Decisions on the industrial energy transition
Compendium

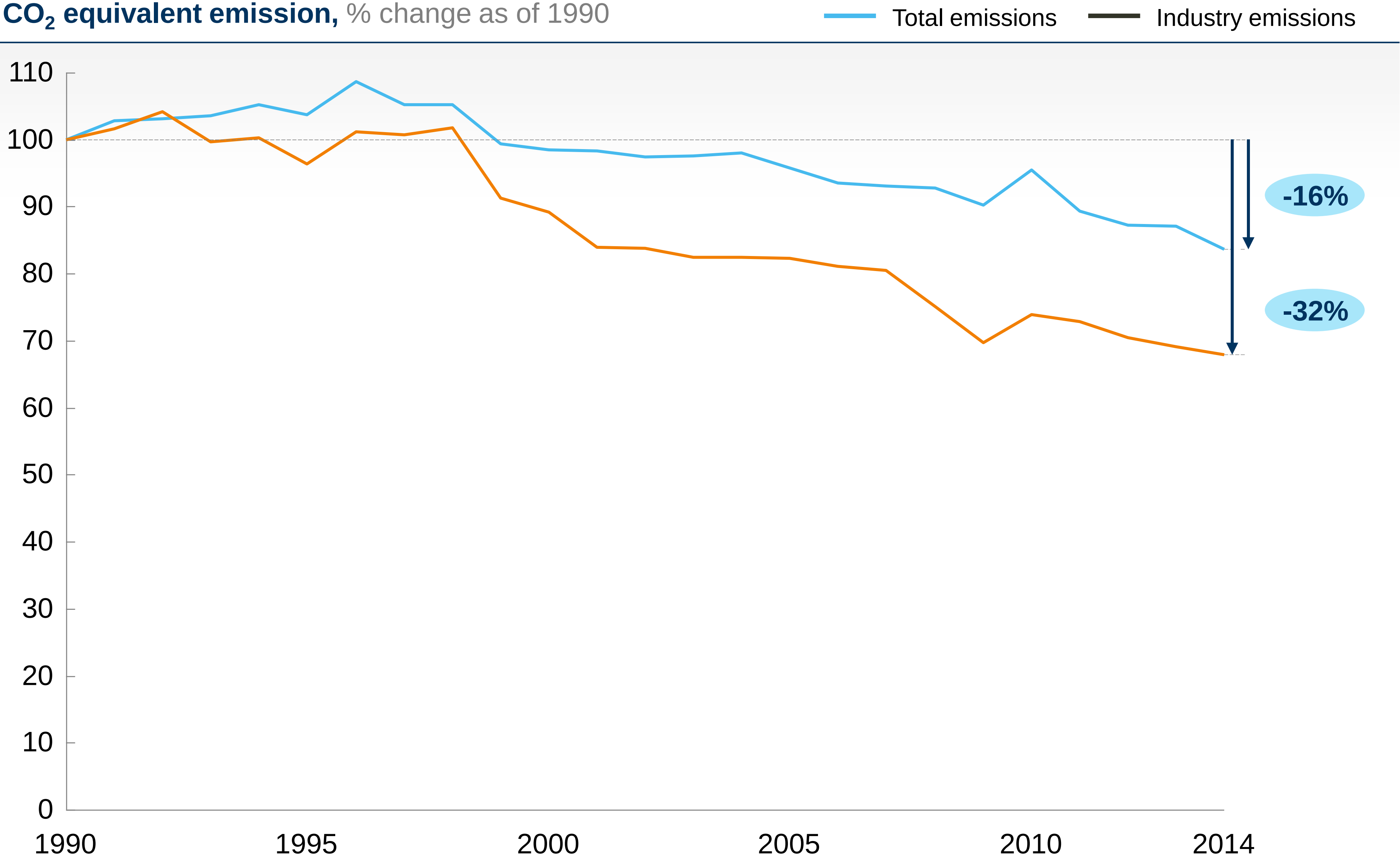
KONINKLIJKE
vemw
Kenniscentrum en belangenbehartiger
van zakelijke energie- en watergebruikers

MARCH 2017

Contents

CO2e emissions from industry have reduced 2x faster than total emissions in the Netherlands

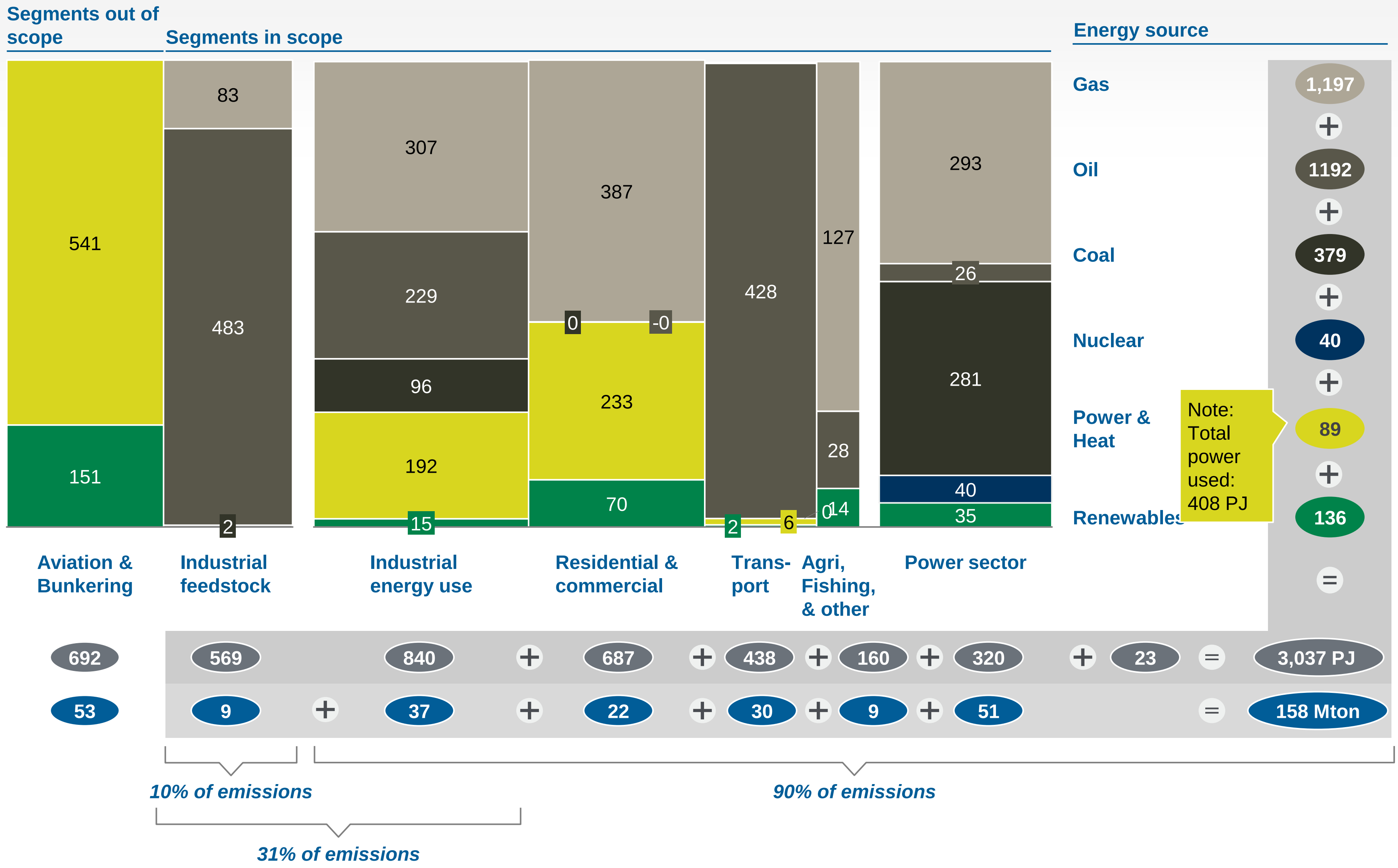
CO_2 equivalent emission, % change as of 1990



SOURCE: CBS, National Inventory Report (1990-2014)

Energy consumption and CO_2 emissions in the Netherlands

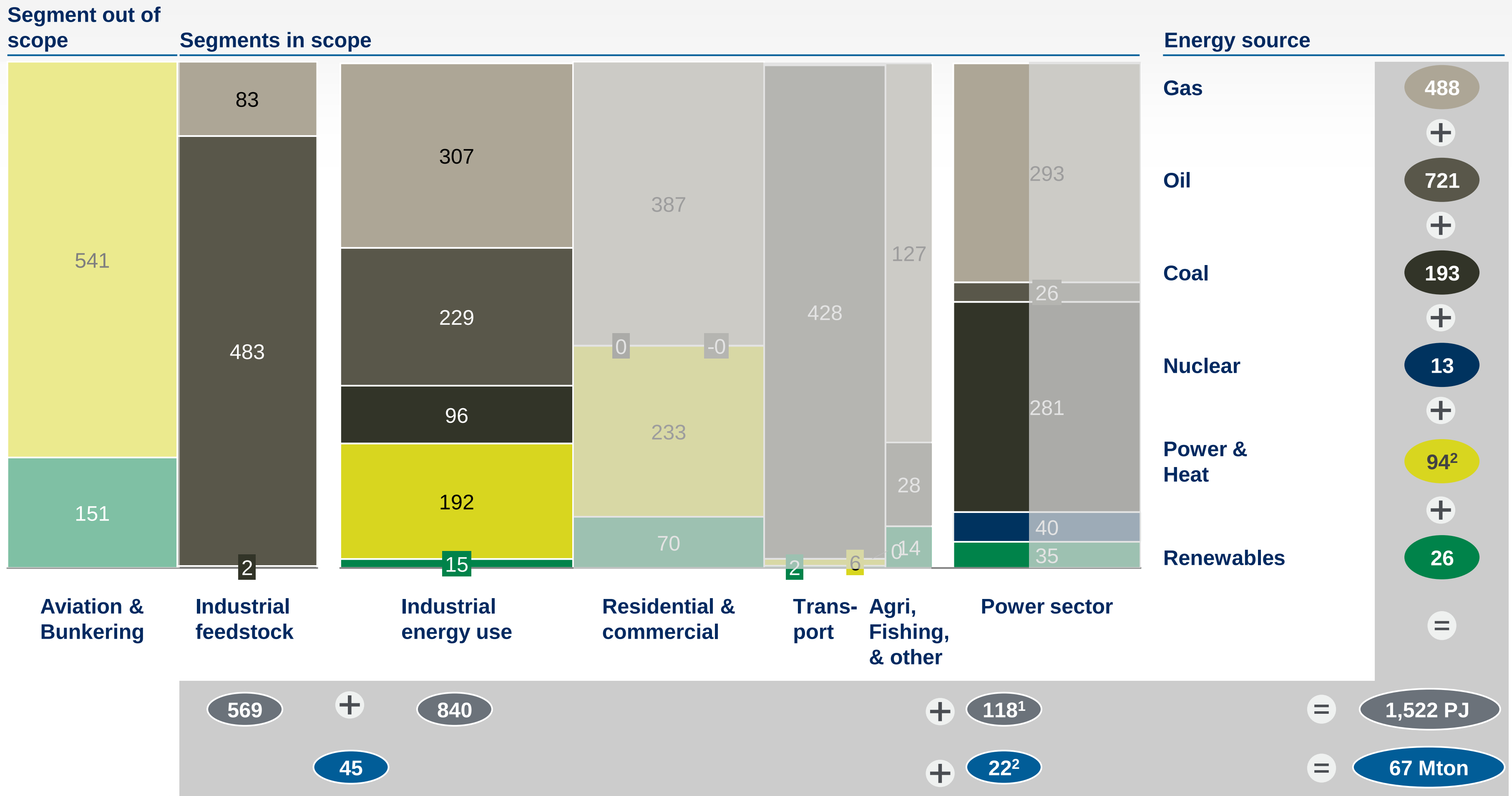
Total net energy demand in the Netherlands by sector and industry, PJ, 2014



SOURCE: Centraal Bureau voor de Statistiek (2014), “Energiebalans” and “Energieverbruik” databases, National Inventory Report 2016, team analysis

Industrial activities – including fair share of power – causes 42% of CO_2 emissions

Total net energy demand in the Netherlands by sector and industry, PJ, 2014, greyed out parts indicate what is not included in industry



31% of direct emissions

42% of power emissions

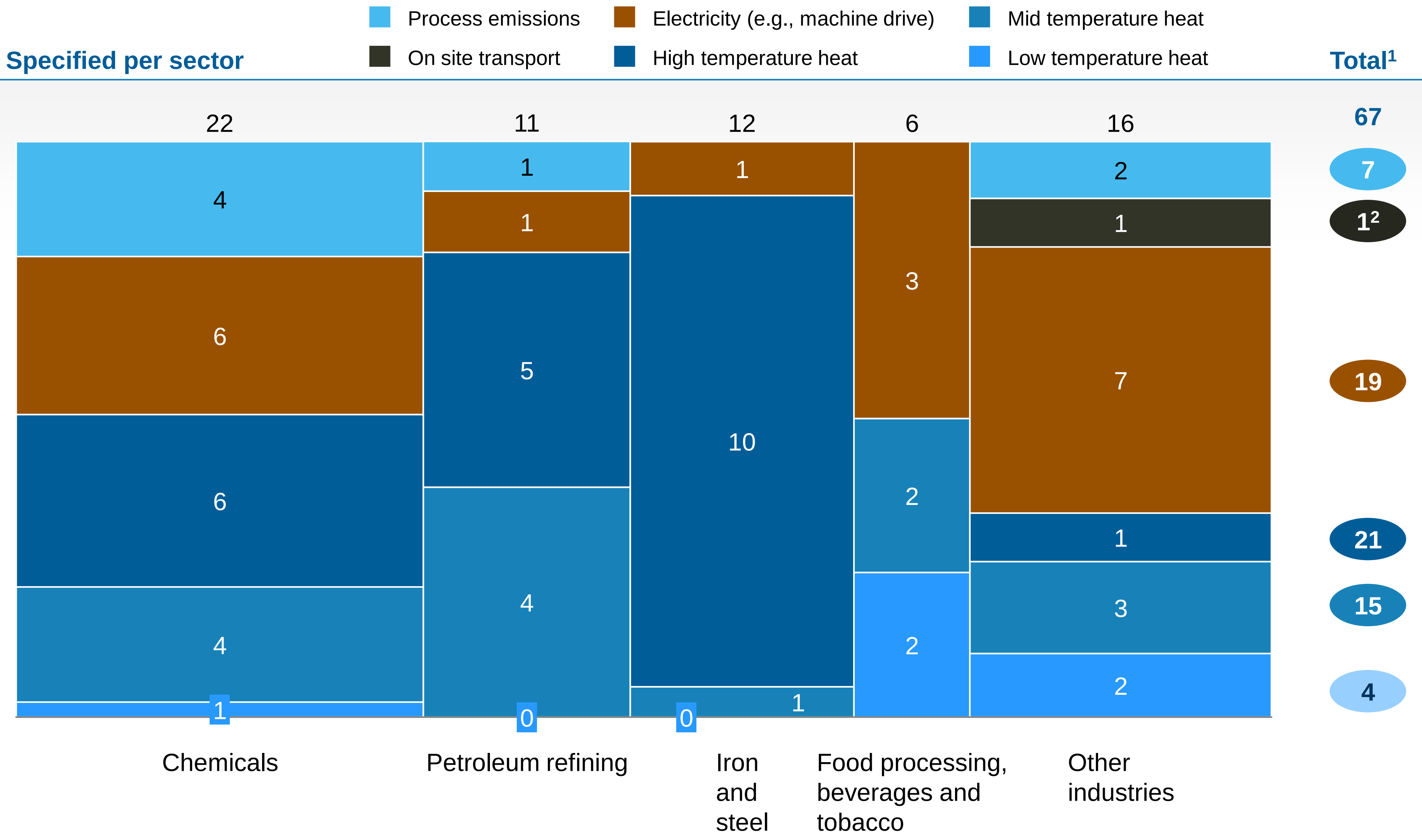
NOTE: this includes 6 $MtCO_2$ that should be fully attributed to the steel sector

