Supporting Information: Integrated decarbonization of hard-to-abate industry utilizing biomass reliefs burden on power sector

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S1. Input data to the optimization problem

This work builds on existing work published in [1, 2]. Please note that all prices are reported in € (2023) and adjusted for inflation following [3]. USD exchange rates are taken from [4].

S1.1. Energy carrier prices and carbon intensities

We extend the set of carriers reported in [1, 2] and include biomass for cement production, coal feedstocks, iron ore, scrap, and limestone. Biomass for cement production mainly consists of low-cost wastes, such as tyres, mixed industrial wastes and animal meal, as well as sewage sludge [5]. Current and forecasted import availabilities and prices are taken from [6]. The carbon intensity for coal corresponds to [7]. The import prices and price development for hard coal used for cement production is derived from [8]. Import prices and price developments until 2050 for metallurgical coal, iron ore, limestone and scrap are taken from [9]. Carbon intensity assumptions for input carriers are based on [10, 11]. The carbon intensity of crude oil [12] is attributed to the carbon intensity of the conversion technology for refining (S1.2).

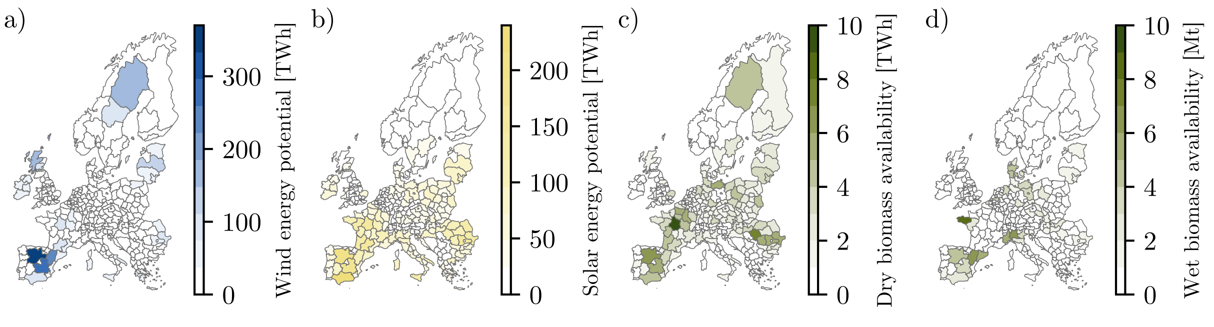

Figure S1: Spatially-resolved technical potentials of renewable energy sources in Europe: (a) wind energy, (b) solar energy, (c) wet biomass, and (d) dry biomass [14, 15]. Wet biomass includes agricultural primary residues such as manure. Dry biomass includes woody residues from agriculture and forestry. Figure reproduced from [1].

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Table S1: Carrier prices and carbon intensities.

Carrier	**Price 2024 [€/MWh]**	**Price 2030 [€/MWh]**	**Price 2050 [€/MWh]**	**CO_2 intensity [tCO_2/MWh]**
electricity [13]	83.68	83.68	83.68	0.0
natural gas [13, 11]	21.22	21.33	31.00	0.1826
dry biomass [6]	23.84	23.21	21.31	0.0
wet biomass [6]	30.27	30.57	32.45	0.0 t/t
biomass cement [6]	0.17	0.15	0.12	0.0
coal cement [8, 11]	18.23	8.81	7.92	0.3193 t/t
scrap [9]	263.03 €/t	263.03 €/t	263.03 €/t	0.0
limestone [9, 10]	74.72 €/t	74.72 €/t	74.72 €/t	0.1200 t/t
iron ore [9]	149.21 €/t	149.21 €/t	149.21 €/t	0.0 t/t
coal [9, 11]	32.39 €/t	32.39 €/t	32.39 €/t	0.3556 t/t

S1.2. Technology parameters

This section reports the technology parameters for each industry. The parameters describing the technology performance are reported in S1.2. The economic technology parameters are reported in S1.2. For detailed information on the transport technology assumptions, please refer to [16].

Table S2: Parameters describing the technology performance of the available conversion technologies for ammonia production. e = electricity, N_2 = nitrogen, NH_3 = ammonia, g = natural gas / biomethane, H_2 = hydrogen, O_2 = oxygen

Production Technologies	**Conversion**	**Efficiency**	**CO_2 capture**	**CO_2 intensity**
Haber Bosch [17]	e $\rightarrow NH_3$	0.654	-	-
	N2 $\rightarrow NH_3$	0.823		
	g $\rightarrow NH_3$	0.251		
	$H_2 \rightarrow NH_3$	5.874		
Electric Haber Bosch [17]	e $\rightarrow NH_3$	0.874	-	-
	$NH_2 \rightarrow NH_3$	0.823		
	$H_2 \rightarrow NH_3$	5.874		
Air separation unit [17, 18]	e $\rightarrow N_2$	0.287	-	-
	$N_2 \rightarrow O_2$	0.998		

Table S3: Parameters describing the technology performance of the available conversion technologies for steel production. s = steel, io = iron ore, ls = limestone, c = coal (metallurgical coal), sc = scrap, g = natural gas / biomethane / hydrogen, DRI = direct reduced iron / scrap

Production Technologies	**Conversion**	**Efficiency**	**CO_2 capture**	**CO_2 intensity**
BF BOF [19]	io → s	1.370	-	-
	ls → s	0.270		
	c → s	0.780		
	sc → s	0.125		
Direct reduction of iron [20]	g → DRI	2.740	-	-
	io → DRI	1.460		
EAF [20]	e → s	0.840	-	-
	DRI → s	1.000		
BF BOF CCS [21]	e → CO_2	0.349	90%	-
	CO_2 → c	0.105		

Table S4: Parameters describing the technology performance of the available conversion technologies for cement production. cc = coal for cement (hard coal), e = electricity, ce = cement, CO_2 = carbon

Production Technologies	**Conversion**	**Efficiency**	**CO_2 capture**	**CO_2 intensity**
Cement plant [5, 22]	cc → cc	0.672	-	0.54
	e → ce	0.097		
Post-combustion capture [23]	cc → CO_2	0.833	90%	-
	e → CO_2	0.025		
Oxyfuel combustion [23]	O_2 → CO_2	0.380	90%	-
	e → CO_2	0.182		

Table S5: Parameters describing the technology performance of the available conversion technologies for refining. op = oil products, H_2 = hydrogen

Production Technologies	**Conversion**	**Efficiency**	**CO_2 capture**	**CO_2 intensity**
Refinery [24, 12, 25]	H_2 → op	0.541	-	0.068

Table S6: Technological parameters for the available industry unspecific conversion technologies. If the electricity balance is negative, electricity has to be provided to the system. e = electricity, H_2 = hydrogen, O_2 = oxygen, g = natural gas / biomethane, db = dry biomass, wb = wet biomass, bm = biomethane, LC = liquid carbon

Production technologies	**Conversion**	**Efficiency**	**CO_2 capture**	**CO_2 intensity**
Electrolysis [26]	e $\rightarrow$ H_2	0.640	-	-
	H_2 $\rightarrow$ O_2	6.239 MWh/kg		
SMR [27]	g $\rightarrow$ H_2	1.299	-	-
	H_2 $\rightarrow$ e	0.041		
SMR with carbon capture [27]	g $\rightarrow$ H_2	1.299	90%	-
	H_2 $\rightarrow$ e	0.016		
Gasification [28]	db $\rightarrow$ H_2	1.613	-	-
	H_2 $\rightarrow$ e	0.093		
Gasification with carbon capture [28]	db $\rightarrow$ H_2	1.613	57%	-
	H_2 $\rightarrow$ e	0.153		
Anaerobic digestion [28]	wb $\rightarrow$ bm	0.435 t/MWh	-	-
Direct air capture [23]	e $\rightarrow$ LC	1.458 MWh/t	-	-
Carbon storage [29]	LC $\rightarrow$ LC	1	-	-1
	e $\rightarrow$ LC	0.038 MWh/t		

Table S7: Economic parameters of the available conversion technologies for ammonia production.

