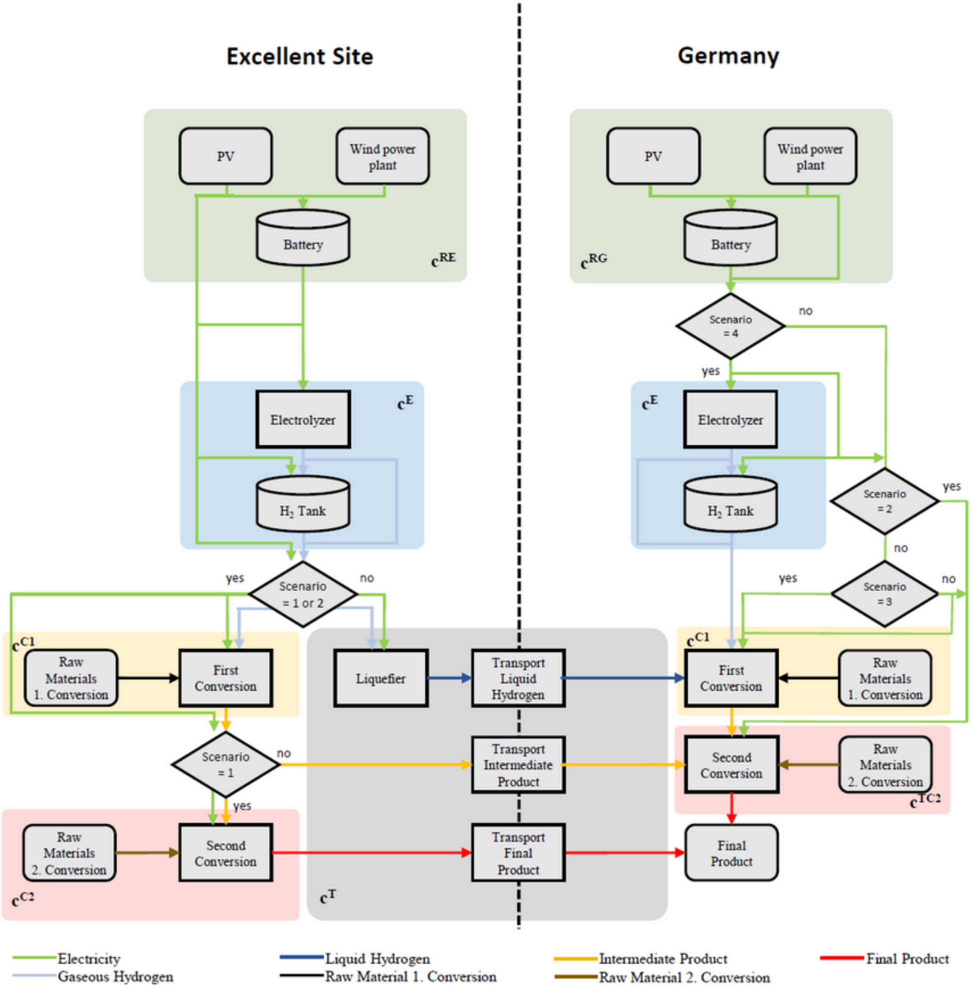
Chair of Economic Theory, FAU Erlangen-Nürnberg