42% of total emissions

SOURCE: Centraal Bureau voor de Statistiek (2014), “Energiebalans” and “Energieverbruik” databases, National Inventory Report 2016, team analysis

Overview of CO_2 emissions, split by functional use

Estimated Mt CO_2/yr, 2014



NOTE: Difference in totals due to rounding

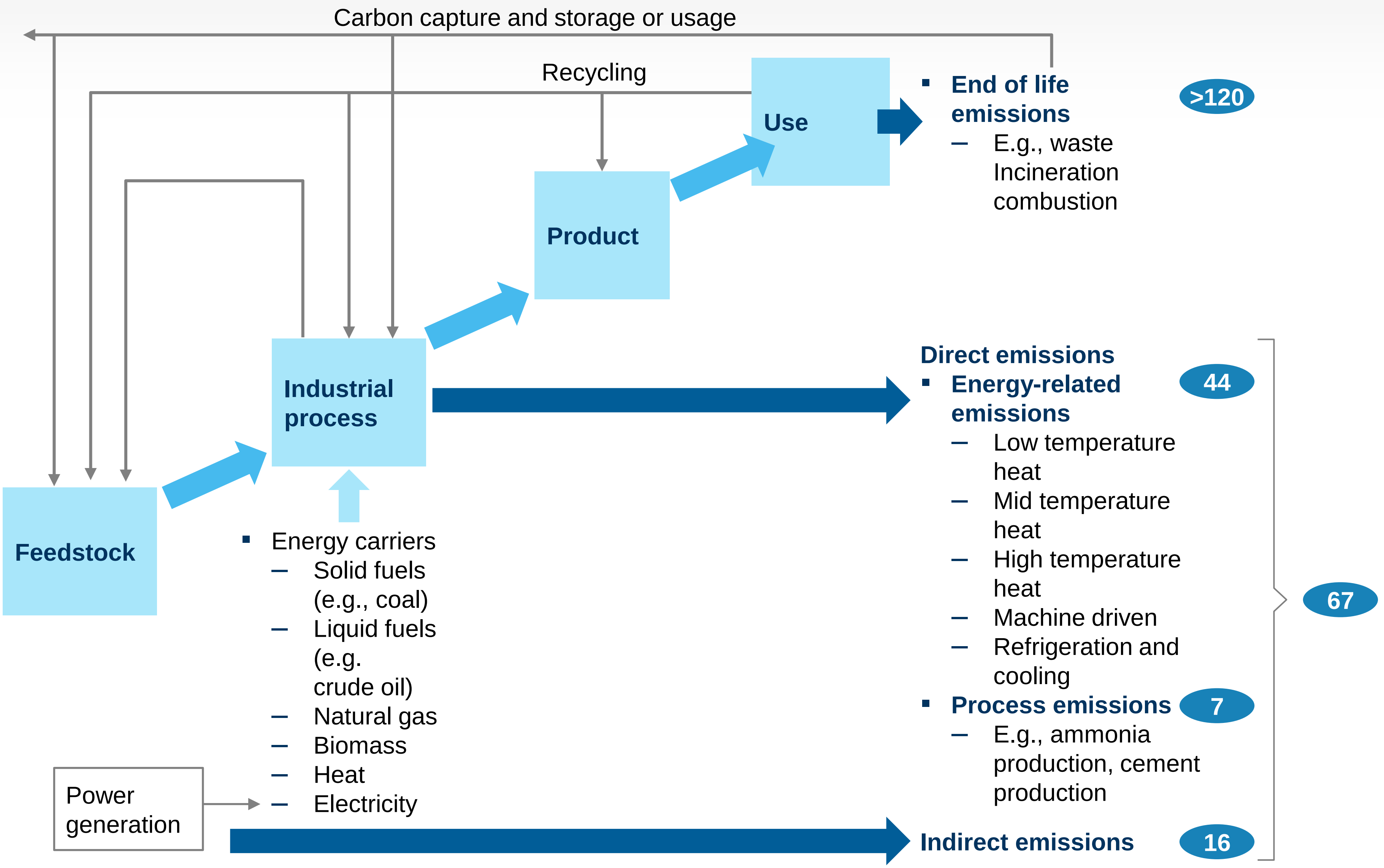
[1] Emissions from biomass are excluded

[2] On-site transport not allocated to specific sectors

SOURCE: Manufacturing Energy Consumption Survey (2013); National Inventory Report (2016); expert interviews; CE Delft Denktank energiemarkt Industrielewarmtemarkt 2013; expert interviews, team analysis

Emissions during product lifecycle

x Emissions (Mt CO_2)
➡ Emissions
➡ Product lifecycle
→ Use of waste streams



Carbon capture and storage or usage

Recycling

Feedstock

Industrial process

Product

Use

- Energy carriers
  - Solid fuels (e.g., coal)
  - Liquid fuels (e.g. crude oil)
  - Natural gas
  - Biomass
  - Heat
  - Electricity

Power generation

- **End of life emissions** >120
  - E.g., waste Incineration combustion

Direct emissions 67

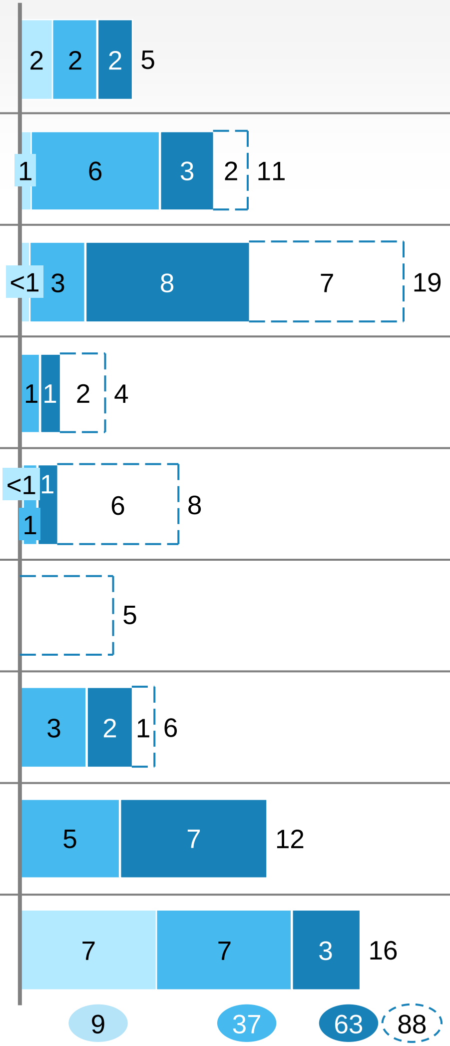
- **Energy-related emissions** 44
  - Low temperature heat
  - Mid temperature heat
  - High temperature heat
  - Machine driven
  - Refrigeration and cooling
- **Process emissions** 7
  - E.g., ammonia production, cement production

Indirect emissions 16

SOURCE: Centraal Bureau voor de Statistiek (2014), “Energiebalans” and “Energieverbruik” databases, National Inventory Report (1990-2014), team analysis

Scenario 1 Current prices: Impact and assumptions

Potential until 2025
Potential 2025-2040
Potential after 2040
Technical potential



Options	Carbon reduction MtCO$_2$	Assumptions: Potential after 2040	Assumptions: Technical potential
1 Implement efficiency measures and options with business cases	2 · 2 · 2 · 5	50% of low temperature heat with heat pumps. 100% of mechanical vapor recompression potential. Energy efficiency 15% of low and mid temperature	Same as potential after 2040
2 Create optionality in Mid T heat by replacing gas boilers with hybrids	1 · 6 · 3 · 2 · 11	100% mid temperature heat excl. steel refining (+50% low temp) 75% mid temperature heat refining (+38% low temp)	100% of mid temperature heat incl. steel, refining
3 Develop CCS/U capabilities	<1 · 3 · 8 · 7 · 19	25% of refining + 100% refining process emissions 55% ethylene 100% ammonia under scenario 1	100% of ammonia, 90% of ethylene, 80% of refining
4 Develop routes to valorize residual streams	1 · 1 · 2 · 4	30% of ethylene production (50% of 60% ethylene that is used for in plastics)	60% of ethylene production (100% of 60% ethylene that is used for in plastics).
5 Start Bio-to-Chem on selective processes	<1 · 1 · 1 · 6 · 8	15% of ethylene 50% of specialty chemicals	100% of ethylene and specialty chemicals
6 Invest in R&D on decreasing hydrogen production costs via electrolysis at scale	5	0% under current electricity/hydrogen prices 100% of ammonia under scenario 2/3	100% of ammonia
7 Invest in R&D on mid and high temperature	3 · 2 · 1 · 6	75% of refining high temperature 100% of other industries and chemicals high temperature excluding ammonia and ethylene	Same as potential after 2040, but 100% of refining high temperature
8 Decide on steel route	5 · 7 · 12	100%	100%
Renewable electricity for machine drive	7 · 7 · 3 · 16	100%	100%
Total (cumulative for carbon reduction)[1]	9 · 37 · 63 · 88		

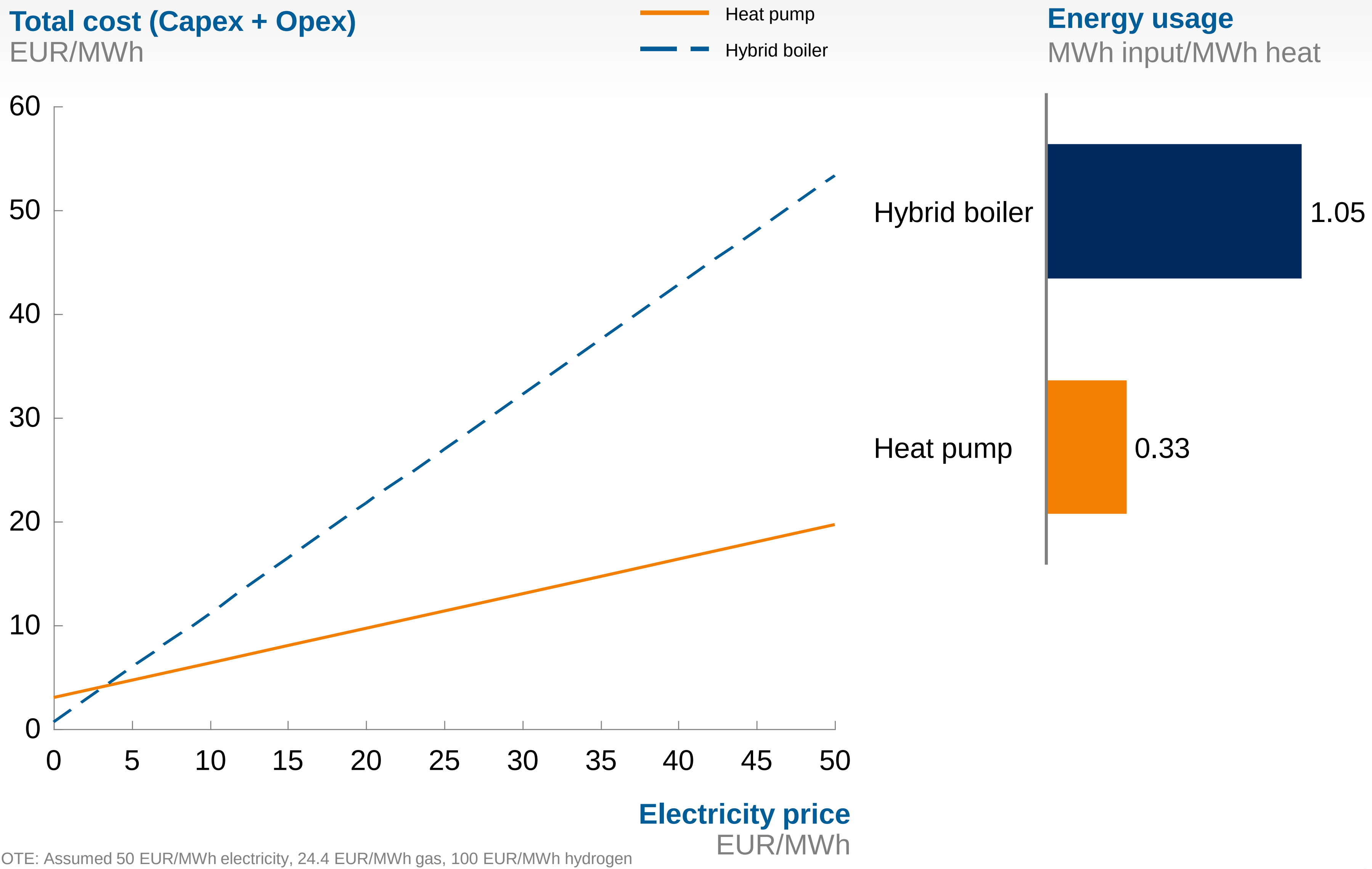
NOTE: Assumed 50 EUR/MWh electricity, 24.4 EUR/MWh gas, 100 EUR/MWh hydrogen. Differences in totals due to rounding

1 Technical potential sums up to more than 100% of emissions due to double counting

Source: Centraal Bureau voor de Statistiek (2014), “Energiebalans” and “Energieverbruik” databases, National Inventory Report (1990-2014), team analysis

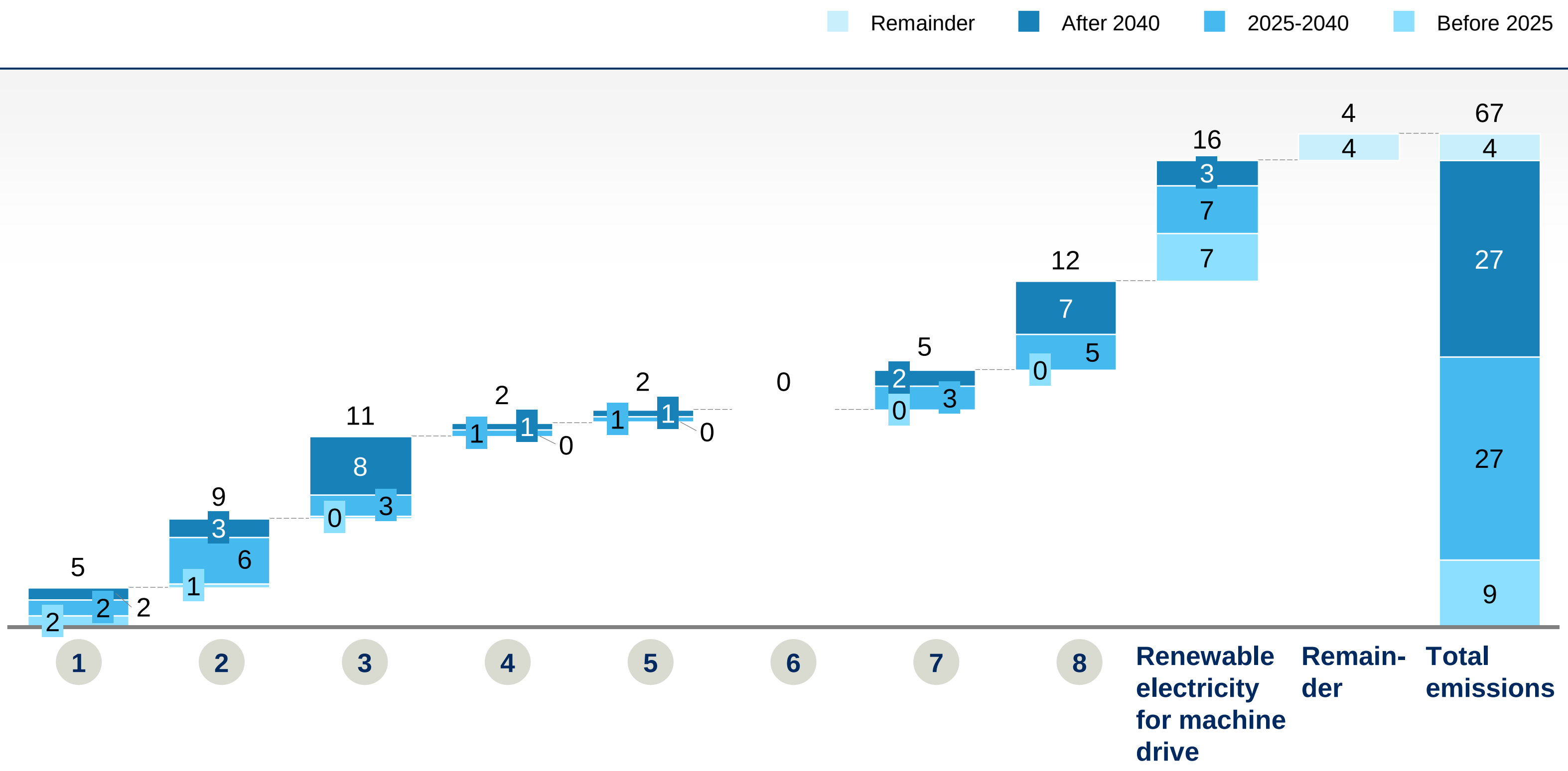
Trade-off between heat pump and hybrid boiler depends on electricity price