Technologies	**Investment [k€/(t_{NH_3}/h)]**	**Fixed O&M [k€/(t_{NH_3}/h)]**	**Variable O&M [€/t_{NH_3}]**	**Lifetime [yr]**
Production				
Haber Bosch [30]	20805	624	0.14	30
Electric Haber Bosch [30]	11235	337	0.14	30
Intermediate Production				
Air separation unit [30]	1011 k€/(t_{N2}/h)	0.0	0.0	30

Table S8: Economic parameters of the available conversion technologies for steel production. BF-BOF: Blast furnace - basic oxygen furnace

Technologies	**Investment [k€/(t_{Steel}/h)]**	**Fixed O&M [k€/(t_{Steel}/h)]**	**Variable O&M [€/t_{Steel}]**	**Lifetime [yr]**
Production				
BF-BOF [31, 32]	5002	1165	0.0	40
Electric arc furnace [31, 20]	1973	629	0.0	25
Direct reduction of iron [31, 20]	2466	168	0.0	25
Carbon capture				
BF-BOF with carbon capture [21]	1403 [k€/(t_{CO_2}/h)]	0.0	0.0	25

Table S9: Economic parameters of the available conversion technologies for cement production.

Technologies	Investment [k€/(t_{Cement}/h)]	Fixed O&M [k€/(t_{Cement}/h)]	Variable O&M [€/t_{Cement}]	Lifetime [yr]
Production				
Cement plant [5]	1492.51	126.42	0.0	25
Carbon capture				
Post combustion capture [23]	5141 [k€/(t_{CO_2}/h)]	155 [k€/(t_{CO_2}/h)]	2.99 [€/(t_{CO_2}/h)]	25
Oxyfuel combustion [23]	4065 [k€/(t_{CO_2}/h)]	203 [k€/(t_{CO_2}/h)]	2.39 [€/(t_{CO_2}/h)]	25

Table S10: Economic parameters of the available conversion technologies for methanol production.

Production technologies	Investment [k€/($t_{Methanol}$/h)]	Fixed O&M [k€/($t_{Methanol}$/h)]	Variable O&M [€/$t_{Methanol}$]	Lifetime [yr]
Methanol synthesis [30]	8895	267	0.0	30

Table S11: Economic parameters of the available conversion technologies for refining.

Production technologies	Investment [k€/($t_{Oil\ Products}$/h)]	Fixed O&M [k€/($t_{Oil\ Products}$/h)]	Variable O&M [€/$t_{Oil\ Products}$]	Lifetime [yr]
Refinery [33]	6827.91	203.82	0.0	30

Table S12: Economic parameters of the available industry-unspecific conversion technologies. SMR: Steam methane reforming.

Technologies	Investment [€/kW_{H_2}]	O&M [€/kW_{H_2}]	Lifetime [yr]
Production			
Electrolysis [26]	1547.26	23.21	10
SMR [26]	1001.09	47.05	25
SMR with carbon capture [26]	1848.17	55.45	25
Gasification [34]	1586.54	79.33	20
Gasification with carbon capture [34]	2606.37	130.32	20
Anaerobic digestion [35]	1464.59 €/kW_{bm}	89.67 €/kW_{bm}	20
Direct air capture [23]	5141.01 k€/(t_{CO_2}/h)	191.29 k€/(t_{CO_2}/h)	25
Conditioning			
Hydrogen compression [36]	88.47	0.068	15
Hydrogen evaporation [36]	5.46	0.16	10
Carbon liquefaction [37]	277.02 k€/(t_{CO_2}/h)	15.66 k€/(t_{CO_2}/h)	15
Storage			
Carbon storage [38]	285.90 k€/(t_{CO_2}/h)	15.71 k€/(t_{CO_2}/h)	-

S1.3. Existing production capacities

The existing production capacities for 2024 are estimated based on [25, 39] and include the Haber-Bosch process for Ammonia production, the blast furnace and basic oxygen furnace (BF-BOF) process (70%) and the direct reduced iron and electric arc furnace (Direct reduction of iron-EAF) process (30%) for steel production, cement plants, methanol plants and refineries. The existing capacities of air separation unit and hydrogen production technologies are also included. We assume that the existing production capacities will phase out in the coming years considering the individual plant lifetimes.

S1.4. Demand scenarios

We base our demand scenarios on the analysis performed by [22]. The total annual demands for each industry are distributed proportionally to the existing regional production capacities reported in the AIDRES database [25].

Ammonia. Ammonia is primarily used as feedstock to produce fertilizers [22]. Without process efficiency improvements and demand reduction measures, ammonia demand is expected to increase by 3%, resulting in a final demand of 18 Mt by 2050 [22]. However, future ammonia demands for fertilizer production can be reduced by about 45% (9.9 Mt by 2050) when considering reduced food waste, enhanced use efficiencies, and the substitution of ammonia-based fertilizers with organic fertilizers. However, the successful implementation of these measures is complex, and the feasibility of such a low-demand scenario remains uncertain [22].

In our reference case we therefore assume that only 60% of the demand reduction potential can be achieved, leading to annual ammonia demand of approximately 13.3 Mt by 2050 [22]. The demands are distributed proportionally to each region based on existing ammonia production capacities reported in the AIDRES database [25].

Steel. Steel is irreplaceable in constructions, infrastructure, transportation and machinery, because of its strength, durability and relatively low cost [39]. Continuing current practices, annual EU steel demands are expected to increase by 15% to support low-emission energy systems and infrastructure, reaching 193 Mt by 2050. However, an optimized use of steel resources could reduce demand by 28%, leading to a steel demands of about 139 Mt by 2050 [22]. Implementing these measures is intricate and requires extensive coordination to resolve misaligned incentives and improve the material efficiency in prevailing models. In our reference case, we consider less ambitious demand reduction efforts, capturing only one-fourth of the identified demand reduction potential, and resulting in annual steel demands of about 181 Mt by 2050 [22].

Cement. Cement serves as the primary binding agent in concrete and therefore plays a vital role in construction [22]. Continuing current practices, cement demands are expected to increase by approximately 10% from 171 Mt in 2024 to 188 Mt by 2050. This increase in demand is driven by a rebound in construction activity, continuous urbanization, and the development of new infrastructure [22]. However, by reducing the share of cement in concrete and decreasing concrete use, a 63% reduction in cement demands could be achieved [22]. However, a succesful implementation of such demand reduction measures is difficult. Therefore, in our reference case, we assume annual cement demands to remain constant at 171 Mt.

Methanol. Methanol is an important base chemical used to in the production of plastics and fuels among other things [22]. Current EU methanol production is estimated at 10 Mt per year [35]. However, demands are expected to increase significantly in coming years to enable increased plastics production via methanol-to-olefins routes. [35] assumes that up to 50% of olefins and BTX will originate from low-carbon methanol by 2050, estimating EU methanol demands to increase to 74 Mt by 2050 [35]. However, with increased recycling efforts and demand reduction measures this large growth in methanol demands might not materialize, and demands may remain stable at around 10 Mt per year. Similar to [40], we therefore assume reduced growth rates for our reference case and estimate 2050 methanol demand at 42 Mt by 2050.