2) Case study on value chains: **Assumptions on input data**

	Unit	Benchmark	Min	Max	Source
Finance					
Interest rate	[%]	7	4	10	
PV					
CAPEX	[€/kW]	336	246	432	[69]
Depreciation period	[a]	30	30	30	[69]
OPEX	[%/a]	1.3	1.3	1.3	[69]
Full load hours at excellent site[3]	[h/a]	1,166	1,574	2,067	[56, 64]
Full load hours in Germany	[h/a]	1,307	1,307	1,307	[56]
Wind					
CAPEX	[€/kW]	1,143	938	1,213	[69]
Depreciation period	[a]	20	20	20	[69]
OPEX	[%/a]	1.1	1.1	1.1	[69]
Full load hours at excellent site[3]	[h/a]	5,056	3,687	6,136	[64, 71]
Full load hours in Germany	[h/a]	2,949	2,949	2,949	[71]
Battery					
CAPEX	[€/kWh]	125	125	125	[18]
Depreciation period	[a]	20	20	20	[18]
OPEX	[%/a]	3	3	3	[18]
Efficiency	[%]	94	94	94	[18]
Electrolysis					
CAPEX	[€/kW]	450	400	500	[44]
Depreciation period	[a]	10	10	10	[44]
OPEX	[%/a]	3	3	3	[44]
Efficiency	[$\%_{LHV}$]	72	72	72	[44]
CGH2 Storage					
CAPEX	[€/kWh]	135	135	135	[30]
OPEX	[%/a]	1	1	1	[30]
Transport					
Distance[3]	[km]	10,500	5,400	13,500	
Cost for steel transport	[€/(t · km)]	0.00093	0.00093	0.00093	[64, 80]
Cost for liquid hydrogen transport	[€/(t · km)]	0.0800	0.0800	0.0800	[64]
Cost for methanol transport	[€/(t · km)]	0.0023	0.0023	0.0023	[64]
Cost for ethylene transport	[€/(t · km)]	0.0034	0.0034	0.0034	[29]
Cost for ammonia transport	[€/(t · km)]	0.0034	0.0034	0.0034	[29]
Cost for urea transport	[€/(t · km)]	0.00093	0.00093	0.00093	[64, 80]

Ammonia production					
Haber-Bosch CAPEX	[$€/kW_{H_2}$]	510	459	561	[29]
Air separation unit CAPEX	[$€/kW_{H_2}$]	197	177	217	[86]
Depreciation period	[a]	30	30	30	[86]
OPEX	[%/a]	2	2	2	[86]
Hydrogen demand (stoichiometric)	[t_{H_2}/t_{NH_3}]	0.178	0.178	0.178	
Hydrogen demand (incl. efficiency)	[t_{H_2}/t_{NH_3}]	0.197	0.197	0.197	[74]
Electricity demand	[MWh/t_{NH_3}]	0.64	0.64	0.64	[74]
Urea production					
CAPEX	[$€/kW_{NH_3}$]	65	59	72	[86]
Depreciation period	[a]	20	20	20	[86]
OPEX	[%/a]	2	2	2	[86]
Electricity demand	[MWh/t_{Urea}]	0.64	0.64	0.64	[86]
CO_2 demand	[t_{CO_2}/t_{Urea}]	0.73	0.73	0.73	[86]
NH_3 demand	[t_{NH_3}/t_{Urea}]	0.57	0.57	0.57	[86]
Methanol production					
CAPEX	[$€/kW_{H_2}$]	100	90	110	[13, 64]
Depreciation period	[a]	20	20	20	[13]
OPEX	[%/a]	4	4	4	[13]
Electricity demand	[MWh/t_{H_2}]	0.39	0.39	0.39	[74]
Hydrogen demand (stoichiometric)	[t_{H_2}/t_{MeOH}]	0.1887	0.1887	0.1887	
Hydrogen demand (incl. efficiency)	[t_{H_2}/t_{MeOH}]	0.2097	0.2097	0.2097	[74]
CO_2 demand (stoichiometric)	[t_{CO_2}/t_{MeOH}]	0.1373	0.1373	0.1373	
Ethylene production					
CAPEX	[$€/t_{Ethylene}$]	191	172	210	[67]
Depreciation period	[a]	20	20	20	[67]
OPEX	[%/a]	3	3	3	[67]
Electricity demand	[$MWh/t_{Ethylene}$]	0.04	0.04	0.04	[67]
Methanol demand	[$t_{MeOH}/t_{Ethylene}$]	2.28	2.28	2.28	[6]
Direct reduction of iron					
CAPEX	[$€/t_{DRI}/a$]	240	216	264	[47]
Depreciation period	[a]	20	20	20	[47]
OPEX	[%/a]	2	2	2	[47]
Hydrogen demand	[t_{H_2}/t_{Steel}]	0.0596	0.0596	0.0596	[8]
Cost for iron ore	[$€/t_{Steel}$]	189	170	208	[49]
Cost for iron pellets	[$€/t_{Steel}$]	84	75.6	92.4	[49]
Electric arc furnace					
CAPEX	[$€/t_{Steel}/a$]	184	166	202	[47]
Depreciation period	[a]	20	20	20	[47]
Electricity demand	[MWh/t_{Steel}]	0.64	0.52	0.76	[47]