Comparison of heat pump and hybrid boiler on cost and energy usage for low temperature heat



NOTE: Assumed 50 EUR/MWh electricity, 24.4 EUR/MWh gas, 100 EUR/MWh hydrogen
SOURCE: Team analysis

Scenario 1 Current prices: Adding up the impact of the 8 decisions



1: Includes annual 0.5% energy efficiency improvement

2: Includes cascaded decarbonization impact on low temperature heat

3: CCS on ammonia, 55% of ethylene and 25% of refining

4: 30% reduction in ethylene production

5: 15% ethylene and 50% specialty chem production biobased

7: Excluding ammonia, ethylene, iron and steel

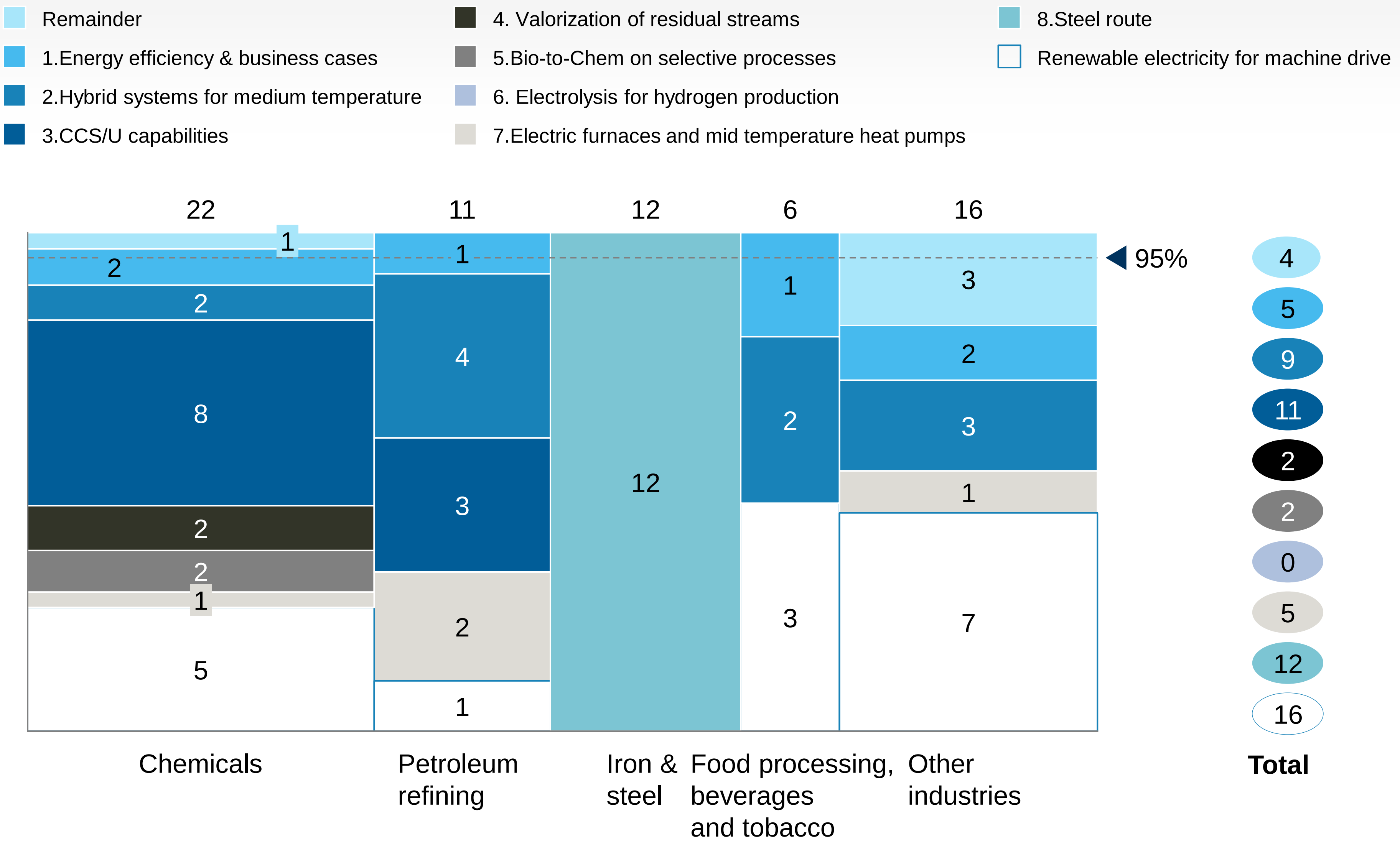
Remainder: 0.7 MtCO2 Chemicals, 3 MtCO2 Other industries incl. cement production and off road transport

NOTE: Assumed 50 EUR/MWh electricity, 24.4 EUR/MWh gas, 100 EUR/MWh hydrogen. Differences in totals due to rounding

SOURCE: Centraal Bureau voor de Statistiek (2014), “Energiebalans” and “Energieverbruik” databases, National Inventory Report (1990-2014), team analysis

Scenario 1 Current prices: Impact of 8 options per industry

Per fuel ($MtCO_2$)



NOTE: Assumed 50 EUR/MWh electricity, 24.4 EUR/MWh gas, 100 EUR/MWh hydrogen. Differences in totals due to rounding

Source: Centraal Bureau voor de Statistiek (2014), “Energiebalans” and “Energieverbruik” databases, National Inventory Report (1990-2014), team analysis

Business cases under different scenarios

Positive business case compared to conventional option

Neutral/suboptimal business case

Negative business case

★ Circular economy impacts decision

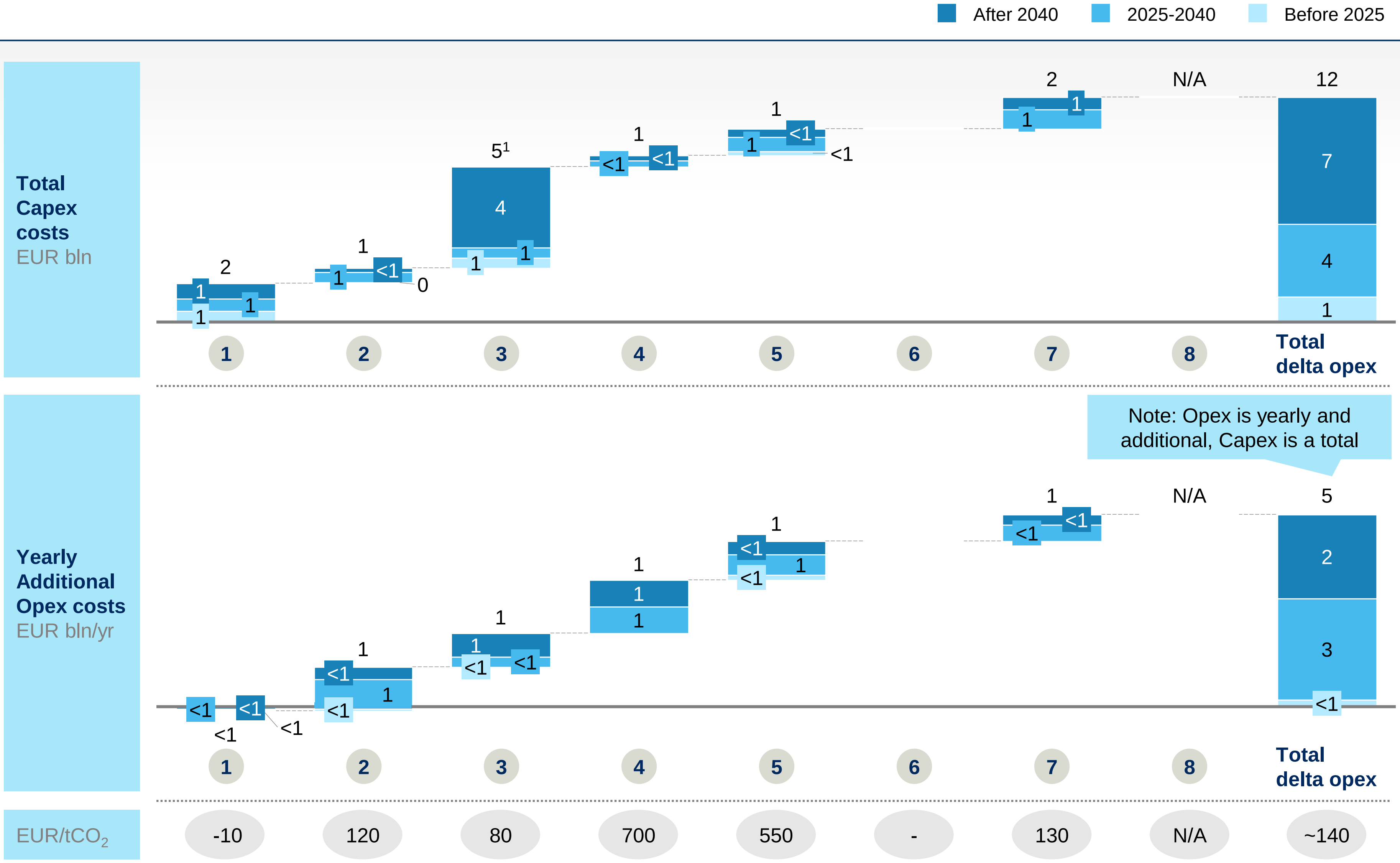
MtCO2 in categories		1. Current prices	2. Electricity price 20 EUR/MWh	3. Electricity 20 EUR/MWh + Hydrogen 73 EUR/MWh
Generic electricity consumption		Electricity renewable Energy efficiency	Electricity renewable Energy efficiency	Electricity renewable Energy efficiency
Generic low temperature heat		Heat pump Use of waste heat	Heat pump Use of waste heat	Heat pump Use of waste heat
Generic medium temperature heat		Mechanical vapor recompression Electric boiler	Mechanical vapor recompression Electric boiler	Mechanical vapor recompression Electric boiler
Generic high temperature heat		Electric furnace	Electric furnace	Electric furnace
Steel production process	★	Hisarna Electric steel rolling and coating	EAF[1] Electric steel rolling and coating	EAF[1] Electric steel rolling and coating
Ammonia production process		Auto thermal + CCS	H_2 from electrolysis	H_2 from electrolysis
Ethylene production process	★	Plastic recycling CCS/U Biomass feedstock	Plastic recycling CCS/U Biomass feedstock	Plastic recycling CCS/U Biomass feedstock
Petroleum refining process		CCS/U	Electrification CCS/U	Electrification CCS/U

NOTE: Assumed 50 EUR/MWh electricity, 24.4 EUR/MWh gas, 100 EUR/MWh hydrogen

SOURCE: Team analysis

[1] Depending on scrap availability

Scenario 1 Current prices: Adding up the cost of the 8 options



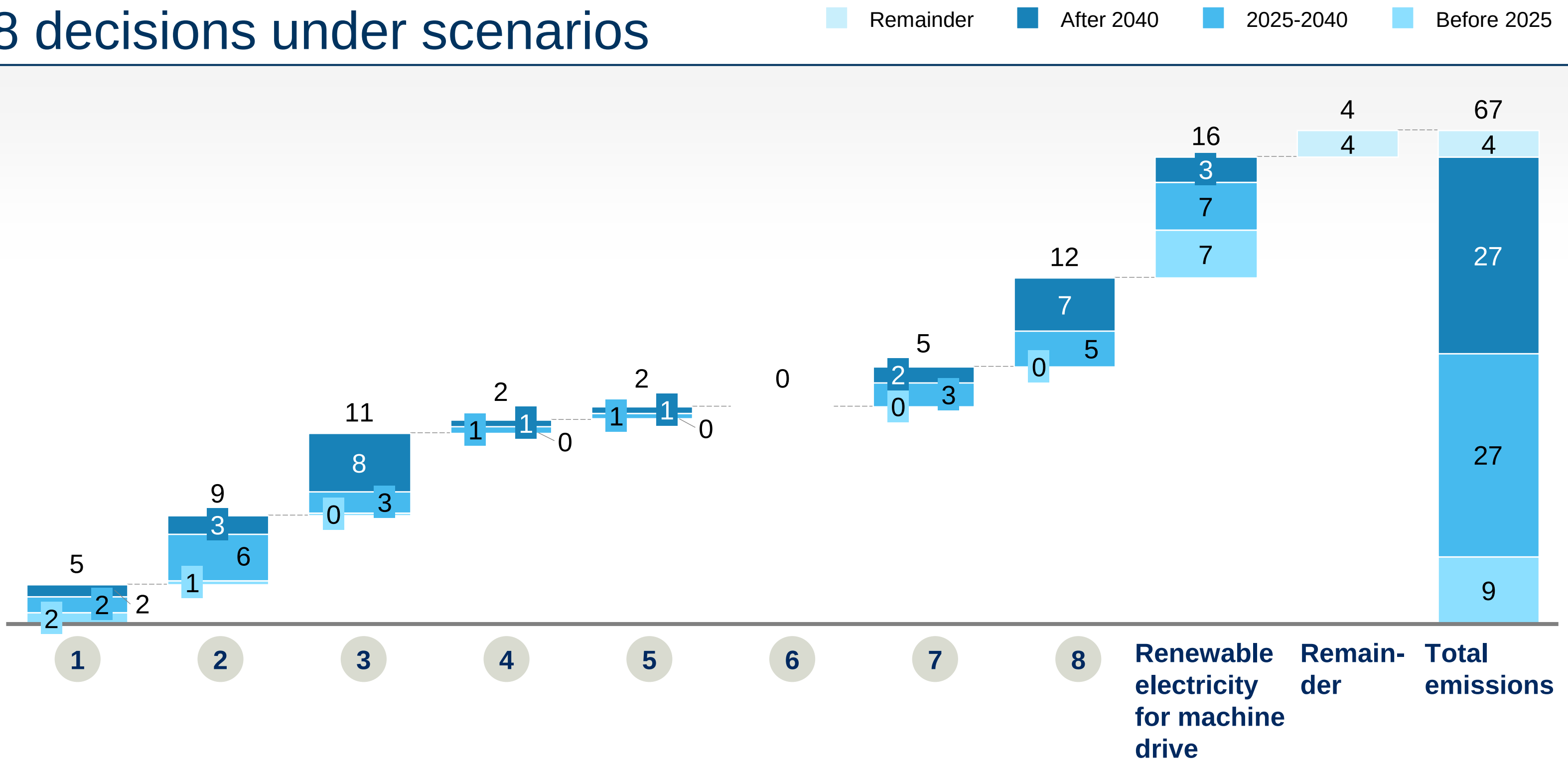
Note: Opex is yearly and additional, Capex is a total