Refining. The refining process of crude oil results in a wide range of products, about 65% of which are transformed into liquid transport fuels such as diesel or gasoline in EU refineries [41].

European production capacity, which was at 388 Mt in 2018, is projected to decrease by about 15% by 2030 and by more than 70% by 2050, reaching 113 Mt. This decline is largely attributed to efficiency improvements in the transport sector and the increased adoption of electric vehicles [25]. [40] goes even further, projecting refineries to phase-out completely by 2050. For our reference case we follow more conservative estimates and assume a slower transition to renewable transport fuels, resulting in demands to decrease by 84% compared to current production levels.

S2. Flow charts of the available production pathways

Fig. S2a-e visualizes the available production pathways for refining, ammonia, steel, cement and methanol industry. Furthermore, Fig. S2f visualizes the available hydrogen production pathways.

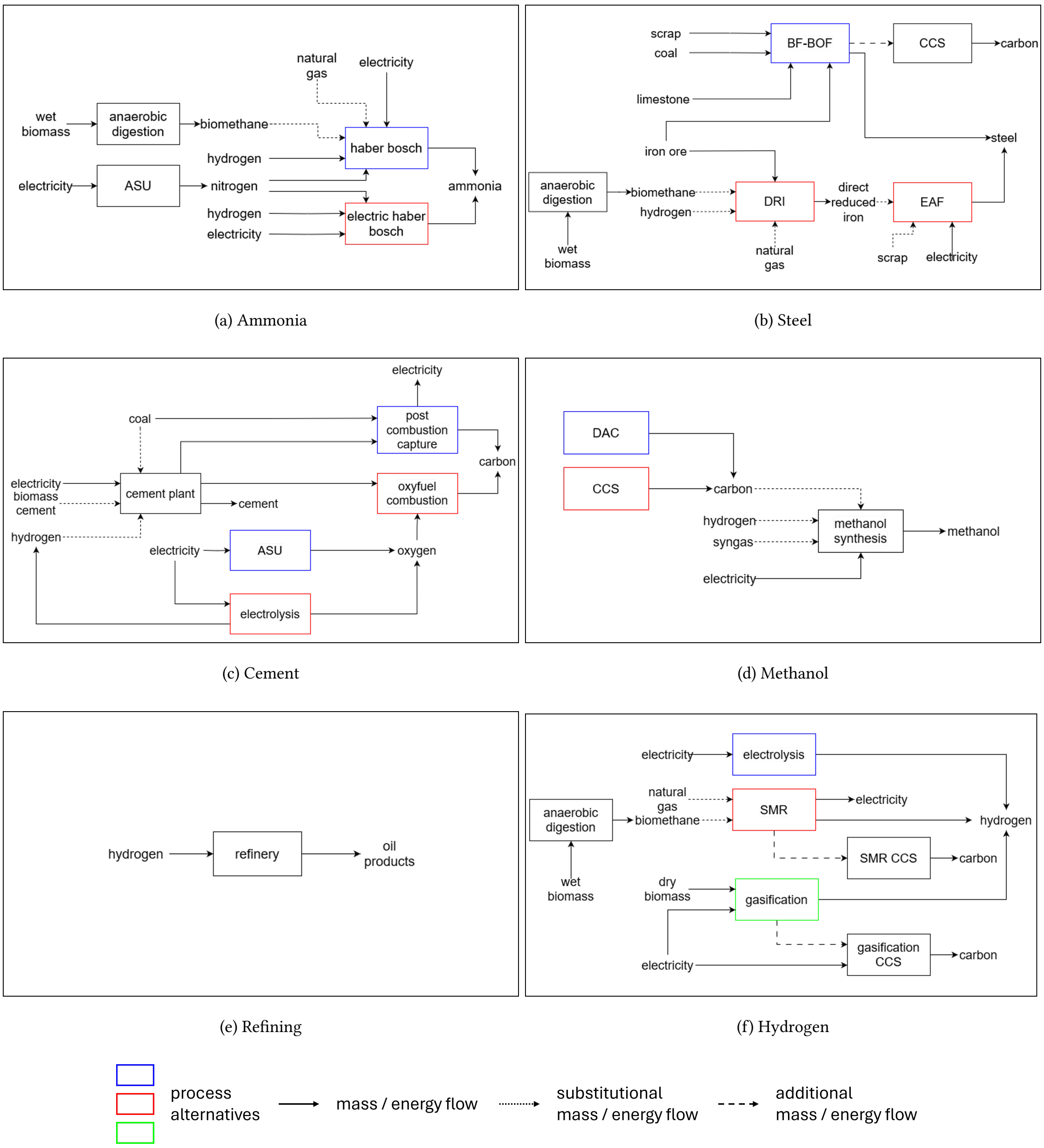

Figure S2: a)-e) Overview of the considered decarbonization pathways for each industry. f) Available hydrogen production pathways.

S3. Annual carbon emissions

Fig. S3 visualizes the annual carbon emissions for each industry in the individual strategy and the integrated strategy for the full set of model results which cover the range of 2024-2050.

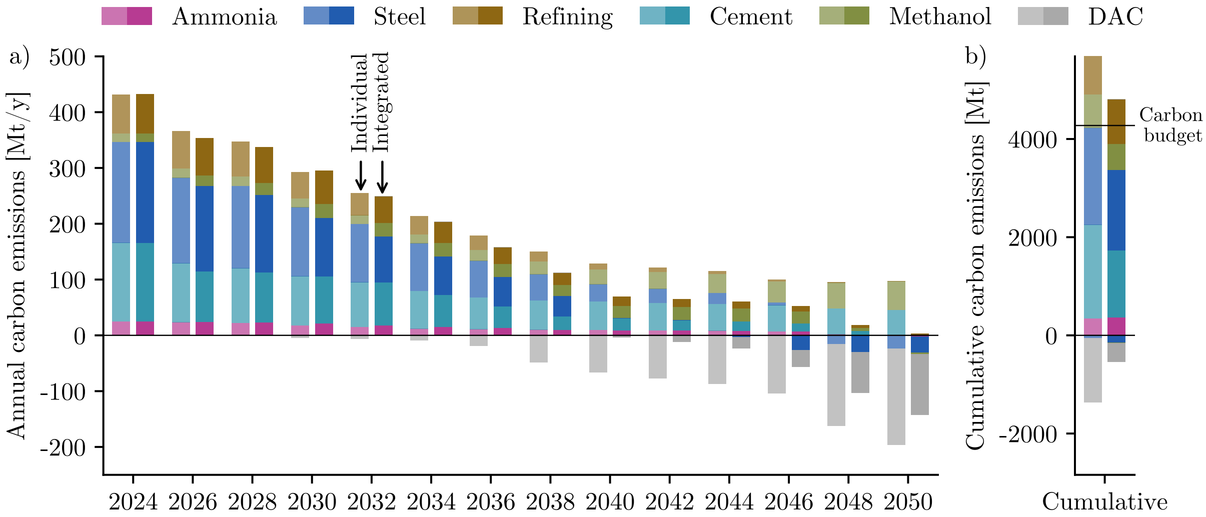

Figure S3: Annual carbon emissions in the individual strategy (light bar, left) and the integrated strategy (dark bar, right) across the considered industries. DAC: Direct Air Capture.

S4. Carbon, hydrogen, and biomethane transport infrastructure

Fig. S4 visualizes the installed transport infrastructure for carbon, hydrogen, and biomethane for 2050 when following the individual strategy (left) and integrated strategy (right).

