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

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What role can hydrogen play in the decarbonization of German industry?

Sector	Share of industrial energy consumption, %	Key processes
Chemical industry	**28.6**	**Ammonia, Methanol, Organic Chemicals (Olefins, Aromatics)**
Metal production & processing	**22.4**	**Iron- and steelmaking**
Coking plants and refineries	10.5	Fuel production
Mineral industry (Cement, Lime, Glass)	**7.3**	**Heat generation**
Pulp & Paper	**6.6**	**Heat & Steam generation**
Others	24.6	-

- Hydrogen will take a key role for decarbonization & defossilization of industry

What did we want to find out?

Research Questions:

- Future demand and distribution of Hydrogen in Germany for industry processes
- Impact on value chains of downstream products and their costs if the value chains transition to carbon-neutral production (case study)

Approach – Demand calculation

Sources

- Sector-specific studies, reports and scientific papers
- EU Emission Trading Scheme
- Association websites/databases
- Company reports

Inputs

- Specific energy consumption
- 2021 production/capacity data
- 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

Result

Total hydrogen demand for each sector/process and each plant

Approach – Scenarios

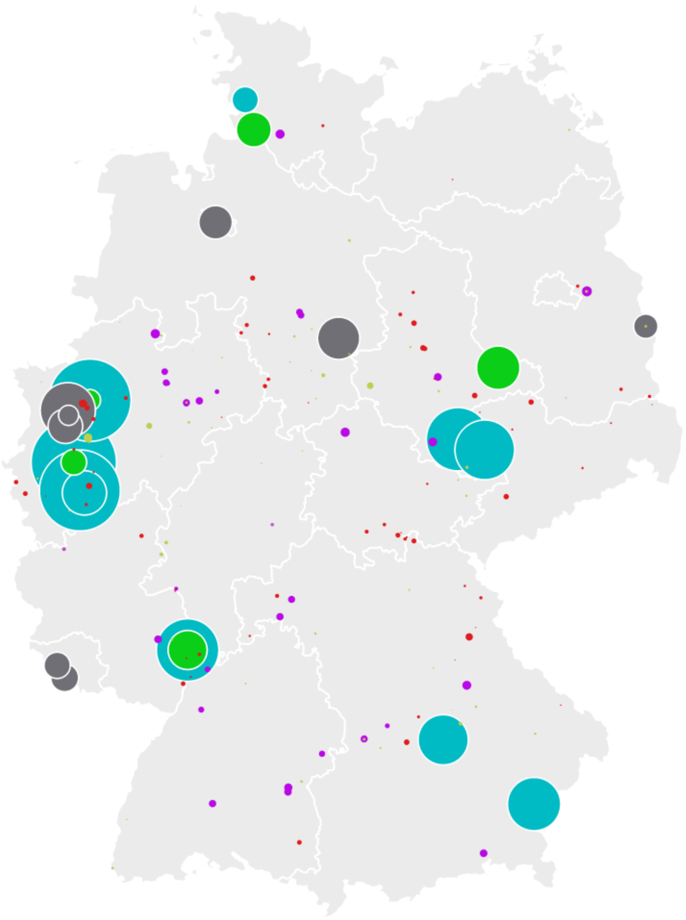
No 100% hydrogen utilization e.g. in heating or steel production

- Lower and higher scenario for hydrogen utilization in each process

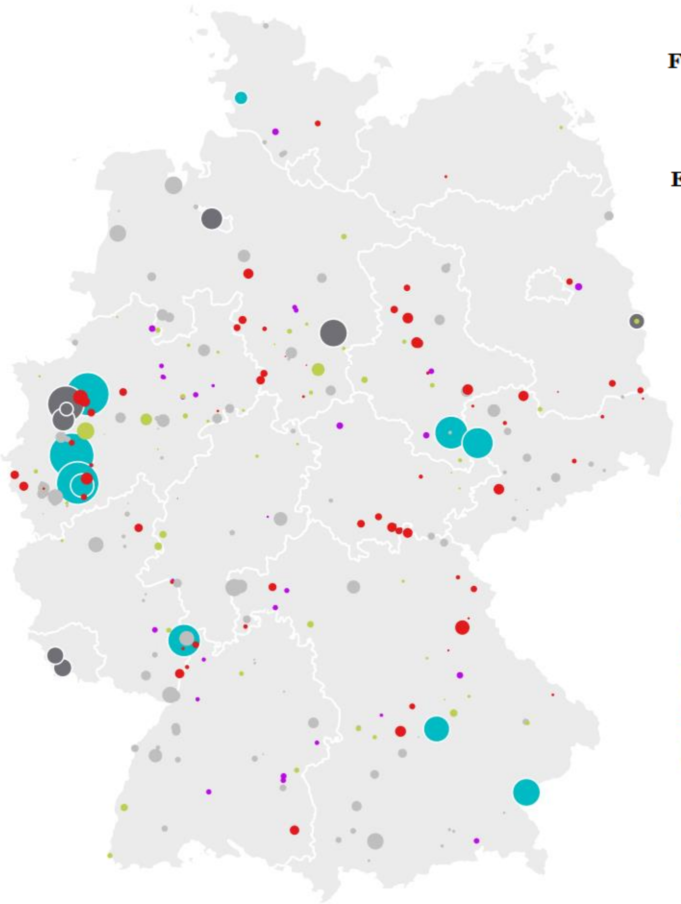
- Lowest and highest hydrogen utilization considered after careful literature review for different possible fuel and technology shares for each analyzed production process