NOTE Assumed 50 EUR/MWh electricity, 24.4 EUR/MWh gas, 100 EUR/MWh hydrogen. Difference in totals due to rounding

1 Only Capex for auto thermal reforming of Ammonia, otherwise no capex for CCS

SOURCE: Team analysis

Impact of 8 decisions under scenarios

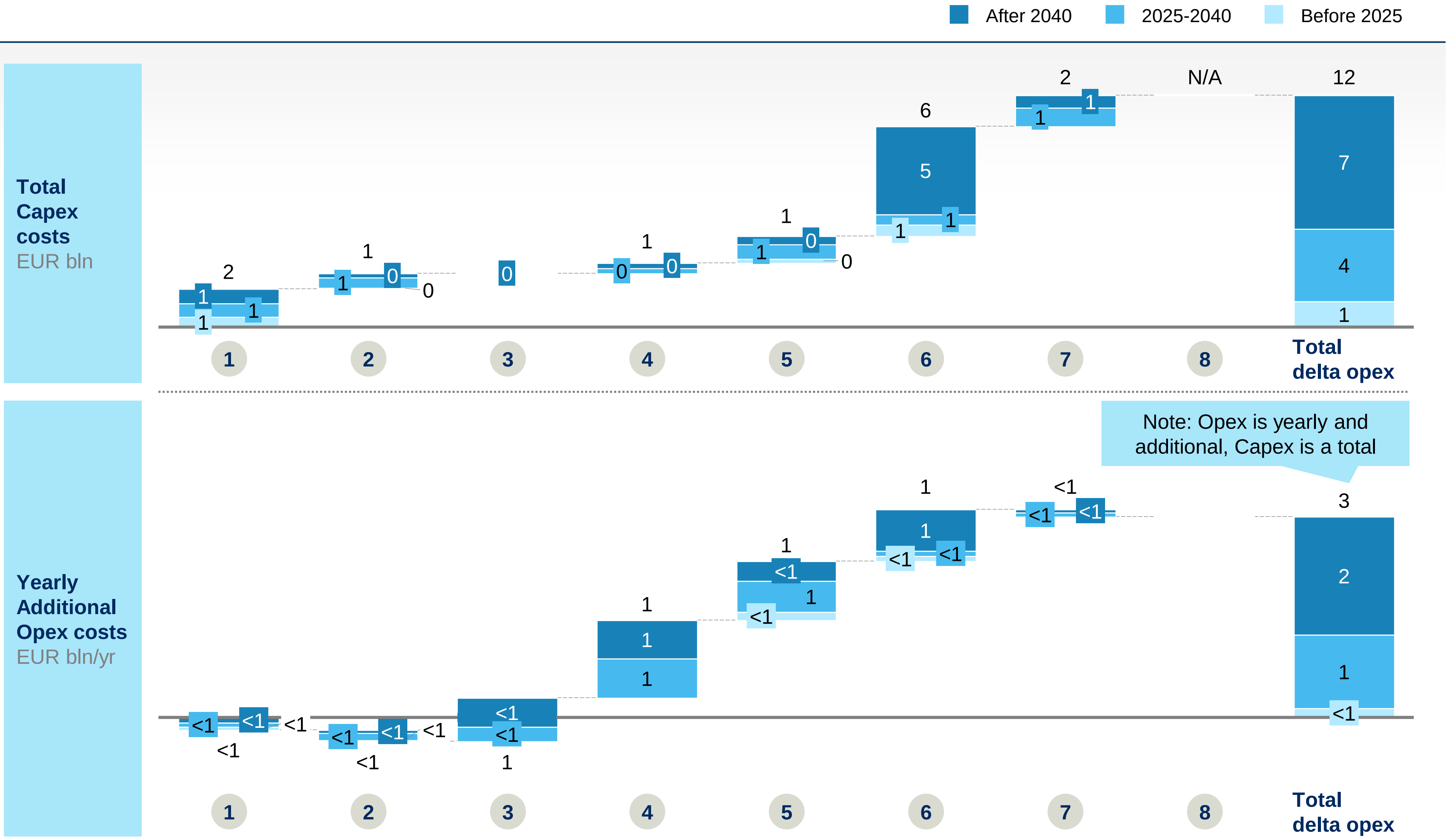


	1	2	3	4	5	6	7	8	Renewable electricity for machine drive	Remainder	Total emissions
Scenario 1: 50 EUR/MWh electricity, 24.4 EUR/MWh gas, 100 EUR/MWh hydrogen	Includes annual 0.5% energy efficiency improvement	Includes cascaded decarbonization impact on low temperature heat	CCS on ammonia, 55% of ethylene and 25% of refining	30% reduction in ethylene production	15% ethylene and 50% specialty chem production biobased		Excluding ammonia, ethylene, iron and steel			0.7 MtCO2 Chemicals, 3 MtCO2 Other industries incl. cement production and off road transport	
Deltas under scenario 2/3: 20 EUR/MWh electricity, and 73 EUR/MWh hydrogen			-4.5		Renewable H2 based ammonia instead of CCS		+4.5				

NOTE: Assumed 50 EUR/MWh electricity, 24.4 EUR/MWh gas, 100 EUR/MWh hydrogen. Differences in totals due to rounding

SOURCE:Centraal Bureau voor de Statistiek (2014), “Energiebalans” and “Energieverbruik” databases, National Inventory Report (1990-2014), team analysis

Scenario 2/3: Adding up the cost of the 8 options



Note: Opex is yearly and additional, Capex is a total

	1	2	3	4	5	6	7	8	Total delta opex
EUR/tCO$_2$	-30	-20	110	650	550	160	-10	N/A	~95

NOTE Assumed 20 EUR/MWh electricity, 24.4 EUR/MWh gas, 73 EUR/MWh hydrogen. Difference in totals due to rounding

SOURCE: Team analysis

Total cost of reaching 95% CO_2 emission reduction

	Scenario 1: 50 EUR/MWh electricity, 24.4 EUR/MWh gas, 100 EUR/MWh hydrogen	**Scenario 2/3: 20 EUR/MWh electricity, and 73 EUR/MWh hydrogen**
Total Capex costs EUR bln	12	12
Additional Opex costs EUR bln/yr	5	3
Implied CO_2 price[1] EUR/tCO_2	~140	~95

[1] Additional Capex per year + Additional Opex per year divided by CO2 reduced

Source: Team analysis

Scenario 1 Current prices: Costs of reducing CO_2 emissions

CO_2 abated % of 1990	**Total capex** EUR bln	**Additional Opex** EUR bln/yr	**Implied CO_2 price** EUR/tCO_2	**Example options**
32%	*Achieved reduction*			
40%	~2	0	**~0**	▪ Heat pumps ▪ Mechanical vapor recompression
60%	8.8	~1	**~45**	▪ Ammonia CCS + Auto thermal ▪ Electric furnaces
80%	9.3	4	**~100**	▪ Hybrid boilers ▪ Ethylene CCS ▪ Steel CCS
95%	12	7	**~140**	▪ Ethylene bio-fuel ▪ Plastic recycling

Note: for illustration, assumed 100 EUR/MtCO2 for 12 $MtCO_2$ in Steel

Source: Team analysis

ILLUSTRATIVE

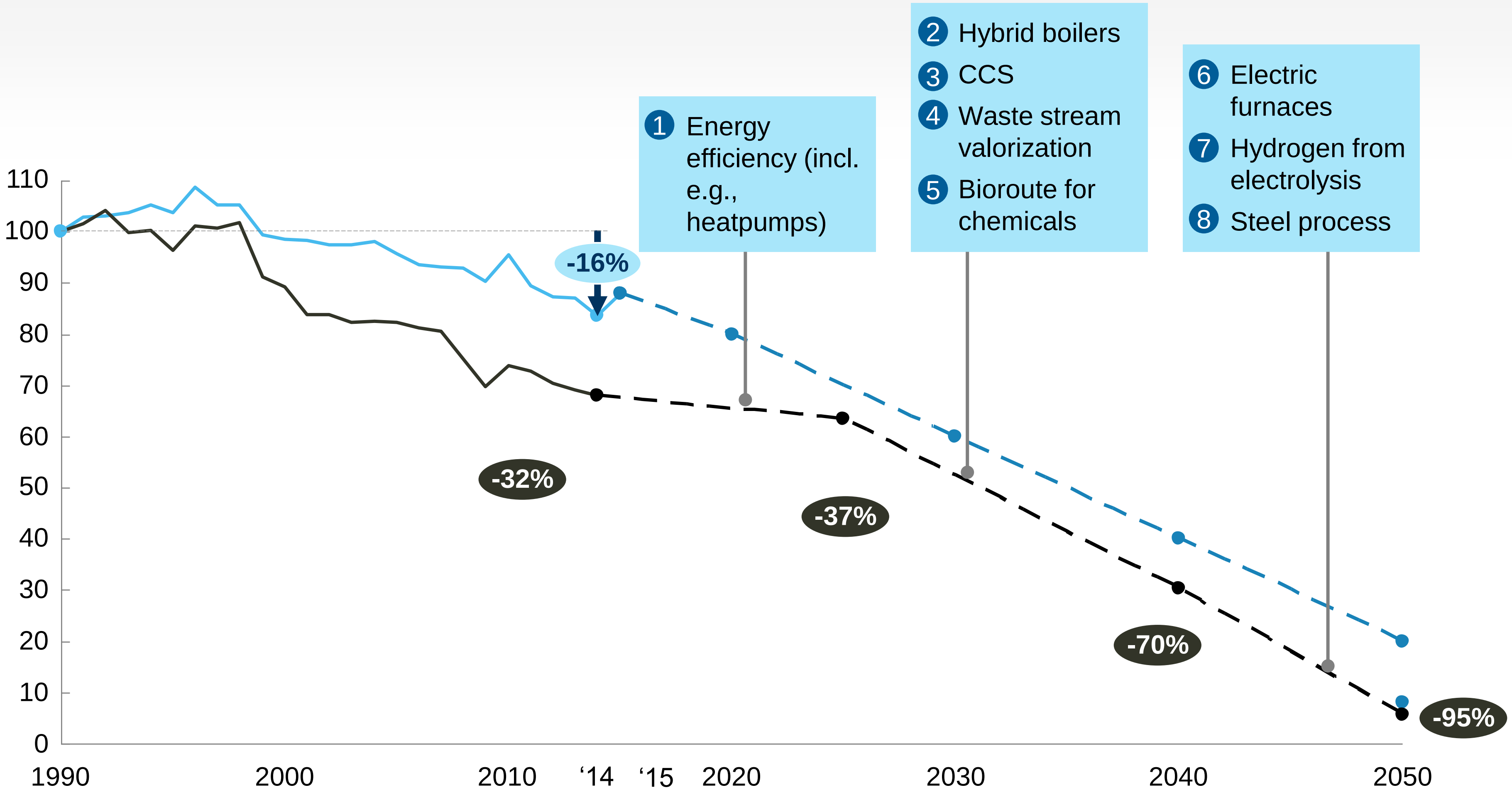
Projection of CO_2e emissions of industry with the 8 options

CO_2 equivalent emission, % change as of 1990

🟦 Option at scale (>50% of maximum impact)

Total emissions

Industry emissions



① Energy efficiency (incl. e.g., heatpumps)

② Hybrid boilers

③ CCS

④ Waste stream valorization

⑤ Bioroute for chemicals

⑥ Electric furnaces

⑦ Hydrogen from electrolysis

⑧ Steel process

CO_2e emission reduction targets

2020	2030	2040	2050
-20%	-40%	-60%	-80% -95%

NOTE: For industry projection only direct emissions included. Assumed that non-CO2 emissions are reduced at the same speed as CO2 emissions. Maximum impact of 8 options assumed

SOURCE: CBS, National Inventory Report (1990-2014), team analysis

Contents

- Pages in narrative
- **Baseline**
- Aspiration
- Business case comparison
- Output workshop I
- Other presented pages

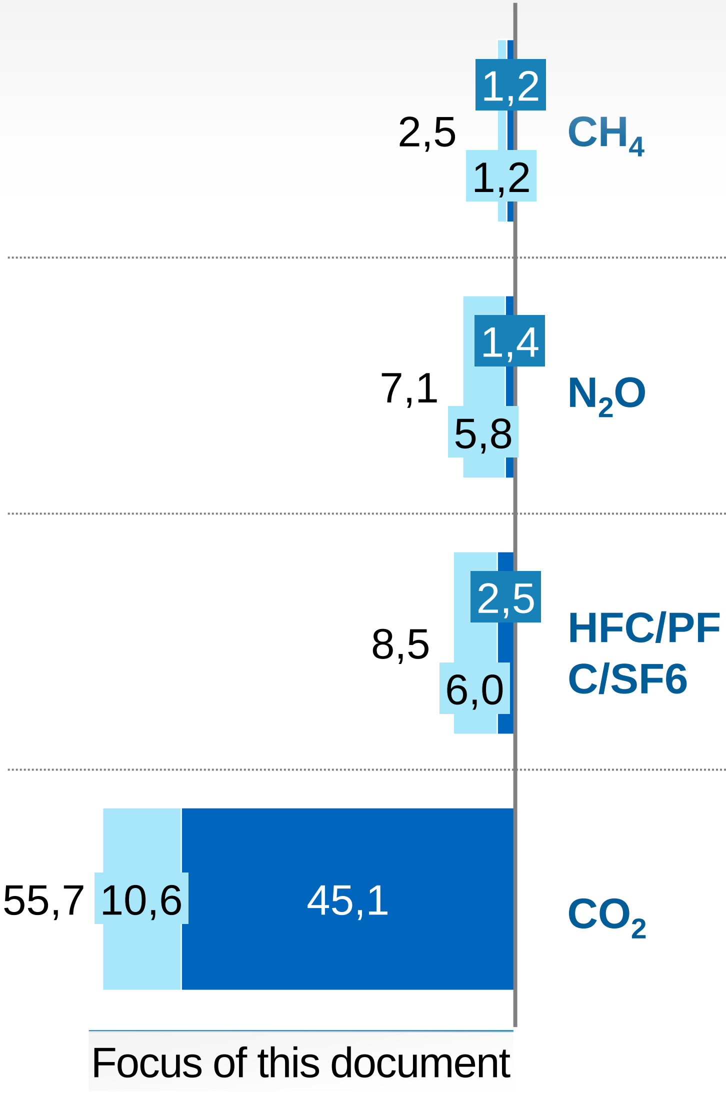
Most GHG emissions from industry are CO_2

Mt CO_2e emissions from Dutch industrial sector, 1990 to 2014

🟦 Reduction 1990 to 2014

🟦 2014

Sources of non-CO2 emissions in 2014



55%	Fugitive emissions from Natural gas, Venting and flaring
34%	Petrochemical and carbon black production

26%	Nitric acid production
74%	Caprolactam, glyoxal and glyoxylic acid production