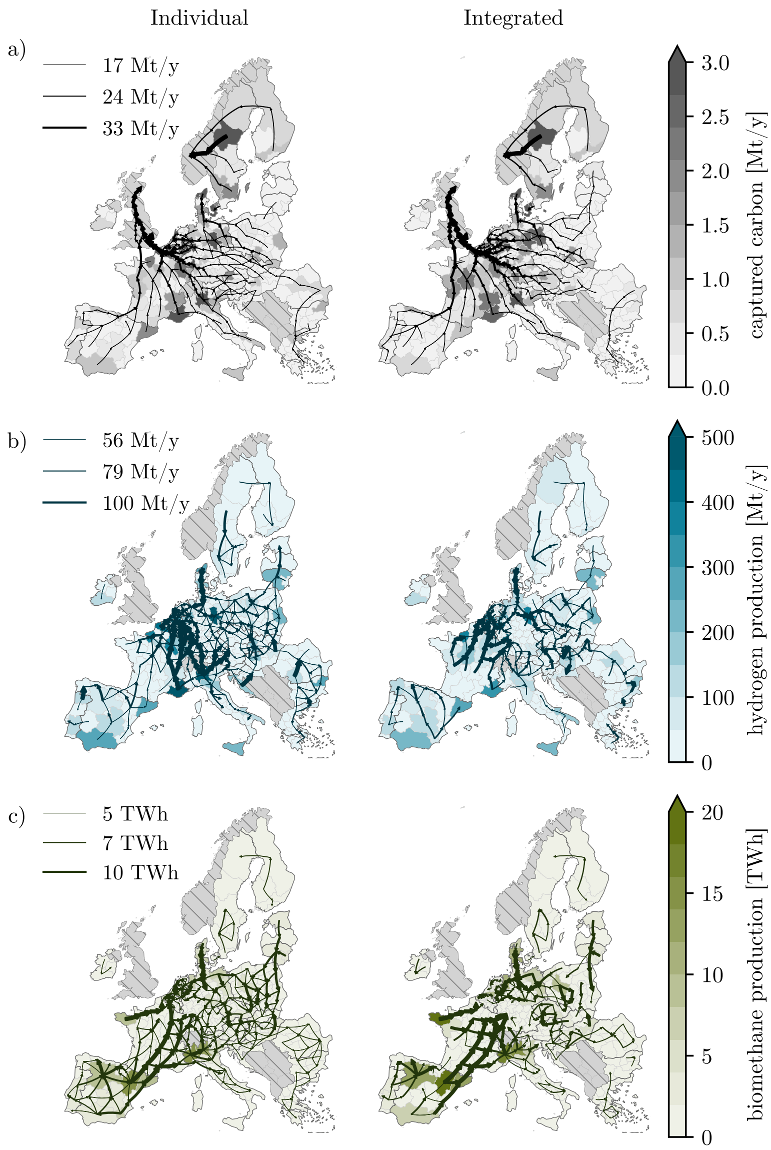

Figure S4: Transport infrastructure for a) carbon, b) hydrogen, and c) biomethane in the integrated strategy (left) and the individual strategy (right).

S5. Hydrogen utilization and production

Fig. S5 visualizes a) the utilization and b) the production of hydrogen in the individual and the integrated strategy. In the integrated strategy, hydrogen is predominantly used in industries that inherently rely on hydrogen in their production, i.e. Ammonia production and refineries. The utilization of hydrogen as an energy carrier to reduce fossil fuel consumption in steel and cement manufacturing remains limited. In contrast, hydrogen production capacities in the individual strategy are 2.5 times larger than in the integrated strategy. Due to the sub-optimal allocation of the biomass resources, much larger electrolytic hydrogen production capacities are required to comply with the annual decarbonization targets and maintain the carbon emission budget.

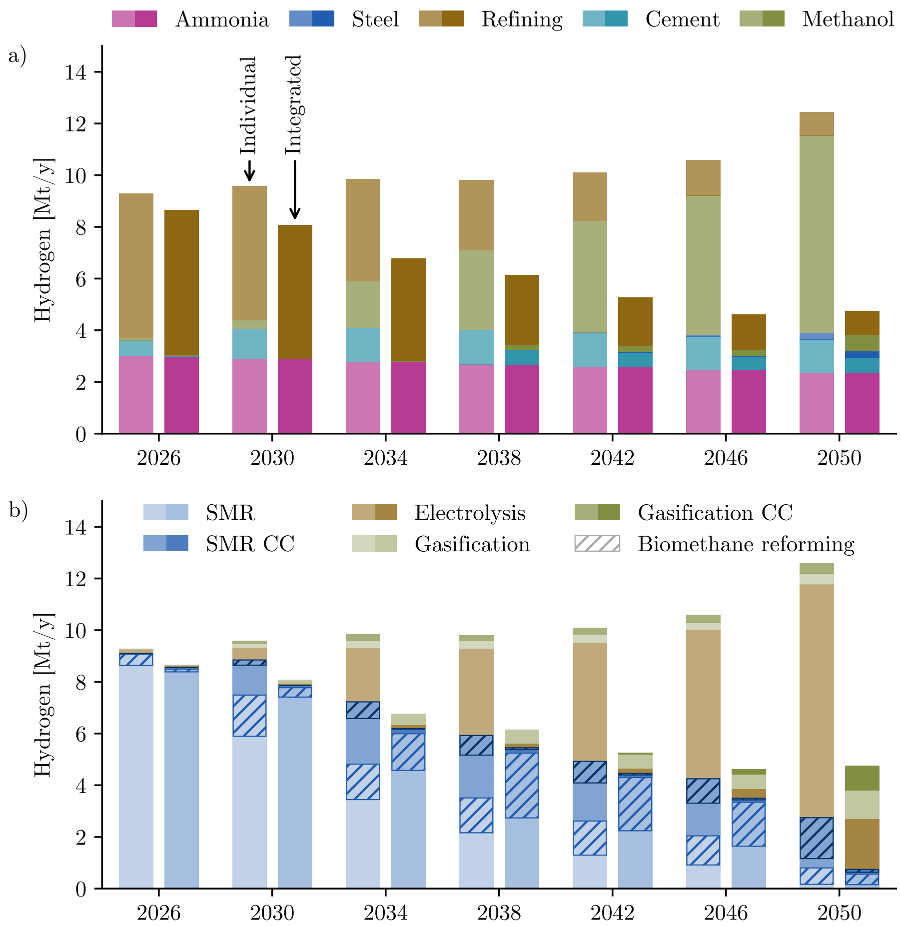

Figure S5: a) Hydrogen consumption per industry and b) hydrogen production per production technology in the individual strategy (left bar, light) and integrated strategy (right bar, dark). SMR: Steam Methane Reforming. CC: Carbon Capture

S6. Industry decarbonization strategies assuming the optimal allocation of biomass and carbon storage resources in the individual strategy

Fig. S6 visualizes the decarbonization pathway in the individual strategy (left bar) and the integrated strategy (right bar) when optimally allocating the carbon budget and the limited resources. The optimal allocation of the limited biomass resources allows for a more efficient use of the available biomass resources in the individual strategy. Nevertheless, synergy effects between industries cannot be captured. As a result, the demand for renewable electricity is still almost 200 TWh higher.