Cost perspective for industrial value chains



- Three excellent locations with favourable renewable energies conditions (Runge et.al. 2019)
  - Patagonia (optimistic), Canada (neutral), Namibia (pessimistic)
- Comparison to production in Germany
- Further scenario with only import of liquefied hydrogen
- Further scenarios with import of intermediate products (ammonia, methanol, DRI)

Backup

Hurdle: No production or plant capacity data available
Approximation: Emission share per plant from EU ETS = Production share per plant

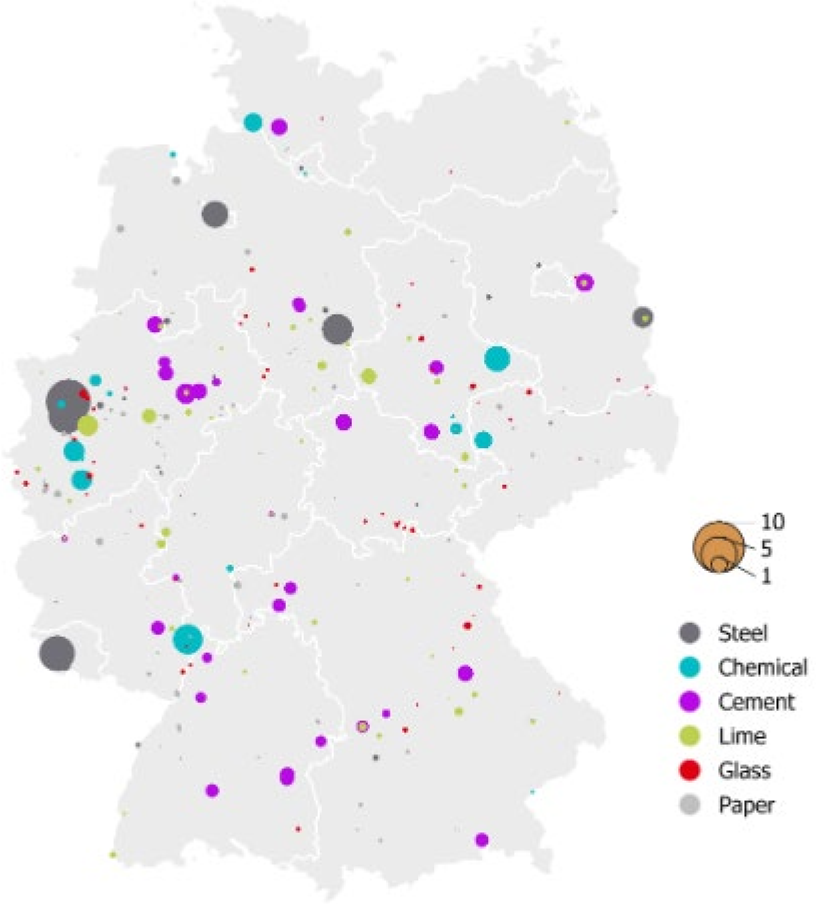
- $Production\ output\ plant\ X\ =\ Total\ production\ of\ sector\ \ Y\ *\ emission\ share\ plant\ X$