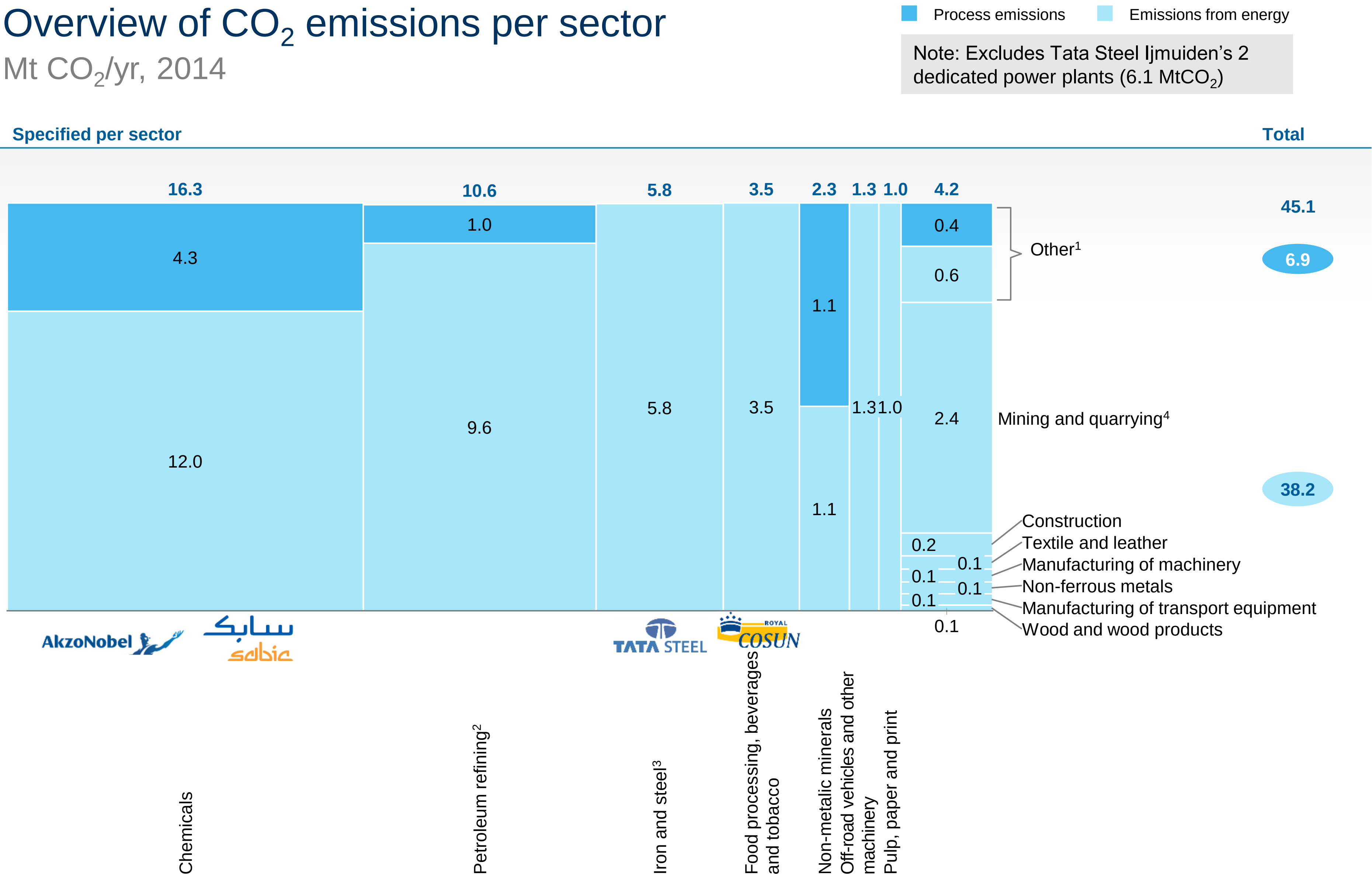
88%	Refrigeration and air conditioning

SOURCE: National Inventory Report (1990 - 2016)

Overview of CO_2 emissions per sector

Mt CO_2/yr, 2014

Note: Excludes Tata Steel Ijmuiden's 2 dedicated power plants (6.1 MtCO_2)



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[1] Other category includes: Non-energy products from fuels and solvent use, other industrial energy consumption, other industrial process emissions

[2] Petroleum refining includes 0.95 Mt CO2 from on-site hydrogen production

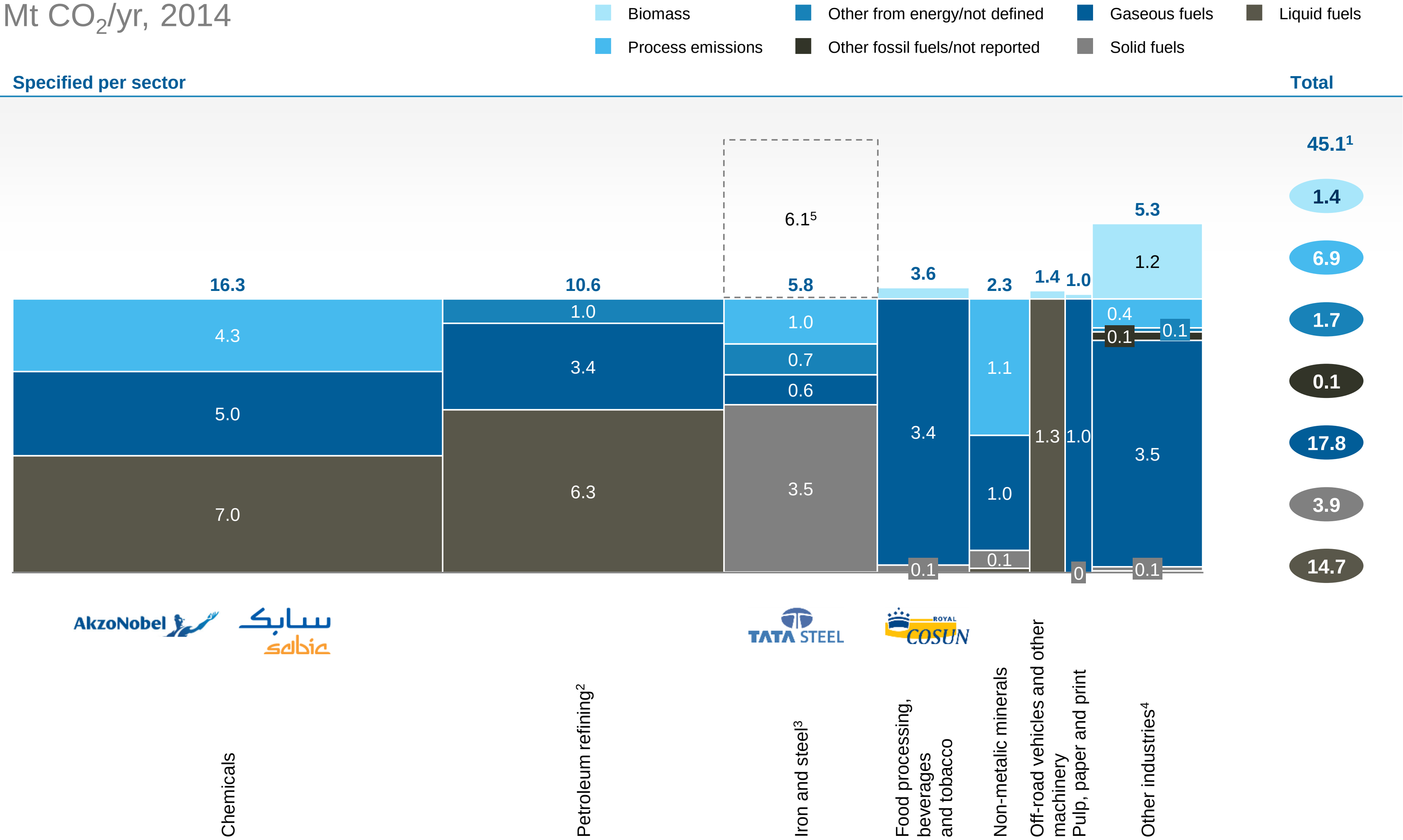
[3] Iron and steel includes emissions from manufacturing of solid fuels and solid fuel transformation

[4] Mining and quarrying includes 2.1 Mt CO2 from oil and gas extraction and 0.06 Mt CO2 from venting and flaring

SOURCE: National Inventory Report 2016, team analysis

Overview of CO_2 emissions per sector per energy source

Mt CO_2/yr, 2014



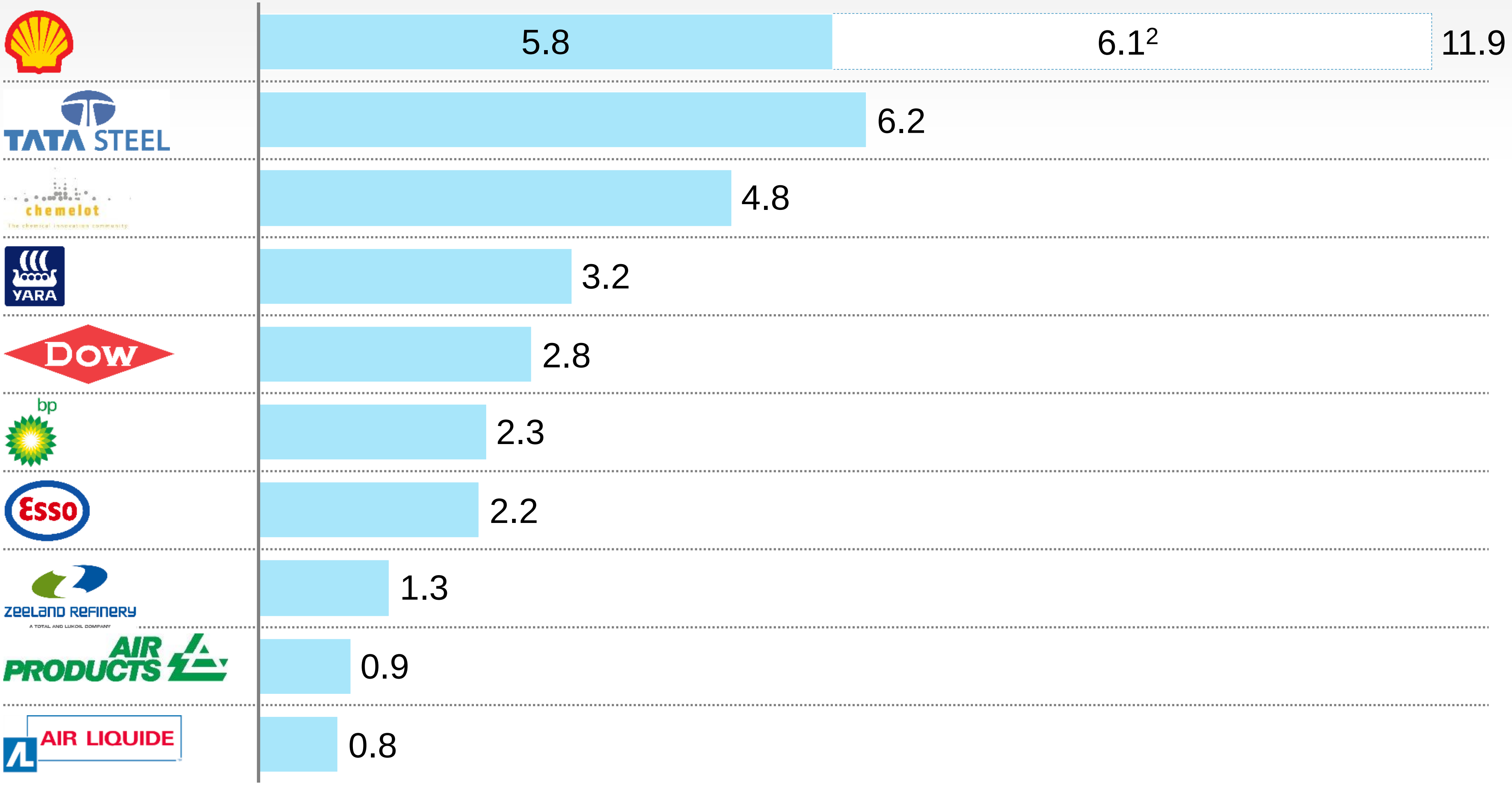
[1] Total excludes CO2 emissions from biomass and dedicated power facilities [2] Petroleum refining includes fuel consumption from 0.95 Mt CO2 from on-site hydrogen production as other from energy/not defined [3] Iron and steel includes emissions from manufacturing of solid fuels and includes solid fuel transformation as other from energy/not defined

[4] Other category includes: Non-energy products from fuels and solvent use, other industrial energy consumption, other industrial process emissions, Mining and quarrying, Construction, Textile and leather, Manufacturing of machinery, Non-ferrous metals, Manufacturing of transport equipment, Wood and wood products [5] Power not included, but emissions from Tata's dedicated power plant shown in dotted line (not to scale)

SOURCE: National Inventory Report 2016

Top 10 industrial players together emit 30 Mton CO_2, 67% of total industry emissions

Companies **CO_2 emission,** Mton in 2014



Total **30.4** **67%[1]**

NOTE Numbers based on PRTR database. Dow and Tata steel numbers same as in company reporting. Yara emissions reported in PRTR Netherlands are higher than emissions reported in Yara's sustainability report (~2 Mt CO2). Others do not report emissions on this level of specificity

1 Percentage of total industry emissions (45.1 MtCO2) according to National Inventory Report 2016

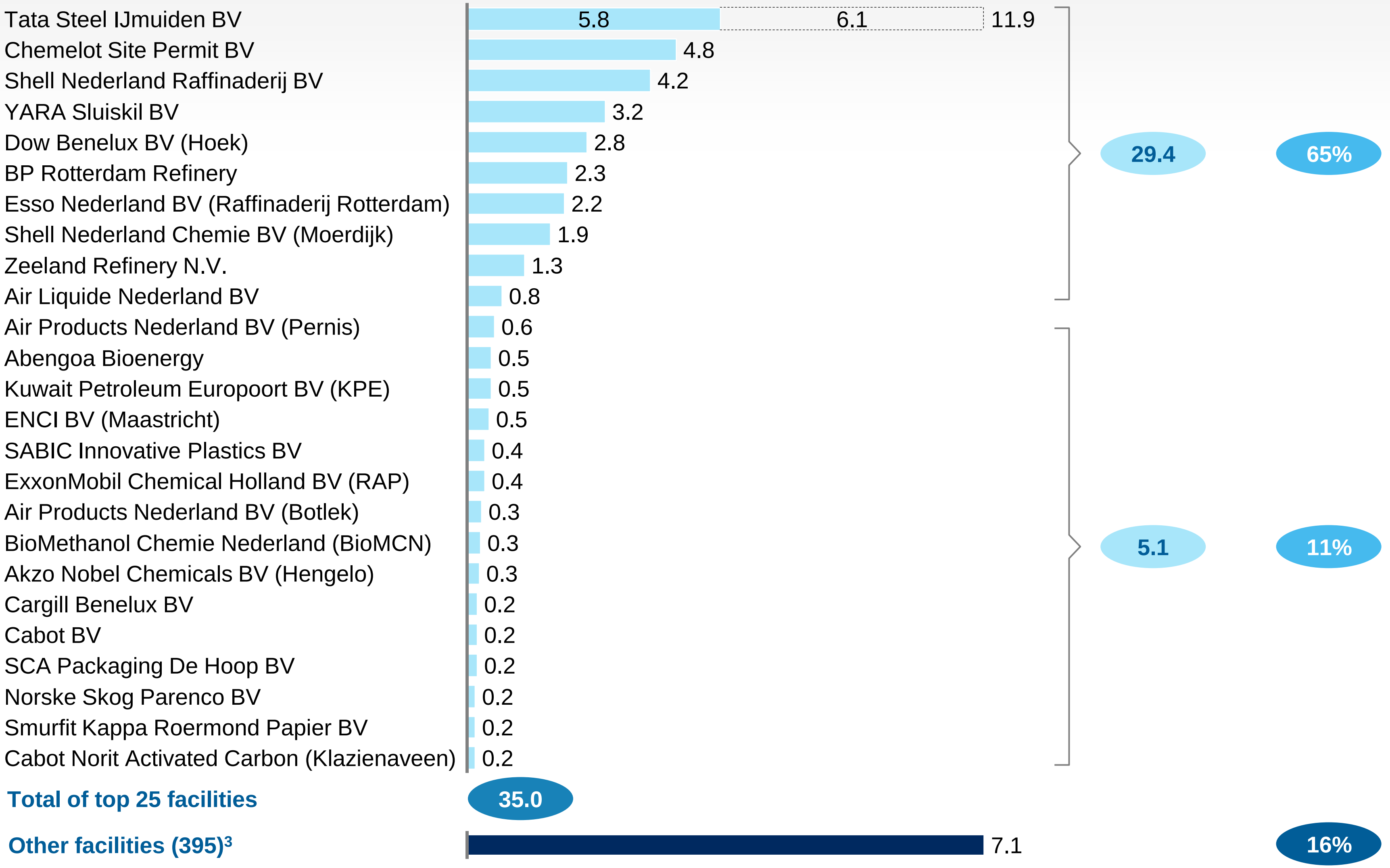
2 Tata Steel Ijmuiden's 2 dedicated power plants of 6.1 MtCO2, other emissions from power not included