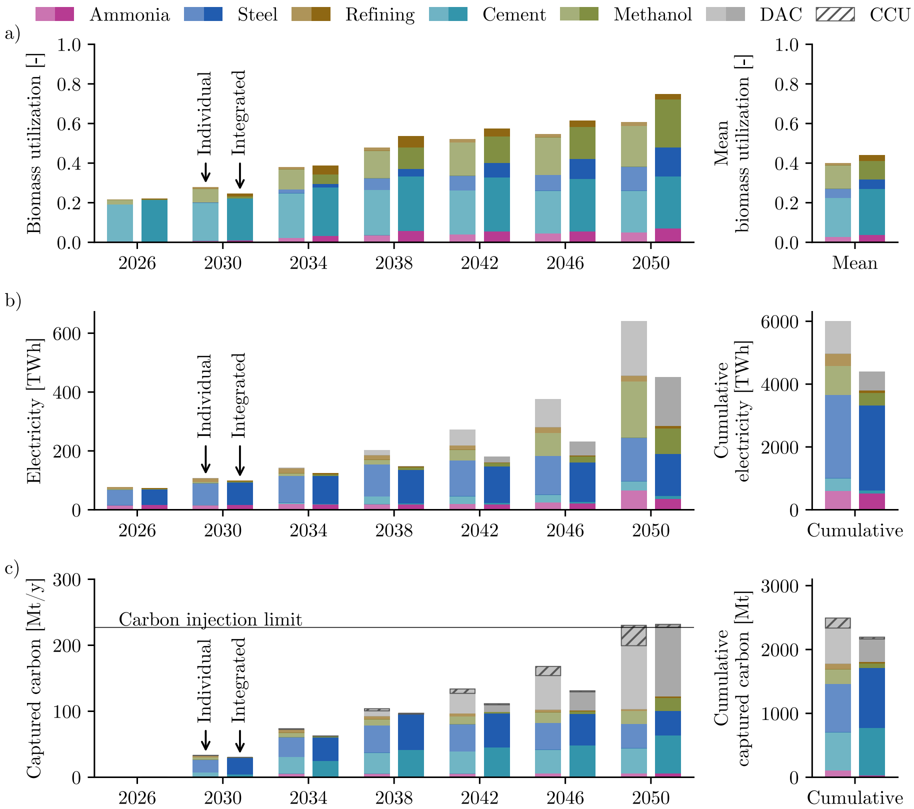

Figure S6: a) Biomass utilization, b) renewable electricity consumption, and c) carbon capture utilization and storage per industry in the individual strategy (light bar, left) and the integrated strategy (dark bar, right). Annual values (left columns) and cumulative values (right column) are shown. A biomass utilization of 1 corresponds to using the full sustainable biomass potential. A more effective allocation of the available biomass resources and increased carbon capture rates across industries reduce the renewable electricity consumption in the integrated strategy by almost 30 %. DAC: Direct Air Capture. CCU: Carbon Capture Utilization.

S7. Industry decarbonization strategies considering varying levels of biomass availability

Fig. S7 visualizes a) biomass utilization, b) electricity consumption, and c) carbon capture utilization and storage per industry in the integrated strategy for varying levels of biomass availability. For reference, the left bar shows the results considering the full biomass availability. In contrast, the middle and right bars visualize the results considering 50 % of the available biomass potential and 0 % of the available biomass potential, respectively. As the level of biomass available for industry decarbonization reduces, increasing amounts of electrolytic hydrogen are required in the transition, increasing the renewable electricity demands by up to 500 TWh. In addition, increasing amounts of carbon are captured and utilized, e.g. for e-methanol production.

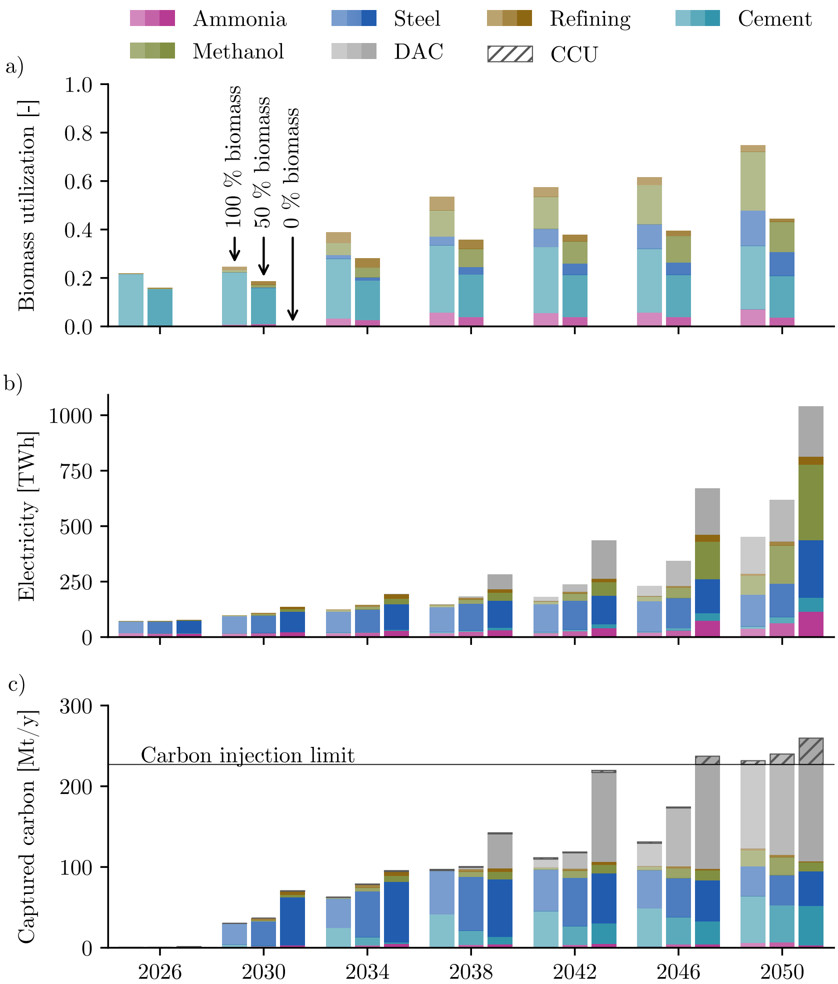

Figure S7: a) Biomass utilization, b) renewable electricity consumption, and c) carbon capture utilization and storage per industry in the integrated strategy considering reduced levels of biomass availability. The left bar shows the results considering the full sustainable potential, the middle bar 50% of the sustainable biomass potential, and the right bar 0% of the sustainable biomass potential, respectively. DAC: Direct Air Capture. CCU: Carbon Capture Utilization.