Backup

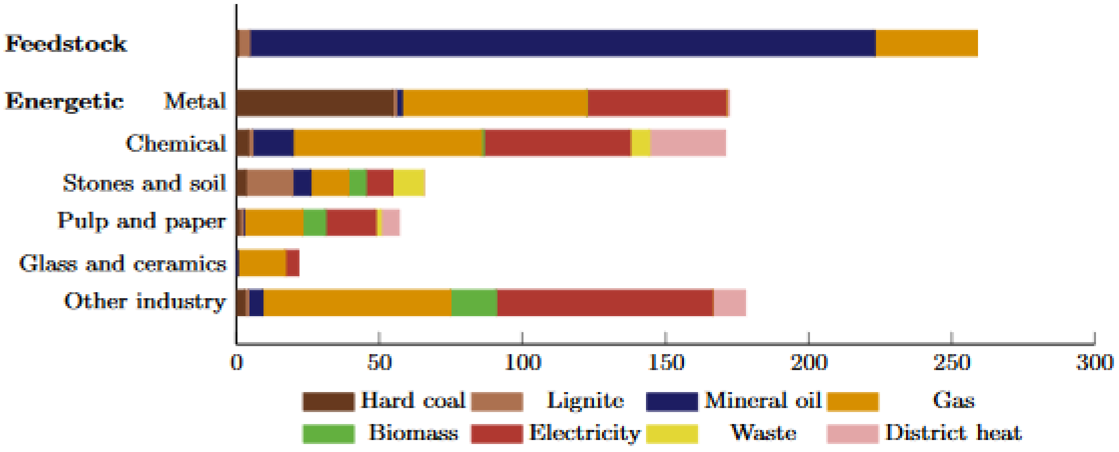
Methanol derivatives	Low H_2	High H_2
Methanol	60	85
Olefins (Ethylene, Propylene)	100	85
BTX (Benzene, Toluene, Xylene)	100	100
Source	[26]	[6]
Total methanol demand	32.2 Mt	29.2 Mt
Methanol-by-H_2/CO_2 amount	**19.3 Mt**	**24.9 Mt**

TABLE 4. Assumptions for calculations on lower and higher MtO/MtA production share for each process (in %)