SOURCE: PRTR Netherlands, National Inventory Report 2016

Top 25 largest emitting facilities in The Netherlands

Top 25 point emitters[1]
Mt CO_2/yr, 2014

Percentage of total CO_2 from industry[2]

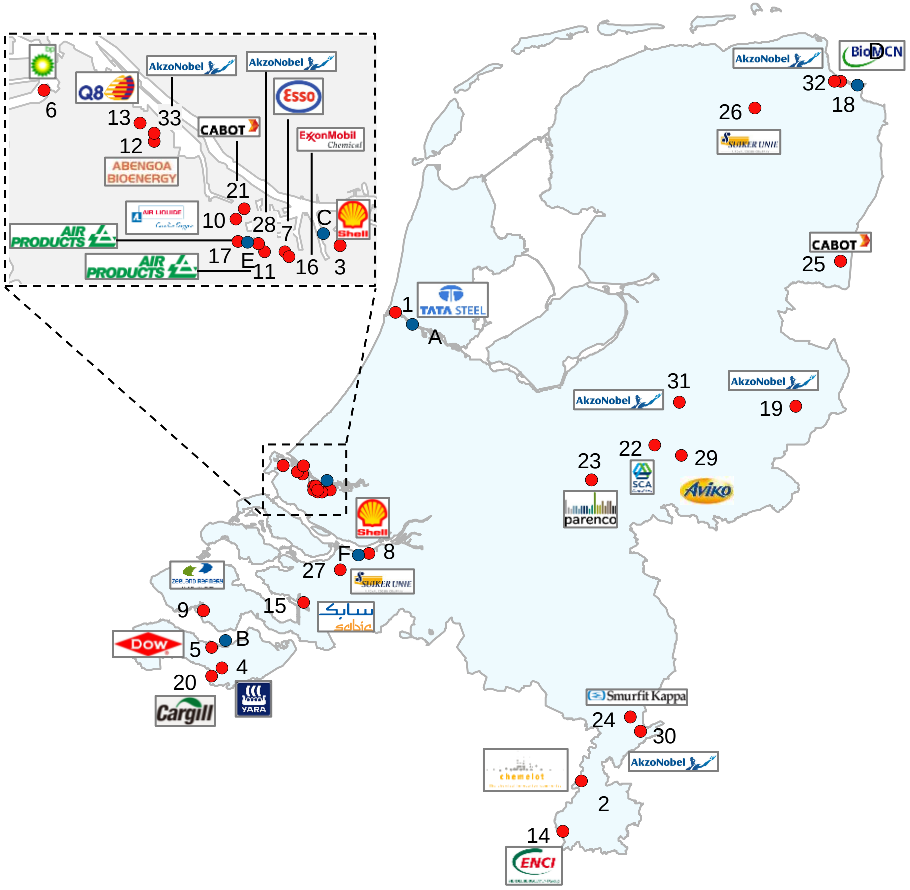


[1] Emissions from power not included, but size of Tata Steel Ijmuiden's dedicated power plant indicated with a dotted line
[2] Total CO2 emissions from industry are 45.1 Mt CO2/yr 2014,
from NIR dataset. Not all facilities in the PRTR dataset. In totals, emissions from dedicated power plant of Iron and steel are not included
[3] Other facilities included in the
PRTR dataset. 8% of the CO2 emissions in the NIR is not accounted for in the PRTR dataset

SOURCE: PRTR Netherlands, National Inventory Report 2016

Footprints of locations

● Industrial facility ● Dedicated electricity facility



No	Rank	Facility	Mt CO_2
1	1	Tata Steel IJmuiden BV	5.8
2	2	Chemelot Site Permit BV	4.8
3	3	Shell Nederland Raffinaderij BV	4.2
4	4	YARA Sluiskil BV	3.2
5	5	Dow Benelux BV (Hoek)	2.8
6	6	BP Rotterdam Refinery	2.3
7	7	Esso Nederland BV (Raffinaderij Rotterdam)	2.2
8	8	Shell Nederland Chemie BV (Moerdijk)	1.9
9	9	Zeeland Refinery N.V.	1.3
10	10	Air Liquide Nederland BV	0.8
11	11	Air Products Nederland BV (Pernis)	0.6
12	12	Abengoa Bioenergy	0.5
13	13	Kuwait Petroleum Europoort BV (KPE)	0.5
14	14	ENCI BV (Maastricht)	0.5
15	15	SABIC Innovative Plastics BV	0.4
16	16	ExxonMobil Chemical Holland BV (RAP)	0.4
17	17	Air Products Nederland BV (Botlek)	0.3
18	18	BioMethanol Chemie Nederland (BioMCN)	0.3
19	19	Akzo Nobel Chemicals BV (Hengelo)	0.3
20	20	Cargill Benelux BV	0.2
21	21	Cabot BV	0.2
22	22	SCA Packaging De Hoop BV	0.2
23	23	Norske Skog Parenco BV	0.17
24	24	Smurfit Kappa Roermond Papier BV	0.17
25	25	Cabot Norit Activated Carbon (Klazienaveen)	0.17
26	30	Suiker Unie Vierverlaten	0.14
27	31	Suiker Unie (Dinteloord)	0.14
28	32	Akzo Nobel Chemicals BV (Botlek)	0.13
29	57	Aviko BV	0.06
30	164	Akzo Nobel Functional Chemicals BV	0.01
31	194	Akzo Nobel Functional Chemicals	0.008
32	275	Akzo Nobel Chemicals BV (Chemie Park Delfzijl)	0.0036
33	418	Akzo Nobel Base Chemicals	0.00002
A	-	Tata Steel IJmuiden BV	6.1
B	-	Dow Benelux BV	1.3
C	-	Shell Nederland Raffinaderij BV	1.2
D	-	Delfzijl Chemie park (incl Akzo Nobel)	0.5
E	-	AirLiquide Nederland BV	0.5
F	-	Shell Nederland Chemie BV (Moerdijk)	0.4

SOURCE: PRTR Netherlands, National Inventory Report 2016

Emissions and energy consumption per sector

Estimates, 2014

● … Mt CO_2/year ● … # Units

	Chemicals	Petroleum refining	Iron and steel	Food processing, beverages and tobacco	Other industries	Total		
Low temperature heat	0.6	0.0	0.0	1.6	1.8	4.0	Gas boiler	*TBD*
Mid temperature heat	4.3	4.4	0.6	1.7	2.6	14	Gas boiler Cogen Gas Furnace	>200 >10
High temperature heat	6.5	4.5	10.2	0.0	1.4	22.0	Gas Furnace BOF/BF	>80 2
Machine drive & cooling refrigeration	6.0	1.2	1.1	3.0	7.4	19.0		
Process emissions	4.3	1.0	0.0	0.0	1.6	7.0		
On site transport					1.3	1.3		
Total	21.7	11.0	11.9	6.2	16.1	67.0		

NOTE Emissions from biomass are excluded. Total emissions include 19.1 MtCO2 emissions from the power sector, based on 99J/yr (TBC). High temperature heat in Iron & Steel includes all emissions from coal, except manufacturing of solid fuels and solid fuel transformation

SOURCE : CBS energieverbruik, CBS energie balans, National Inventory Report 2016, expert interviews, team analysis

Emissions and energy consumption per sector

Estimates, 2014

… Mt CO_2/year … # Units

	Chemicals[1]	Petroleum refining[2]	Iron and steel[3]	Food processing, beverages and tobacco[4]	Other industries	Total[5]
Low temperature heat	0.6 Gas boiler TBD	0.0	0.0	1.6 Gas boiler TBD	1.8	4.0 Gas boiler TBD
Mid temperature heat	4.3 Gas boiler, Cogen 60 Gas Furnace TBD	4.4 Gas boiler 5 Cogen 11 Gas Furnace 100	0.6 Gas boiler 5 Cogen 2 Gas Furnace 3	1.7 Gas boiler, Cogen >100 Gas Furnace TBD	2.6	14.0 Gas boiler, Cogen >200 Gas Furnace >103
High temperature heat	6.5 Gas furnace 54	4.5 Gas Furnace 25	10.2 Furnaces 15 BOF/BF 2	0.0	1.4	22.0 Gas Furnace ~80 BOF/BF 2
Machine drive & cooling refrigeration	6.0	1.2	1.1	3.0	7.4	19.0
Process emissions	4.3	1.0	0.0	0.0	1.6	7.0
On site transport					1.3	1.3
Total	21.7	11.0	11.9	6.2	16.1	67.0

NOTE Emissions from biomass are excluded. Total emissions include 19.1 MtCO2 emissions from the power sector, based on 99 PJ/yr (TBC)

1 Assumptions: 30 checmical site with two mid temperature gas boilers/gogen each. 4 ammonia, 4 ethylene and 10 hydrogen plants with respectively 1, 10 and 1 high temperature gas furnaces

2 Assumptions: 5 refineries in the Netherlands, standard refinery composed of 1 gas boiler, 20 gas furnace medium temperature and 5 gas furnace high temperature

3 Exclude ~120 coke furnaces, 60-80 batch annealing furnaces

4 Assumptions: 50 plants with 2 boilers/cogen per plants

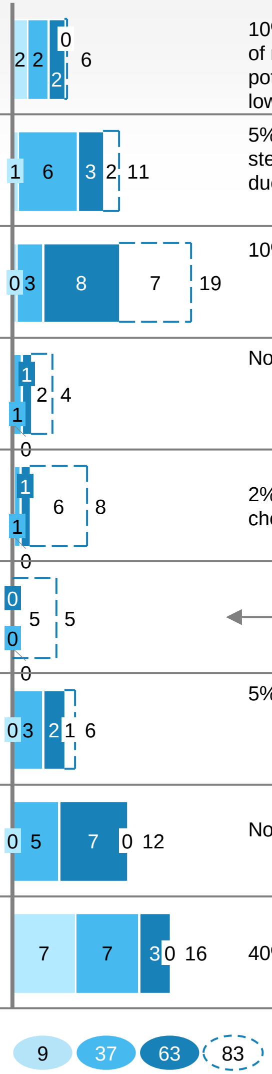
5 total equipment numbers exclude other industries

6 High temperature heat includes all emissions from coal, except manufacturing of solid fuels and solid fuel transformation

SOURCE : CBS energieverbruik, CBS energie balans, National Inventory Report 2016, expert interviews, team analysis

Impact of decisions – All assumptions

🟦 Potential until 2025	🟦 Potential after 2040
🟦 Potential 2025-2040	⬚ Technical potential



Options	Carbon reduction MtCO$_2$	Assumptions: Potential until 2025	Potential 2025 - 2040	Potential after 2040	Technical potential
1 Implement efficiency measures and options with business cases	2 2 2 0 6	10% of low temperature heat. 50% of mechanical vapor recompression potential. Energy efficiency 5% of low and mid temperature	25% of low temperature heat. 100% of mechanical vapor recompression potential. Energy efficiency 10% of low and mid temperature	50% of low temperature heat. 100% of mechanical vapor recompression potential. Energy efficiency 15% of low and mid temperature	Same as potential after 2040
2 Create optionality in Mid T heat by replacing gas boilers with hybrids	1 6 3 2 11	5% of mid temperature heat excl. steel. 2.5% of low temperature heat due to heat cascading	75% mid temperature heat excl. steel, refining (+38% low temp.) 50% mid temperature heat refining (+25% low temp.)	100% mid temperature heat excl. steel refining (+50% low temp) 75% mid temperature heat refining (+38% low temp)	100% of mid temperature heat incl. steel, refining
3 Develop CCS/U capabilities	0 3 8 7 19	10% ammonia	10% of refining + 50% refining process emissions 15% ethylene 20% ammonia	25% of refining + 100% refining process emissions 55% ethylene 100% ammonia	100% of ammonia, 90% of ethylene, 80% of refining
4 Develop routes to valorize residual streams	1 2 4 1 0	No reduction	15% of ethylene production (25% of 60% ethylene that is used for in plastics)	30% of ethylene production (50% of 60% ethylene that is used for in plastics)	60% of ethylene production (100% of 60% ethylene that is used for in plastics).
5 Start Bio-to-Chem on selective processes	1 6 8 1 0	2% of ethylene and specialty chemicals	10% of ethylene 25% of specialty chemicals	15% of ethylene 100% of specialty chemicals	100% of ethylene and specialty chemicals
6 Invest in R&D on decreasing hydrogen production costs via electrolysis at scale	0 5 5 0 0	← 0% under current electricity / hydrogen prices →			100% under low electricity / hydrogen price (scenario 2/3)
7 Invest in R&D on mid and high temperature	0 3 2 1 6	5% refining	50% of refining, other industries and chemicals excluding ammonia and ethylene	75% of refining 100% of other industries and chemicals excluding ammonia and ethylene	100%
8 Decide on steel route	0 5 7 0 12	No reduction	40% of production 50% of downstream processing	100%	100%
Renewable electricity for machine drive	7 7 3 0 16	40% in line with NL targets	80%	100%	100%
Total (cumulative for carbon reduction)[1]	9 37 63 83				

NOTE: Assumed 50 EUR/MWh electricity, 24.4 EUR/MWh gas, 100 EUR/MWh hydrogen

[1] Some parts of the industrial emissions are impacted by more than one decision, so sum is more than 100% of emissions

Impact of options – Assumptions

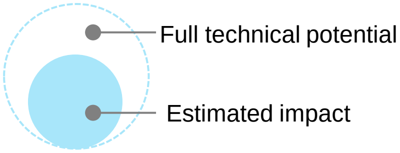
○ Full technical potential
● Estimated impact

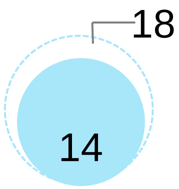
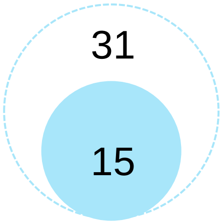
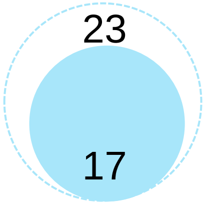
	Options	Carbon reduction $MtCO_2$
1	Implement efficiency measures and options close to a positive business case in low-temperature heat and machine drive, such as magnetic coupling, heat pumps, heat networks, and mechanical vapor recompression.	6 5
2	Create optionality in medium-temperature heat processes by starting now to replace boilers at the end of their lifetime or at large maintenance with hybrid or dual electricity/gas systems.	11 9
3	Develop and scale carbon capture capabilities to potentially use for part of the ethylene production, steel production, and petroleum refining emissions. The captured carbon can be either reused (CCU) or stored (CCS).	19 11
4	Develop routes to valorize residual streams and create circularity in our industrial processes. Examples are development of a hub in Rotterdam around plastic recycling, the use of steel scrap for steel production, and the cascaded use of biomass waste for minerals and biogas. A syngas platform can also be considered to valorize waste.	4 2
5	Start bio-to-chemicals for specific high-end processes such acetic acids from beet waste or wood, or parts of ethylene production with biofuel as a feedstock.	8 2
6	Invest in R&D on decreasing hydrogen production costs via electrolysis at scale, focused on capex reduction and efficiency improvement. Business cases can be derisked through integration with initiatives such as mobility	5 0
7	Invest in R&D pilots to develop medium-temperature heat pumps, high-temperature electric furnaces and new processes with lower heat demand. The latter two can potentially be used in refining and other high-temperature heat processes.	6 5
8	Prepare to decide on the steel route in the coming years. EAF has large decarbonization potential, but availability of high-quality steel scrap is limited. Alternatively, emissions can be reduced with HIsarna and/or BF/BOF combined with CCS/CCU.	12
	Renewable electricity for machine drive	16