Sector	# of plants	Low H_2 share, %	High H_2 share, %
Crude steel	8	40.6	59.0
Ammonia	5	100.0	100.0
Methanol	10	60.0	85.0
Cement clinker	33	20.0	30.8
Lime	57	20.0	100.0
Glass	75	20.0	100.0
Paper	141	0.0	71.5

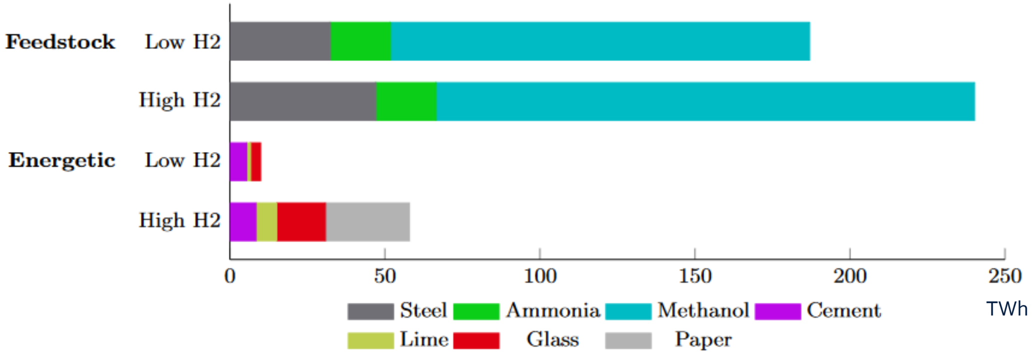
Resulting hydrogen demand and distribution