Backup

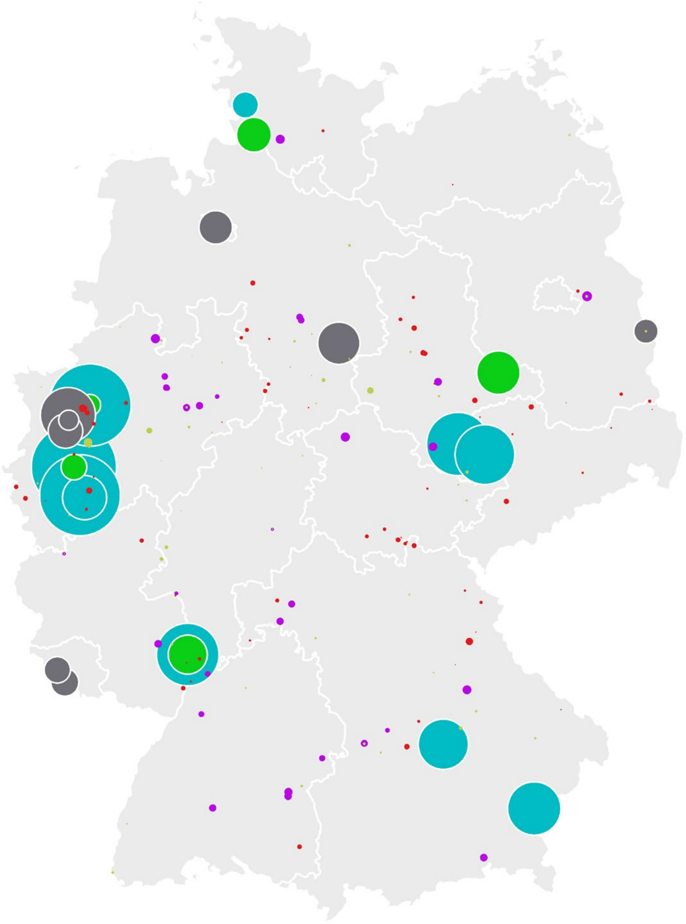


2021 emissions

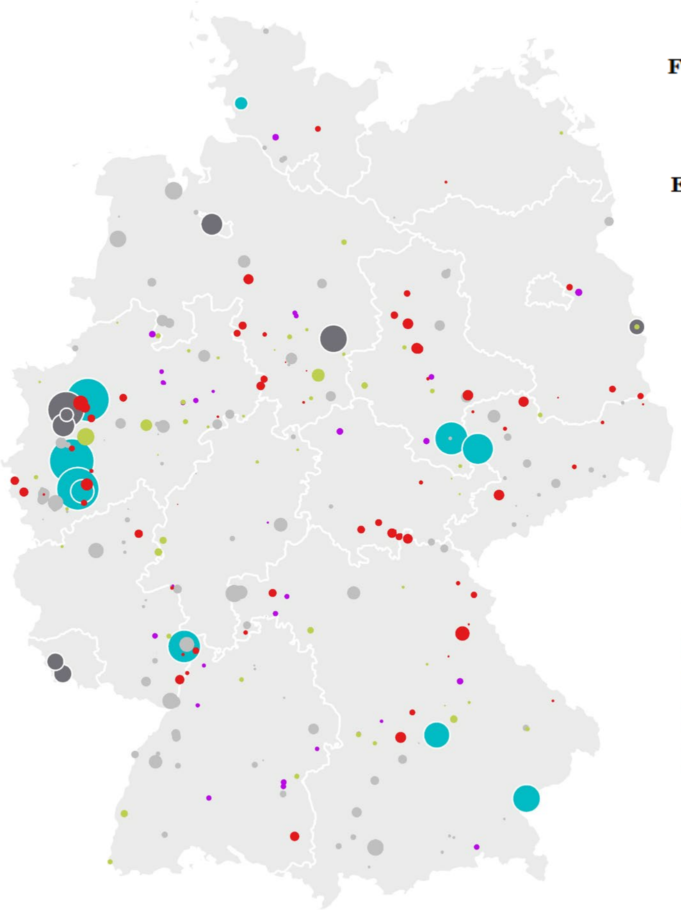


2021 energy demand

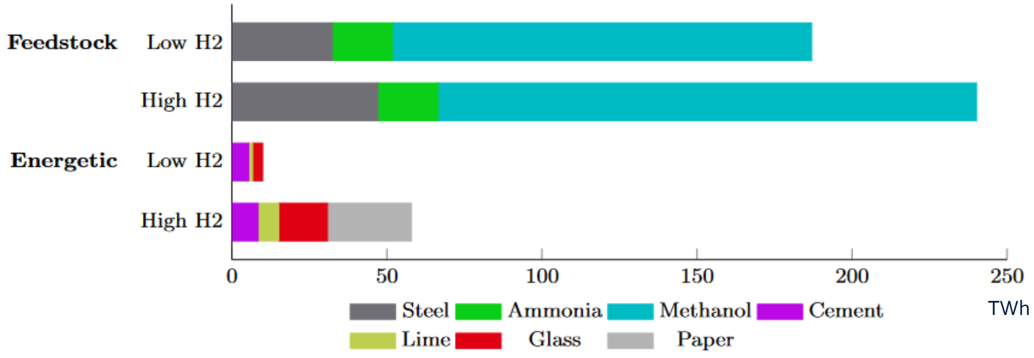
Resulting hydrogen demand and distribution



Lower bound scenario



Δ between higher and lower H_2 demand scenarios



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