NOTE: Assumed 50 EUR/MWh electricity, 24.4 EUR/MWh gas, 100 EUR/MWh hydrogen 1 Some parts of the industrial emissions are impacted by more than one decision, so sum is more than 100% of emissions

SOURCE : Team analysis

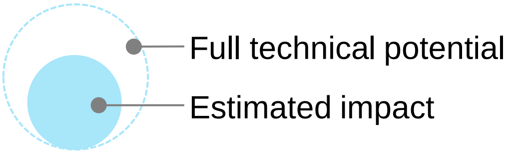
We see options for industry decarbonization along three categories

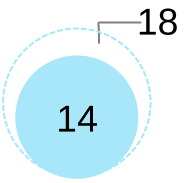
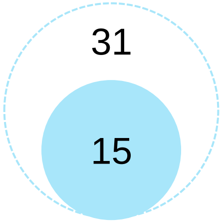
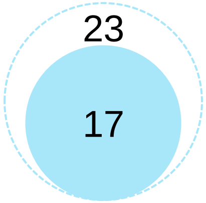


	Description	**Carbon reduction** MtCO$_2$ estimation
Options ready for rollout, given the right support mechanisms	▪ Energy efficiency improvement that has a close to positive business case, such as heat pumps ▪ Creating optionality in energy for medium-temperature heat by replacing gas boilers with hybrid boilers or a dual gas/electricity system	 18 14
Options that require scaling up in the next years	▪ CCS/CCU for industrial applications such as chemical processes and petroleum refining ▪ Valorization of waste streams (e.g., plastic recycling, biomass cascades) ▪ Biomass as a feedstock for chemical production	 31 15
Options that require innovation in the next years	▪ Lower cost electrolysis at scale for hydrogen production ▪ Innovations in medium and high heat, e.g., temperature electric furnaces, medium temperature heat pumps ▪ Decision on a low carbon steel making process	 23 17

These options can reduce industry CO$_2$ with 95%, if electricity use by industry can be 100% renewable in 2050

We see options for industry decarbonization along three categories



	Description	**Carbon reduction** MtCO$_2$
Options ready for rollout, given the right support mechanisms	▪ These options are **proven technologies** in the industry, and have close to positive business cases ▪ The focus is on capturing emissions from **low and medium temperature heat** processes ▪ Examples are installation of heat pumps, further energy efficiency measures and replacing gas with hybrid boilers	 18 14
Options that require scaling up in the next years	▪ These options are technologies that are in most cases known to the industry on a small scale, but need **further development and scale up** before a full roll out is possible ▪ The focus is on capturing emissions from **ethylene, ammonia and refining processes** ▪ Examples are CCS/CCU, plastic recycling and creating ethylene (plastic) from bio-fuel	 31 15
Options that need innovation	▪ These options need **significant innovation** before ready for further scale up, but are vital to increase optionality in decarbonization pathways in the medium to long term ▪ The focus is on capturing emissions from ammonia (and other hydrogen related processes) and **medium to high temperature heat** ▪ Examples are decreasing costs of electrolysis and developing heat pumps for medium temperature heat	 23 17

Contents

Building on intrinsic capabilities (1/2)

Diversified Industry

1. **Highly integrated clusters of industrial activity,** with various types of industry players located close to each other

2. **Diversified Industry: 1) sophisticated chemicals industry,** spanning the value chain from petroleum refining to specialty-chemical manufacturing **2) growing and innovative food and agrisector,** generating EUR 52,2 billion GDP, responsible for 20% of total Dutch export (2nd largest exporter of food and agri products in the world after the USA)

3. **A well-developed, diverse offshore (wind) industry,** with construction and maintenance companies such as Boskalis and Van Oord as well as data and analytics providers such as Fugro, and oil and gas producers like Shell

Connectivity

4. **High standard electricity and gas networks: 1) Extensive electricity connectivity with the rest of Europe,** visible in the Netherlands' standing as Europe's second-largest importer of energy and second-largest exporter **2) Dense and highly reliable gas network**

5. **A world-class transport and logistics sector** that includes the ports of Rotterdam and Amsterdam (the largest and fourth-largest in Europe) combined with the best navigable inland waters in the world, Schiphol airport (third largest in Europe by cargo volume), and storage facilities (Vopak, Oiltanking, WTI)

Innovation

6. **Research and development capacity** mainly in **1) Agrifood** in Wageningen University and Research Center (WUR) and **2) (Chemical) Engineering** in Technical University Delft

Building on intrinsic capabilities (2/2)

Diversified Industry	**1 Highly integrated clusters of industrial activity**	▪ One of the clusters in Europe with most cross-sectoral activity identified
	2 Diversified Industry **1. sophisticated chemicals industry** **2. growing and innovative food and agrisector**	▪ 2nd in EU Competitive Industrial Performance Index ▪ Home to 19 of the top 25 leading chemical companies ▪ 2nd largest exporter of food and agri products in the world after the USA
	3 A well-developed, diverse offshore (wind) industry	▪ Cluster with many Dutch (based) offshore companies active in the European (and global) offshore industry
Connectivity	**4 High standard electricity and gas networks**	▪ Electricity network: among top 10 most reliable and most connected networks globally ▪ Gas network most dense in Europe, with 99.995% reliability
	5 A world-class transport and logistics sector	▪ No 1 on DHL's Global Connectedness Index, measured by flows of goods, people, information ▪ No 2 overall in the world for overall logistics performance, based on seaports, airports, railways and highways, and digital infrastructure
Innovation	**6 Research and development capacity** **1. Agrifood** **2. (Chemical) Engineering** in Technical University Delft	▪ Ranked no4 on the Global Innovation Index ▪ Wageningen top 3 global Agrifood University ▪ Chemical Engineering in Delft top 10 global in QS Ranking

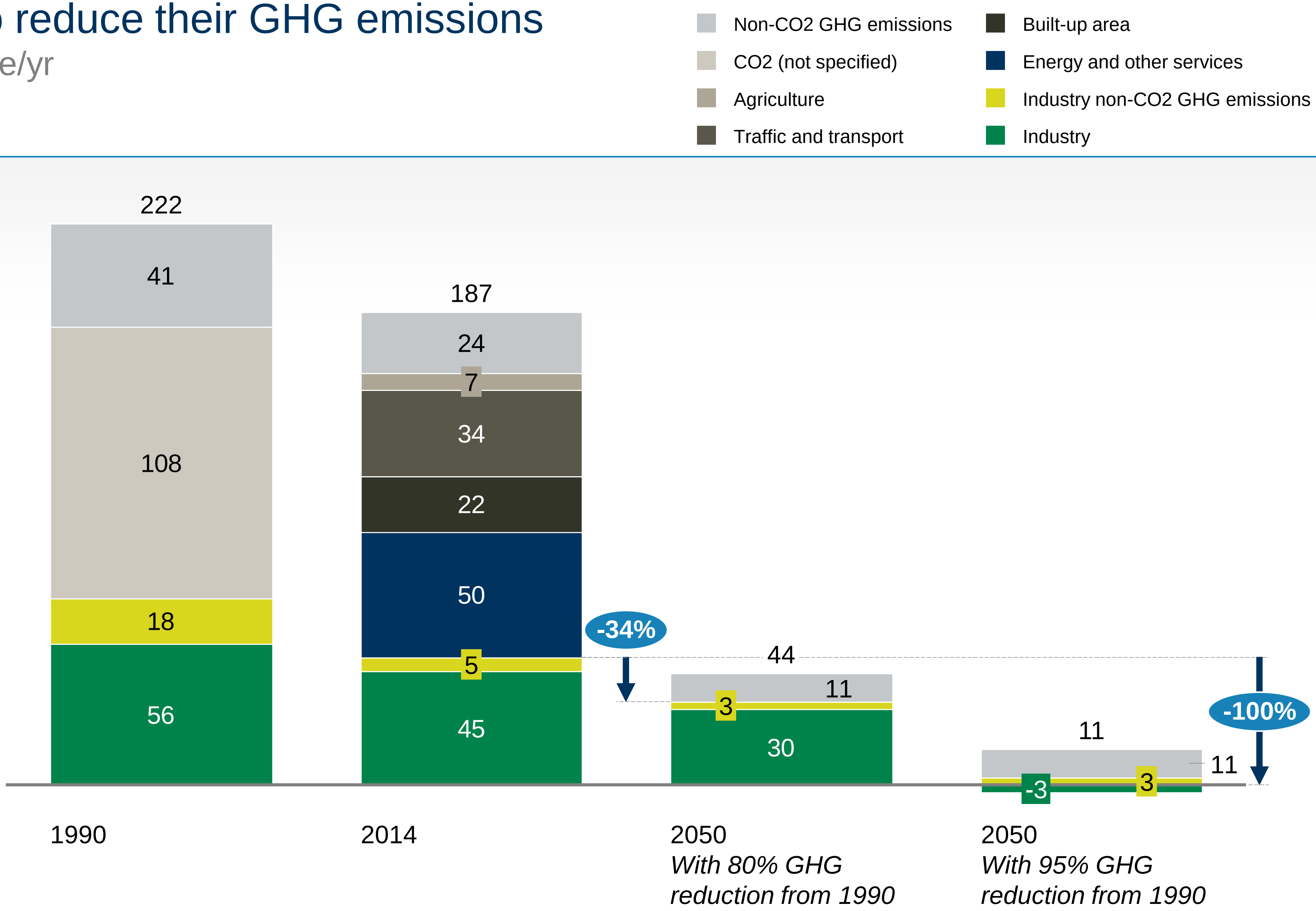
Intrinsic NL capabilities per solution type

🟩 Strong fit/large value 🟦 Clear fit/value ⬜ No clear connection

	Diversified industry			Connectivity		Innovation	
	1 **Highly integrated clusters**	2 **Diversified industry (chemicals, agri-food sector)**	3 **Well-developed, diverse off-shore industry**	4 **High standard electricity and gas networks**	5 **World-class transport & logistics sector**	6 **Agrifood (WUR)**	**(Chemical) Engineering (TUD, TUE)**
Electrification	⬜	⬜	🟦 Shallow sea that is ideal for offshore wind development	🟦 Opportunity for balancing electricity peaks	⬜	⬜	🟦 Engineering innovation needed for e.g. electric furnaces
Hydrogen	⬜	🟦 Salt caverns of chemical industry can be used for hydrogen storage	🟦 Intermittency of offshore wind could lead to low cost of electricity for hydrogen production	🟦 Existing network of natural gas pipelines can be extended to hydrogen use	⬜	⬜	⬜
Bio	⬜	🟦 Strong and diverse chemical and agricultural industries already in place	⬜	⬜	⬜	🟩 World class agricultural research institutes to develop bioroutes for chemical sector	🟦 Chemical engineering innovation needed for e.g. or electric ethylene cracking
CCS/U	🟩 Relatively easy to apply CCU across players close together with strong links	🟦 Large ammonia production, for which carbon is relatively easy to capture (already happens today)	🟩 ▪ Existing off shore network & structure, with depleted offshore O&G fields ▪ Know how	🟦 Existing network of natural gas pipelines can be retrofitted/ extended with CO2 network	⬜	⬜	🟦 Chemical engineering innovation needed for CCU (syngas, hydrogen)
Circular Economy	⬜	🟦 Many possibilities to match input and output streams	⬜	⬜	🟩 Hubs (e.g. Rotterdam) can be used for collection of recycled products (e.g. plastic)	⬜	🟦 Chemical engineering innovation needed to enable alternative product designs

If other sectors reduce their emissions from CO_2 to zero, industrial sector has to reduce their GHG emissions

Mt CO_2e/yr



NOTE: Non-CO2 GHG emission assumption in 2015 of 14 Mt CO2e taken from RLI report (2015). Assumed that share of industrial non-CO2 GHG emissions will reduce with 50%, in line with total non-CO2 GHG emissions, so from 5 Mt CO2 in 2014 to 3 Mt CO2 in 2050

SOURCE: CBS Statline, RLI Rijk zonder CO2 (2015), National Inventory Report (2009 & 2016)

Ambition level for industry

FOR DISCUSSION

Reduction in GHG emissions to reach national targets

% reduction in industry emissions from 2014

	Narrative	2020 20% reduction	2030 40% reduction	2040[2] 60% reduction	2050 80-95% reduction
Fair share	The industrial sector will reduce their GHG emissions in line with the targets set by the Dutch government	0%[1]	12% reduction	41% reduction	71%-93% reduction
Minimum effort 80%	Other sectors reduce their GHG emissions to zero in 2050, the remaining budget will be for the industrial sector	*Depends on the trajectory*			34% reduction
Minimum effort 95%	Other sectors reduce their GHG emissions to zero in 2050, the remaining budget will be for the industrial sector				100% reduction

Depending on decarbonization options chosen, targets between now and 2050 can be developed

[1] 20% reduction of GHG emissions from 1990 already achieved

[2] No official statement for 2040 target, linear interpolation assumed

SOURCE: RLI Rijk zonder CO2 (2015), National Inventory Report (2016)

8 options contribute to strengthening current and attracting new economic activity

NOT EXHAUSTIVE

Strengthen current intrinsic capabilities	Attract new companies and investments
Use and reinforce the densely **integrated industrial clusters** as a unique starting point for **CCU** deployment	Advanced development of CCU application attracts companies looking to tap into alternative feedstock options
Apply world class **knowledge in agrifood and chemicals** to develop **hydrogen** capabilities and **bio-to-chem** routes on selective processes	Best know-how and examples of hydrogen and bio-to-chem attracts investment of companies e.g. on specialty chemicals
Build on excellent **logistics sector** (including port of Rotterdam) to create a **recycling hub** in The Netherlands	Most efficient and easy to reach recycling hub attracts large amounts of waste and new recycling companies

Long term and stable outlook on the Dutch energy market and its regulation to support healthy and reliable environment for new investments

Contents

- Pages in narrative
- Baseline
- Aspiration
- **Business case comparison**
- Output workshop I
- Other presented pages

NOT EXHAUSTIVE

Options to reduce GHG emissions from industry

Grey text = Deprioritized/out of scope

	Category	Options	Case study[1]
Degree of change	By making existing processes more efficient	More efficient equipment	
		Contactless magnetic coupling for rotating equipment	
		Use of waste heat for pre-heating of feedstock	bp
		Smart technology for process optimization	
	By changing the energy source used in existing processes	Electrification of equipment/heat (heat pump or boiler)	
		Renewable hydrogen for heat (fuel cell or boiler)	
		Use of (waste) heat from own/other industrial processes	kpn
		Use of (waste) biomass for own/other industrial processes	ROYAL COSUN HEINEKEN
		Use of syngas/biofuel/biogas	Smurfit Kappa
		Add biomass as feedstock	
		Use of renewable electricity instead of 'grey' electricity	AkzoNobel
	By changing the process	Bio-based chemicals	
		Renewable hydrogen as feedstock for chemicals	
		HIsarna process for steel making	TATA STEEL
		Electrification of ammonia production	
		DRI-EAF with biogas and/or hydrogen for steel making	
		Adsorption drying for food processing	
	Changing the output	EAF instead of BOF for steel making	
		Hydrocracker instead of FCC for petroleum refining	
Other	By using/ storing GHG emissions	CSU (E.g., CO_2 for greenhouses, CO_2 as feedstock, CO_2 to methanol	AIR LIQUIDE DOW
		CCS	
	Cross-sectoral optimization	Syngas platform	
		Hydrogen platform	
		Circular economy	