Lower bound scenario

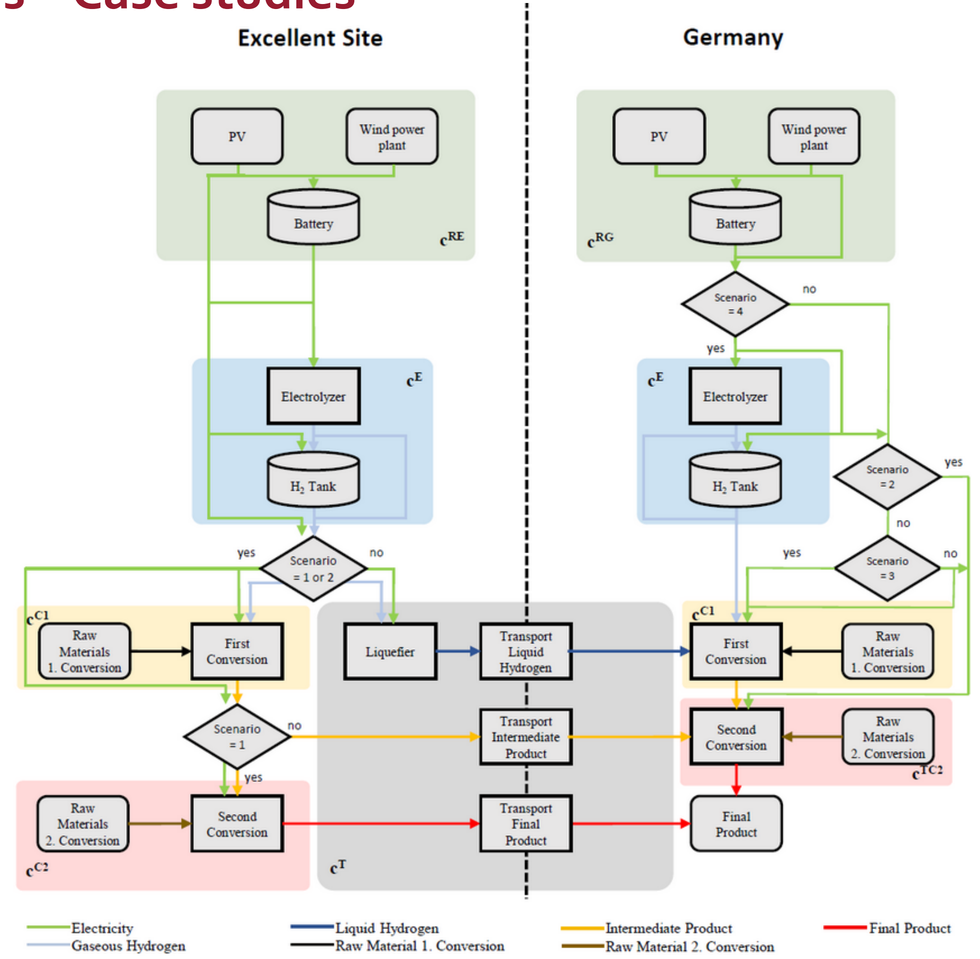


Δ between higher and lower H_2 demand scenarios



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**

Cost perspective for the transformation of conventional value chains to hydrogen-based value chains – Case studies



Model

Linear optimization:
Minimizing total costs of each value chain
incl. transport (steel, urea, ethylene)

Objective Function

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

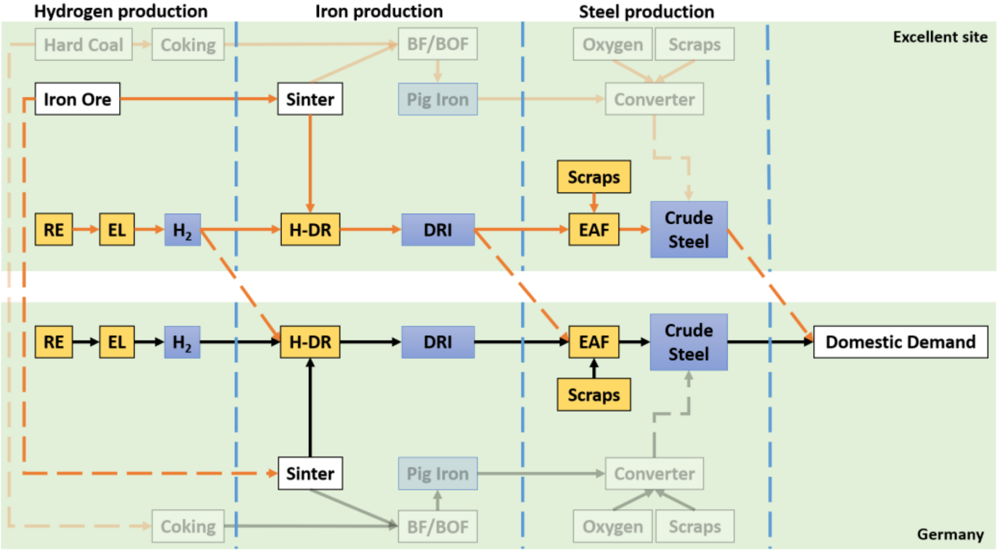
Parameters

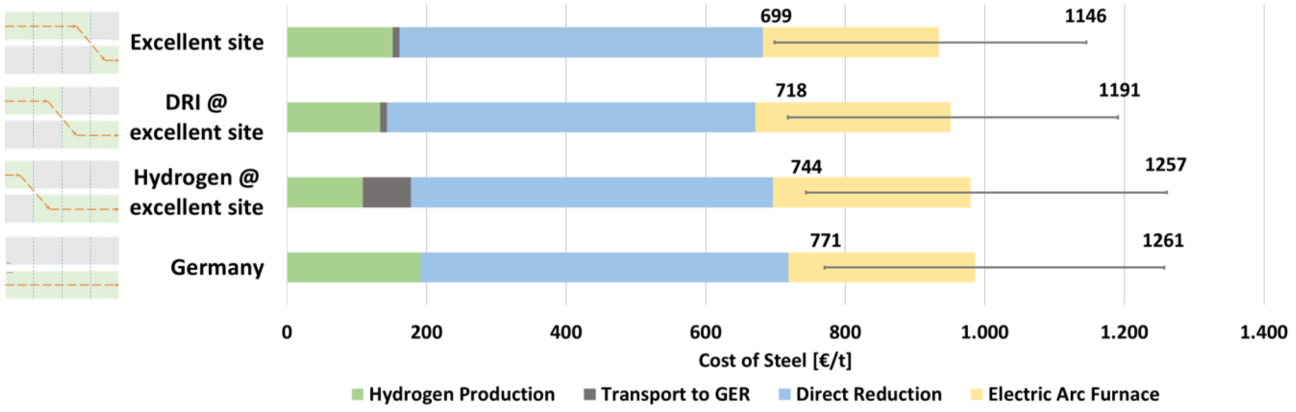
CAPEX/OPEX, Renewable energy vectors, storage, transport distance, SECs, raw materials, …