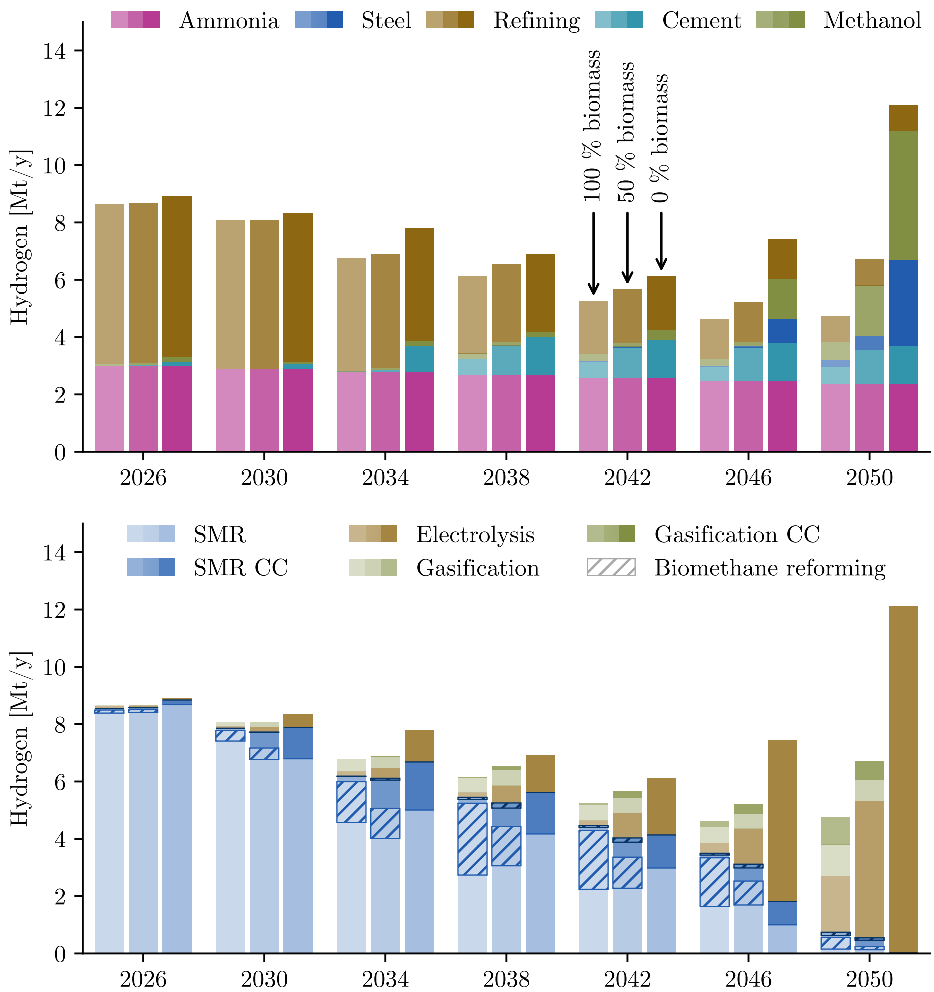

Figure S8: a) Hydrogen consumption per industry and b) hydrogen production per production technology in the individual strategy. The left bar shows the results considering the full sustainable potential, the middle bar 50% of the sustainable biomass potential, and the right bar 0% of the sustainable biomass potential, respectively. SMR: Steam Methane Reforming. CC: Carbon Capture

S8. Industry decarbonization strategies considering unconstrained carbon storage injection limits

Fig. S9 compares the decarbonization strategies when considering limited carbon storage injection rates (left bar) and unconstrained annual carbon storage injection rates (middle and right bar). If the full biomass potential is available for industry decarbonization and annual carbon storage rates are unconstrained, about 250 Mt/y of carbon would be stored underground by 2050 (Fig. S9c, middle bar). When planning industry transition without the use of biomass resources and considering unconstrained annual carbon storage rates, about 300 Mt/y of carbon would be stored underground by 2050 (Fig. S9c, right bar). In both cases, we observe that when carbon storage injection rates are unlimited, larger shares of DAC capacities are deployed and the coupling of production processes with carbon capture units reduces.

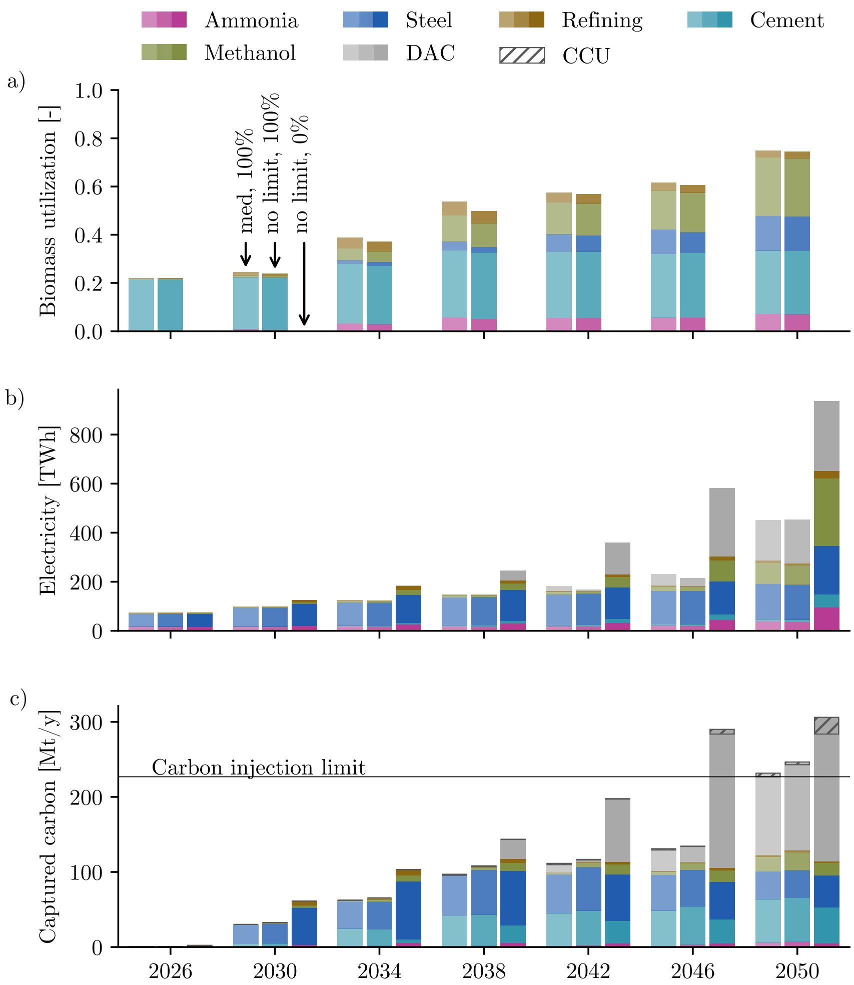

Figure S9: a) Biomass utilization, b) renewable electricity consumption, and c) carbon capture utilization and storage per industry in the integrated strategy considering varying annual carbon storage injection rates and biomass availability. For reference, the left bar shows the results considering the full sustainable biomass potential and limited carbon storage injection rates presented in the main paper ("limit, 100 %"). The middle bar also considers the full sustainable biomass potential but does not limit the annual carbon storage injection rates ("no limit, 100 %"). The right bar also considers unlimited annual carbon storage injection rates, but no biomass is available for industry decarbonization ("no limit, 0 %"). DAC: Direct Air Capture. CCU: Carbon Capture Utilization.

S9. Industry decarbonization strategies for high demands and varying biomass availabilities

Fig. S10 visualizes biomass utilization, renewable electricity consumption, and carbon capture utilization and storage per industry in the integrated strategy. For reference, the results for medium demands and the full biomass potential are visualized ("medium, 100 %", left bar). In addition, the results for high demands and full biomass potential ("high, 100 %", middle bar) and for no biomass (high, 0 %", right bar) are presented. If biomass is unavailable for industry decarbonization and industry demands are high, electricity demands increase by up to a factor of three. These increased electricity demands are mainly due to an increased reliance on electrolytic hydrogen and DAC in the transition.