Decision variables

Levelized Costs of final product in €/t
Capacities of conversion and production plants

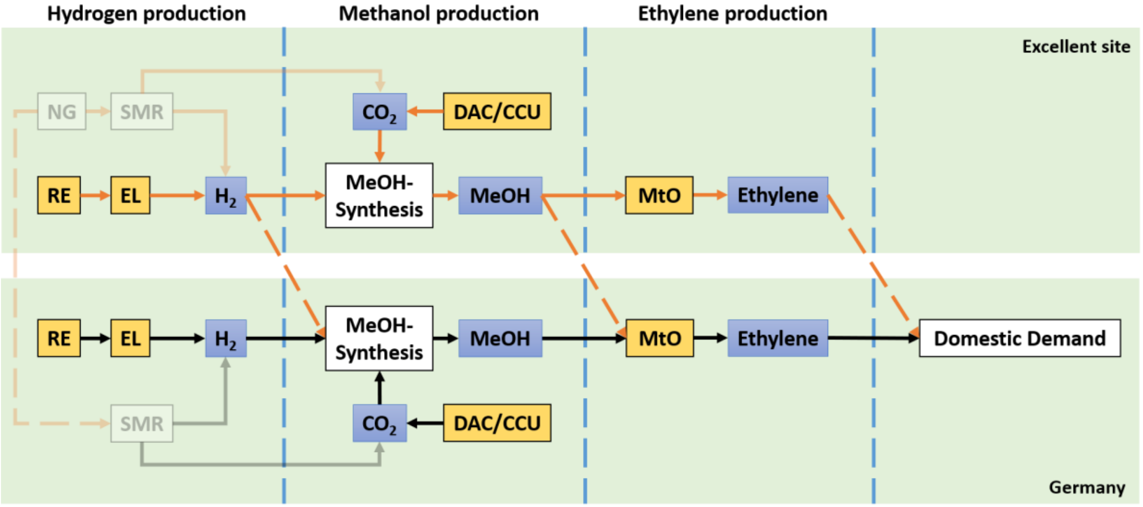
Cost perspective for industrial value chains – Steel

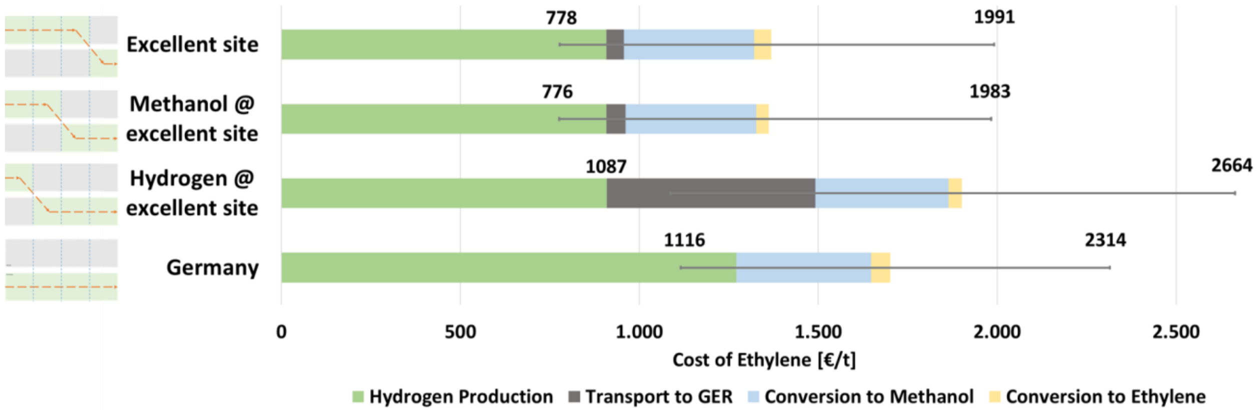




- Hydrogen has a rather small share of 11-19% of the levelized costs of steel
- Relocation may be less a matter of cost but more of location advantages such as workforce and customer proximity
- Overall small cost advantages when steel value chain is relocated to favourable sites

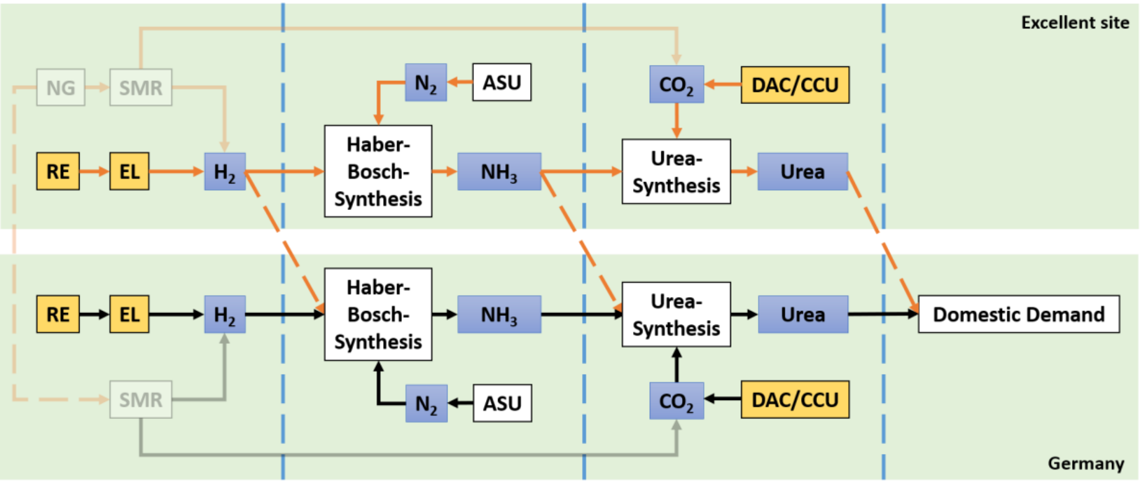
Cost perspective for industrial value chains – MeOH/Olefins

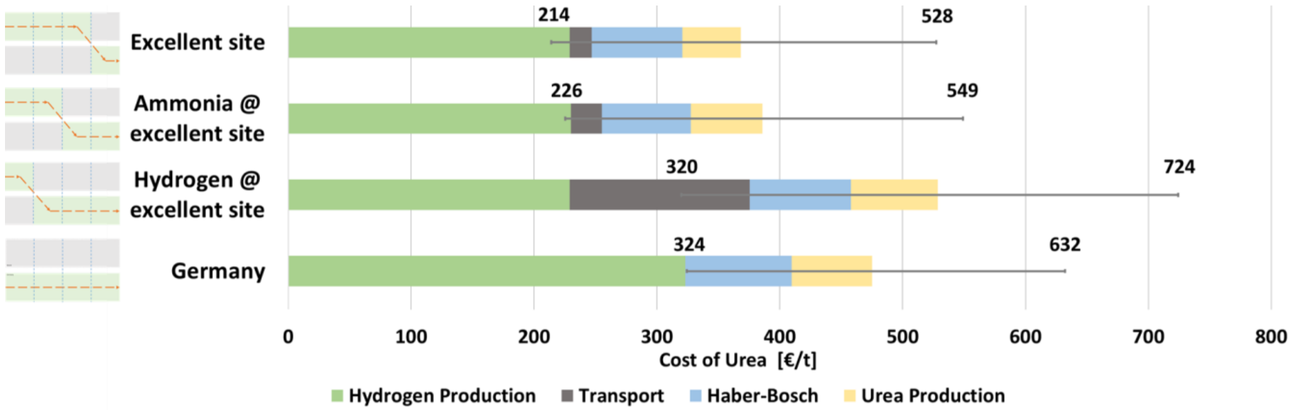




- Levelized costs are second-highest when the entire process chain takes place in Germany.
- Transport of methanol or ethylene over long distances is much easier and cheaper than the transport of elemental hydrogen
- Relocation of further process steps including hydrogen production is significantly cheaper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