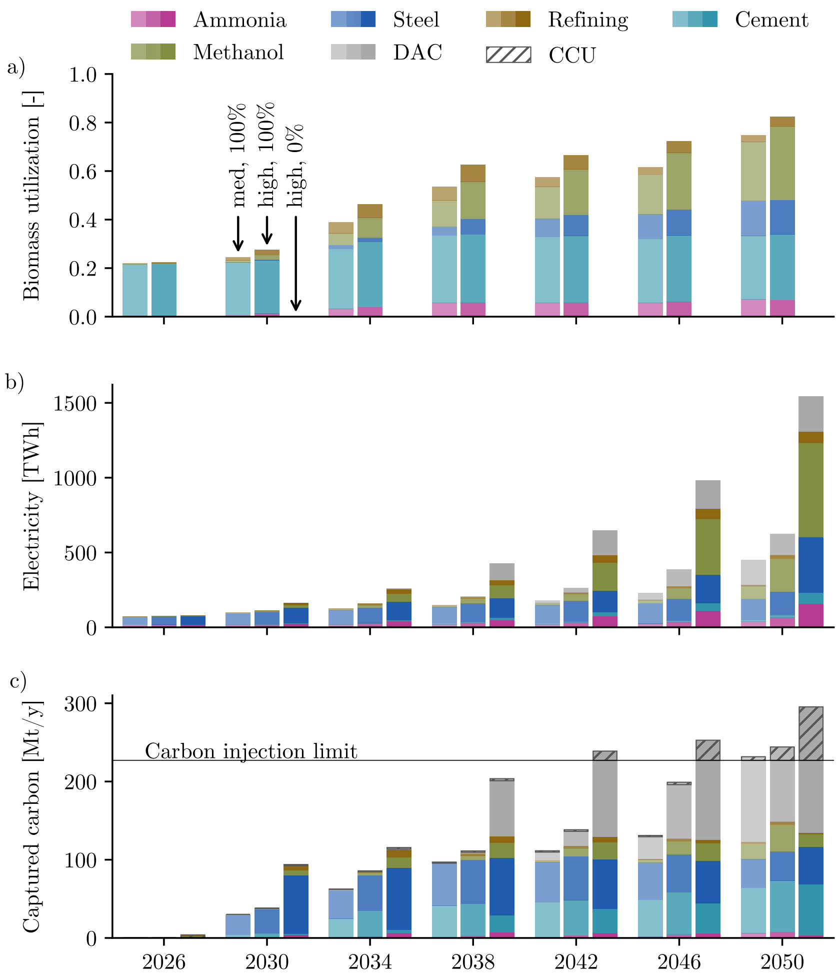

Figure S10: a) Biomass utilization, b) Carbon capture utilization and storage, and c) renewable electricity consumption per industry in the integrated strategy considering reduced levels of biomass availability. For reference, the left bar shows the results considering the full sustainable biomass potential and medium hydrogen demands as presented in the main paper. The middle bar also considers the full sustainable biomass potential but considers high demands. The right bar also assumes high demands but assumes that biomass is unavailable for industry decarbonization. DAC: Direct Air Capture. CCU: Carbon Capture Utilization.

S10. Electricity, carbon capture, and hydrogen use across different end demand scenarios

Fig. S11 visualizes (a) the electricity consumption, (b) carbon capture, (c) and the use of hydrogen for ammonia production and refineries when considering low, medium (reference), and high end-product demands. Ammonia production and refineries require hydrogen; therefore, the same amount of hydrogen is used independently of the biomass scenario. However, if the availability of biomass is reduced and/or end-product demands increase, we denote increased electricity demands and an increased deployment of CCS.

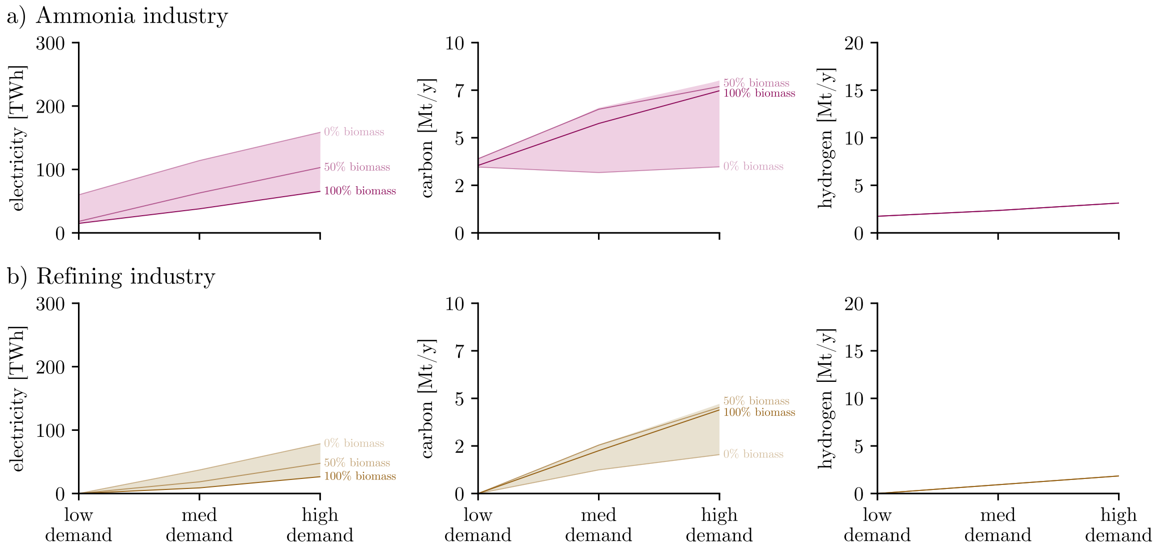

Figure S11: Electricity consumption, carbon capture, and hydrogen production for a) ammonia industry and b) refining industry in the integrated strategy in 2050 when considering low, medium (reference), and high demands.

S11. Impact of different cost scenarios on the industry decarbonization pathways

We investigate the sensitivity of our results in the integrated strategy, considering three different cost scenarios:

1. Hydrogen scenario: Scenario with reduced electrolyzer cost
2. Electricity scenario: Scenario with reduced cost of the direct electrification options
3. CCS scenario: Scenario with reduced cost for the coupling of CCS

The cost assumptions are summarized in S11. Fig. S12 visualizes the change in the annual emissions per industry. We note that decreased electrolyzer cost and decreased electrification cost do not have a large impact on the annual emissions and changes remain below 3 % in the hydrogen and the electricity scenario. However, if CCS becomes more cost-efficient, we observe an increased deployment of CCS units in Steel and Cement industry, reducing the reliance on biomass-derived fuels and DAC across industries (Fig. S13c and Fig. S13a, respectively). Nonetheless, changes in the annual emissions remain below 6 % on average.

Table S13: Investment cost for the technologies included in the different cost scenarios. EAF: electric arc furnace. CC: carbon capture. BF-BOF: blast furnace and basic oxygen furnace. SMR: steam methane reforming

Technologies	**Unit**	**2024**	**2030**	**2040**	**2050**
Hydrogen scenario					
Electrolysis [30]	k€/MW_{H_2}	1547	591	435	279
Electricity scenario					
Electric Haber Bosch [30]	k€/(t_{NH_3}/h)	8299	7085	5061	3036
EAF [31, 20]	k€/(t_{Steel}/h)	1972	1972	1972	1972
Electrolysis [30]	k€/MW_{H_2}	1547	591	435	279
CCS scenario					
Post combustion capture [23]	k€/(t_{CO_2}/h)	4300	1680	1440	1200
Oxyfuel combustion [23]	k€/(t_{CO_2}/h)	3400	2520	2360	2200
Carbon capture unit for BF-BOF [21]	k€/(t_{CO_2}/h)	1017	1017	1017	1017
Direct air capture [23]	k€/(t_{CO_2}/h)	5141	2980	2140	1300
Carbon Storage [38]	k€/(t_{CO_2}/h)	114	114	114	114
SMR-CC [26, 42]	k€/MW_{H_2}	1848	1660	1346	1032
Gasification with CC [34]	k€/MW_{H_2}	2487	2320	2185	2048