Cost perspective for industrial value chains – Urea





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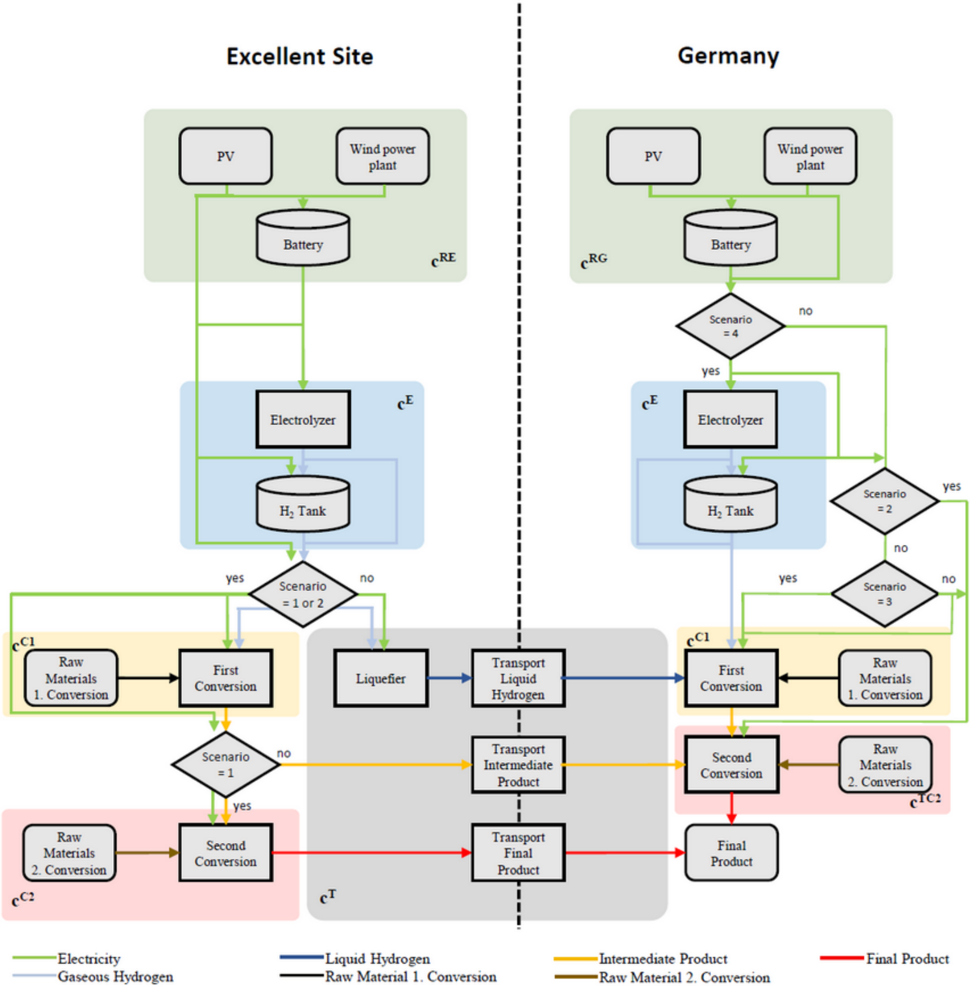
Conclusions – Transformation of global industrial value chains?

- Industrial hydrogen demand will rise significantly and can not be fully covered by domestic production
- Addition/removal of individual process steps and energy sources
- Development of new infrastructures with regard to H_2 and CO_2 necessary
- Expanded global trade in intermediate products (e.g. olefins, MeOH, carbon)
- Less value creation in Germany and the EU? More investments in favorable locations especially for hydrogen-intensive products?
- Scaling up and ramp-up of hydrogen production and infrastructure important for Germany and Europe to stay competitive and keep at least parts of the industrial value chains

Thank you for your attention ☺

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 %)

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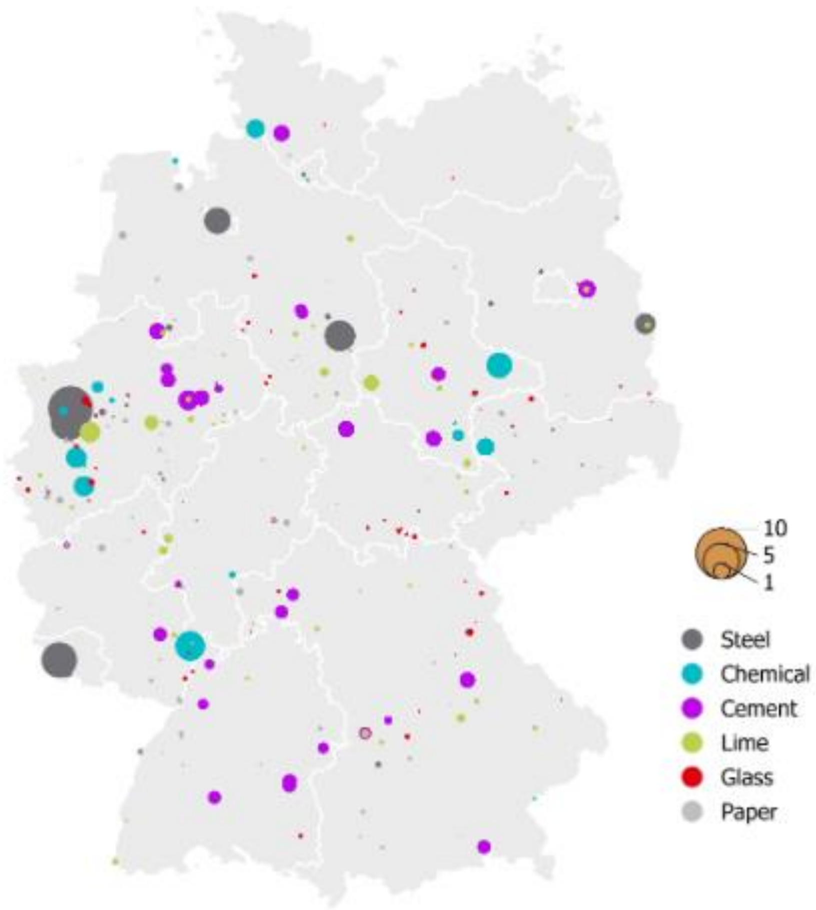
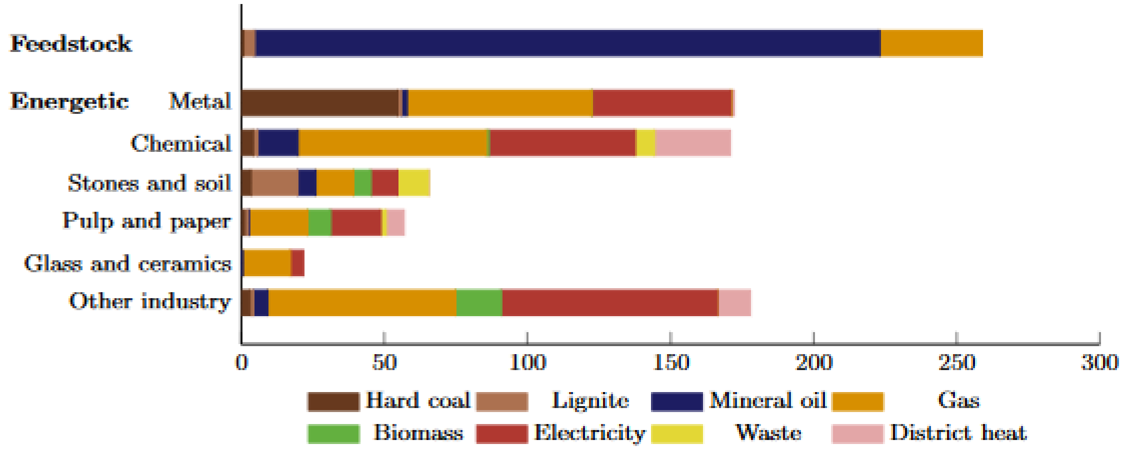