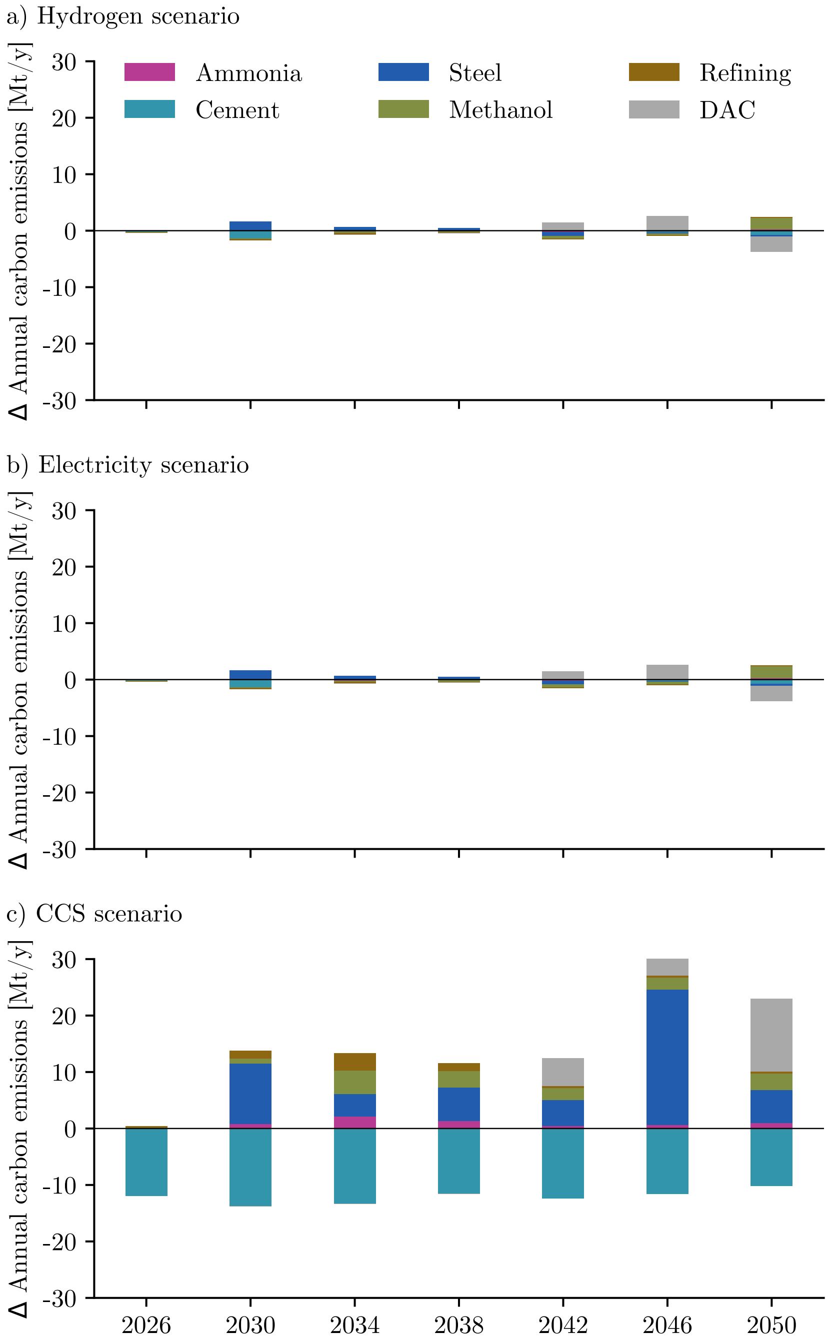

Figure S12: Change in annual carbon emissions per industry in the integrated strategy considering a) reduced electrolyzer cost, b) reduced electrification costs, and c) reduced cost for the coupling with carbon capture and storage. The installation of direct air capture units (DAC) and the coupling of biomass-based production processes with carbon capture and storage enables carbon dioxide removal.

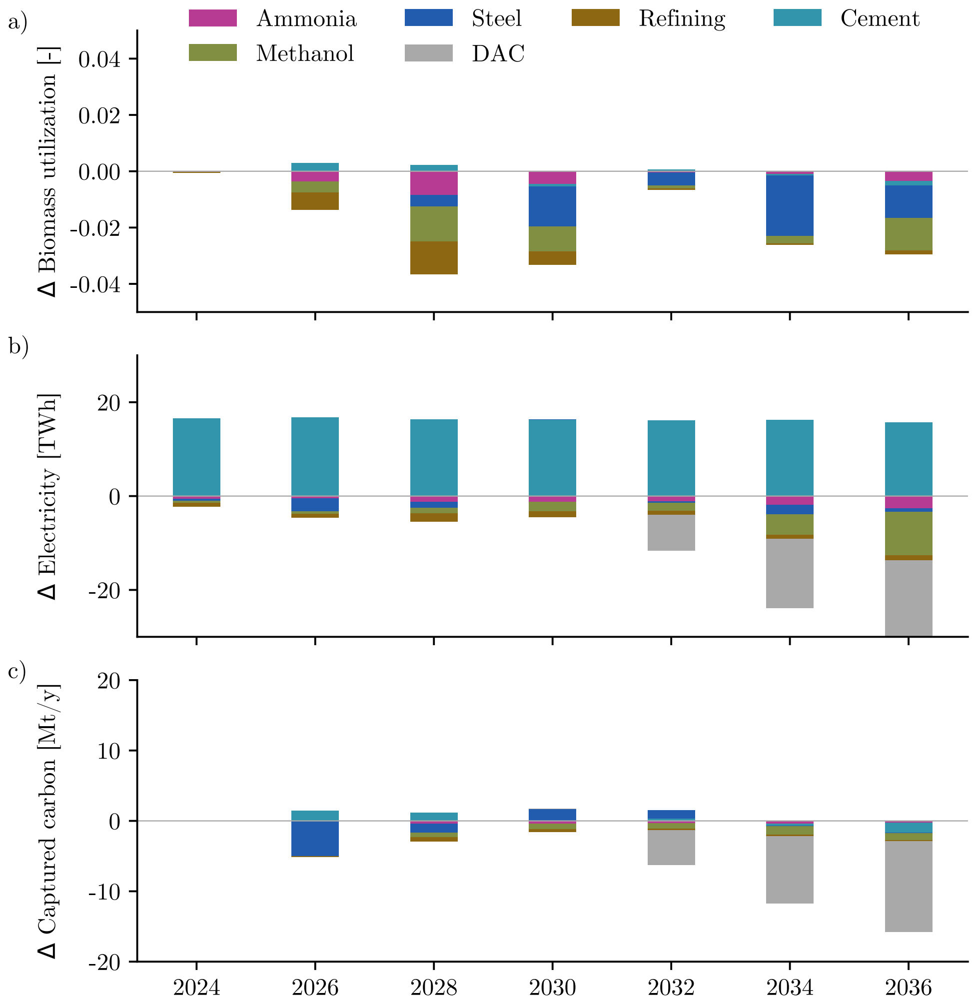

Figure S13: Change in a) biomass utilization, b) carbon capture utilization and storage, and c) renewable electricity consumption per industry in the integrated strategy considering reduced cost for the coupling with carbon capture and storage. DAC: Direct Air Capture.

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