2021 emissions

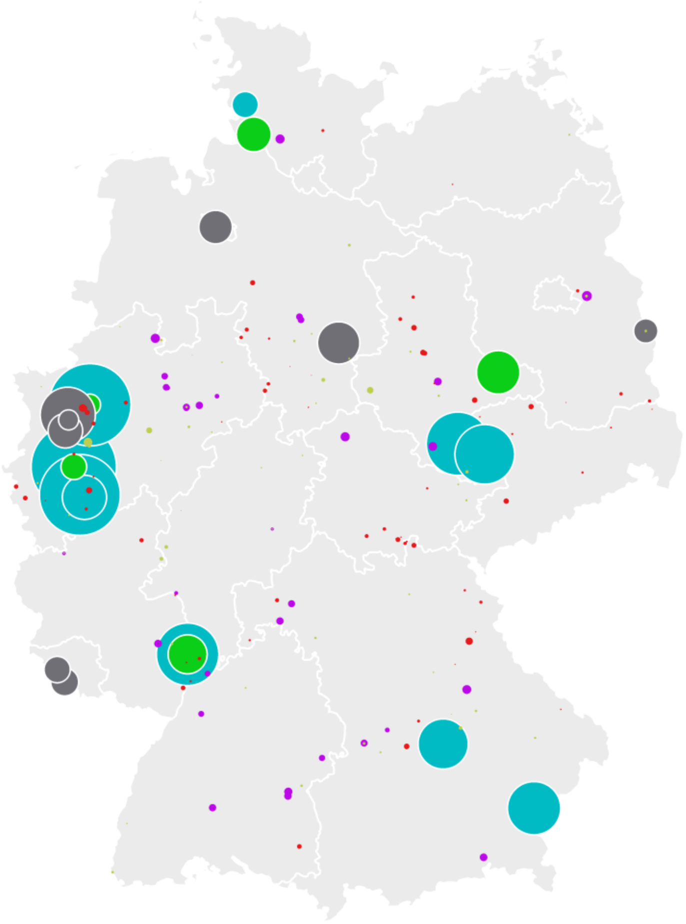


2021 energy demand

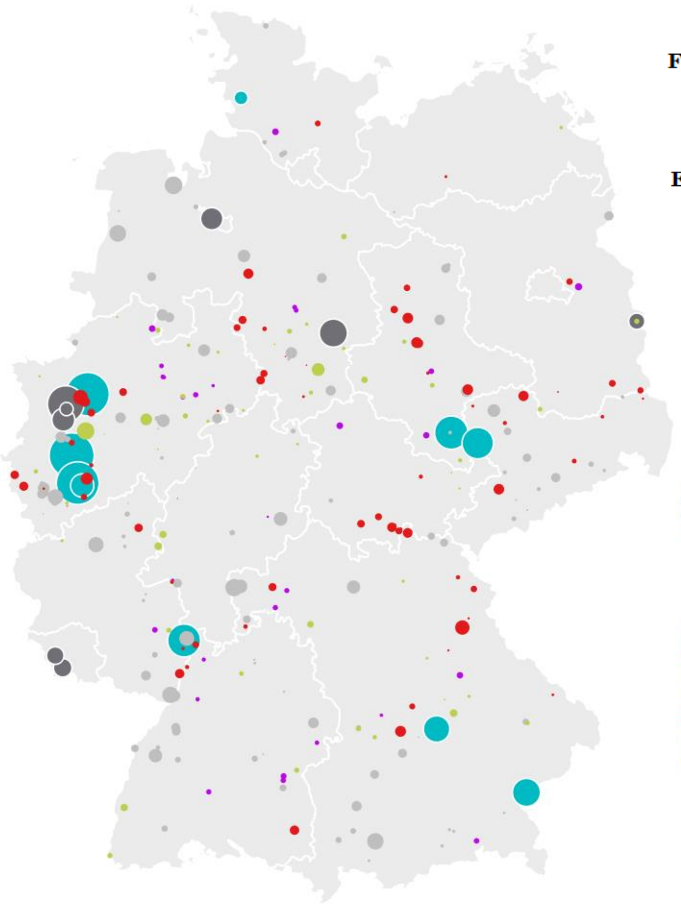
	Unit	Benchmark	Min	Max	Source
Finance					
Interest rate	[%]	7	4	10	
PV					
CAPEX	$[€/kW]$	336	246	432	[69]
Depreciation period	$[a]$	30	30	30	[69]
OPEX	$[\%/a]$	1.3	1.3	1.3	[69]
Full load hours at excellent site[3]	$[h/a]$	1,166	1,574	2,067	[56, 64]
Full load hours in Germany	$[h/a]$	1,307	1,307	1,307	[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	$[€/(t \cdot km)]$	0.00093	0.00093	0.00093	[64, 80]
Cost for liquid hydrogen transport	$[€/(t \cdot km)]$	0.0800	0.0800	0.0800	[64]
Cost for methanol transport	$[€/(t \cdot km)]$	0.0023	0.0023	0.0023	[64]
Cost for ethylene transport	$[€/(t \cdot km)]$	0.0034	0.0034	0.0034	[29]
Cost for ammonia transport	$[€/(t \cdot km)]$	0.0034	0.0034	0.0034	[29]
Cost for urea transport	$[€/(t \cdot km)]$	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]

Resulting hydrogen demand and distribution



Lower bound scenario



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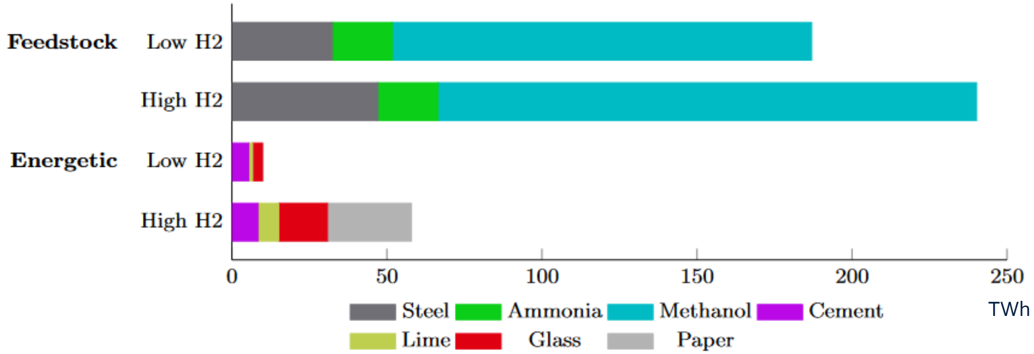

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