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1 Company case studies taken from the VEMW report. Excluded: Power sector (incl. WKK), hydrogen waste stream as a feedstock by Yara,

SOURCE: VEMW Samen op weg naar minder (2016)

List of assessed options (1/2)

Emissions per type of energy use

	Electricity consumption	Low temperature heat (<100ºC)	Medium temperature heat (100-500ºC)	High temperature heat (>500ºC)
Con-ventional option	Grey electricity	Gas boiler	Gas boiler Cogeneration	Gas furnace
Alternative options assessed	Renewable electricity Energy efficiency measures (including magnetic coupling)	Heat pump Biogas boiler Hydrogen fuel cell (Waste heat)	Electric boiler Biogas boiler Hydrogen fuel cell Dual / hybrid boiler Mechanical vapor recompression (Waste heat)	Electric furnace Biogas furnace Hydrogen furnace

List of assessed options (2/2)

Emissions from specific processes

	Steel production	Ammonia production	Ethylene production	Petroleum refining
Con-ventional option	▪ BF/BOF ▪ Conventional steel rolling and coating	▪ Natural gas and SMR	▪ Naphtha feedstock	▪ Conventional
Alternative options assessed	▪ Hisarna ▪ DRI-EAF Gas, Bio or H2 ▪ EAF ▪ Electrification of steel rolling and coating	▪ Natural gas and SMR + CCS ▪ Renewable H2 on site ▪ H2 from external source ▪ Autothermal reforming + CCS	▪ H2 based ▪ Electrification ▪ Biofuel as feedstock ▪ Bio-ethanol as feedstock ▪ Conventional ethylene + CCS ▪ Plastic recycling	▪ Conventional + CCS ▪ Biogas for heat demand ▪ Electrification of heat demand ▪ Hydrogen for heat demand ▪ (Bio refining)

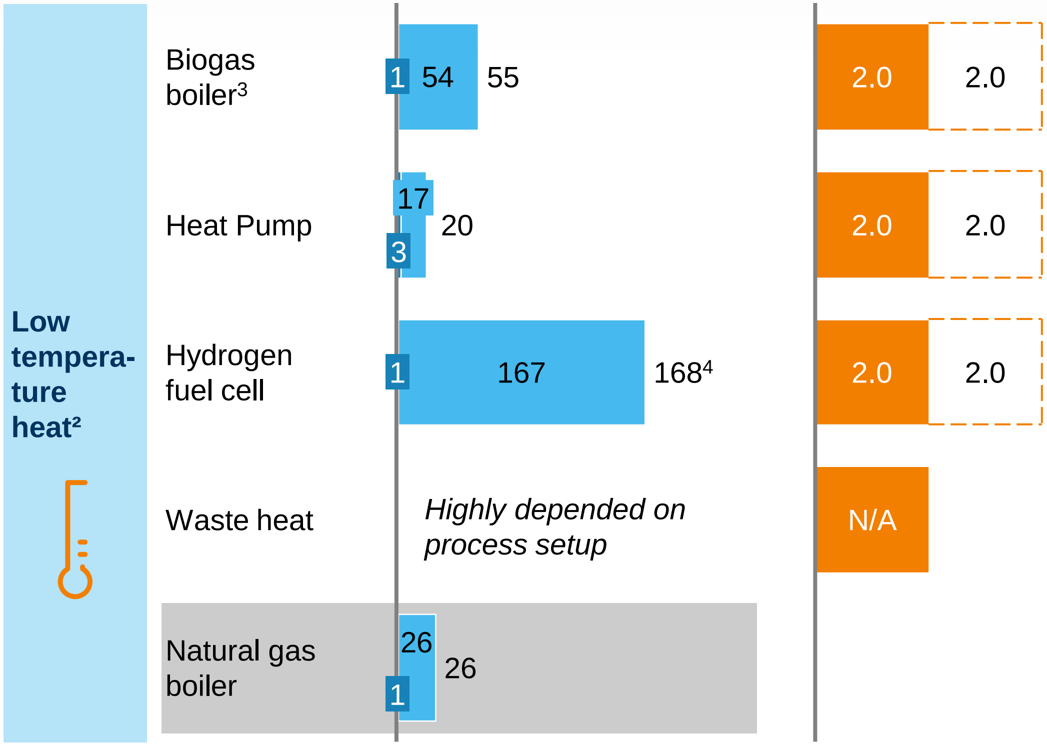
← ▪ Separate analyses – CCU: using CO(2) and H2 to make methane or methanol →

1 Some overlapping overlap

Approach of the comparison pages

- A scan has been made of the decarbonization technologies suited for different types of energy demand (low, medium, high temperature heat) and some key production processes (ammonia, ethylene, steel, petroleum refining). The numbers should be seen as an approximation, as the exact costs and benefits differ per process setup
- As a simplification, the operational costs only include fuel costs and costs of CCS. They do not include maintenance or operational costs. Rationale is that given the large fuel use of the equipment and the large difference in fuel costs between alternative options, the fuel costs are the main driver of a decision, besides investment costs
- To get to a cost per tCO_2, the delta in operational costs (Opex) per year and the delta in investment costs (Capex) per year between the conventional alternative (for heat: gas boiler, gas furnace; for a process: the conventional fossil fuel process) and the decarbonization option. These deltas are summed and the total is divided by the amount of CO_2 that is reduced. Given that the delta in capex is taken, it is assumed that equipment is replaced at end of life. To get to the Capex per year, the Capex is divided by the lifetime of the equipment. The result is a cost per reduced carbon dioxide (EUR/tCO_2) per year

Decarbonization options for low temperature heat



🟢 High 🟡 Medium 🔴 Low

	Alternative options	Cost estimate 2015[1] EUR/MWh heat output	Reduction potential MtCO2/yr	Decarbonization Cost EUR/tCO2	Assessment of potential	Conclusion
Low temperature heat²	Biogas boiler[3]	CAPEX 1, OPEX 54; total 55	Carbon reductions 2.0; assumed cascaded from Mid T 2.0	165	🟡	Potential scarcity of sustainable resource
	Heat Pump	OPEX 17, CAPEX 3; total 20	Carbon reductions 2.0; assumed cascaded from Mid T 2.0	-35	🟢	High capex investment cost, but depending on the process setup a positive business case over the lifetime of the heat pump
	Hydrogen fuel cell	CAPEX 1, OPEX 167; total 168[4]	Carbon reductions 2.0; assumed cascaded from Mid T 2.0	810	🟡	High fuel costs
	Waste heat	*Highly depended on process setup*	N/A	N/A	🟢	Cost and impact depend on process integration. Generally most of waste heat is already used
	Natural gas boiler	OPEX 26, CAPEX 1; total 26				

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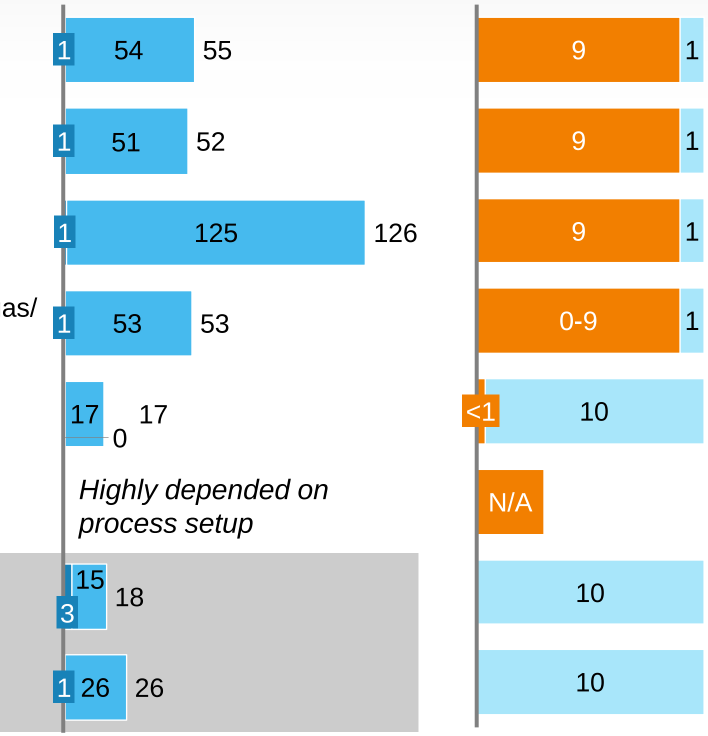
1 Assumed 50 EUR/MWh electricity, 24.4 EUR/MWh gas, 100 EUR/MWh hydrogen
2 Low temperature: 0 – 100 C.
3 Biogas assumed to be twice as expensive as natural gas
4 Hydrogen option overstated due to fuel cell use vs. burner

SOURCE: Nottingham energy, Expert Interview, IEA Bioenergy taskforce, UK 2050 Pathway, NREL, DOE

Decarbonization options for medium temperature heat

Legend: 🟦 OPEX 🟦 CAPEX ⬜ Conventional option | 🟧 Carbon reductions 🟦 Remaining CO2 | 🟢 High 🟡 Medium 🔴 Low



Medium temperature heat[2]

Alternative options	Cost estimate 2015[1] EUR/MWh heat output			Reduction potential[5] MtCO2/yr		Decarbonization Cost EUR/tCO2	Assessment of potential
	CAPEX	OPEX		Carbon reductions	Remaining CO2		
Biogas boiler[3]	1	54	55	9	1	138	🟡 Potential scarcity of sustainable resource
Electric boiler	1	51	52	9	1	123	🟢 Electricity is under current price levels more expensive than natural gas. Proven technology
Hydrogen fuel cell[4]	1	125	126	9	1	483	🟡 Very high fuel price
Dual natural gas/ electric boiler	1	53	53	0-9	1	*Only emission reduction when electricity price < gas price*	🟢 Only emission reduction if electricity price is lower than the gas price. Proven technology
Vapor re-compression	0	17	17	<1	10	-78	🟢 Only applicable for distillation or evaporation processes
Waste heat	*Highly depended on process setup*			N/A		N/A	🟢 Cost and impact depend on process integration. Generally most of waste heat is already used
Cogeneration	3	15	18		10		
Natural gas boiler	1	26	26		10		

Besides changing the energy source for medium temperature heat, energy efficiency investments can be done. These depend highly on the process.
Heat pumps for medium temperature heat could become an interesting energy efficient choice. However, these still require innovation

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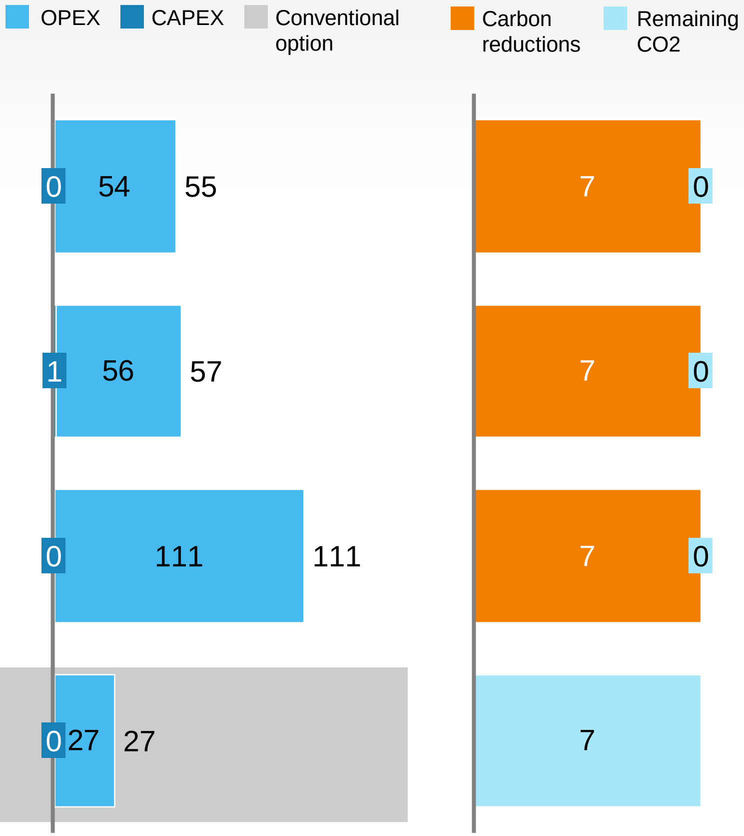
1 Assumed 50 EUR/MWh electricity, 24.4 EUR/MWh gas, 100 EUR/MWh hydrogen
2 Mid temperature: 100 – 500
3 Biogas assumed to be twice as expensive as natural gas
4 Hydrogen option overstated due to fuel cell use vs. burner
5 Excluding steel, including medium temperature heat used in chemical processes other than ammonia and ethylene (~35%); excluding cascading to Low Temperature heat since this is included in Low Temperature heat page

SOURCE: Nottingham energy, Expert Interview, IEA Bioenergy taskforce, UK 2050 Pathway, NREL, DOE

Decarbonization options for high temperature heat



🟢 High 🟡 Medium 🔴 Low

	Alternative options	Cost estimate 2015[1] EUR/MWh heat output: CAPEX	OPEX	Total	Reduction potential[4] MtCO2/yr: Carbon reductions	Remaining CO2	Decarbonization Cost EUR/tCO2	Assessment of potential
High temperature heat[2]	Biogas furnace[3]	0	54	55	7	0	114	🟡 Potential scarcity of sustainable resource
	Electric furnace	1	56	57	7	0	123	🟡 Innovation needed to achieve high temperatures in electric furnaces
	Hydrogen furnace	0	111	111	7	0	353	🟡 High fuel price
	Natural gas furnace	0	27	27		7		

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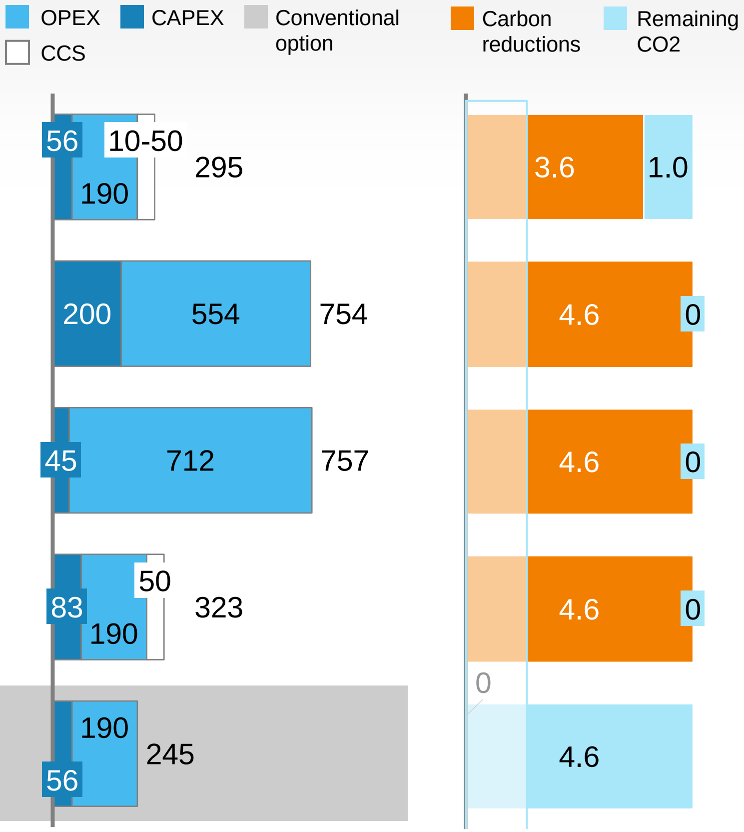
1 Assumed 50 EUR/MWh electricity, 24.4 EUR/MWh gas, 100 EUR/MWh hydrogen
2 High temperature: > 500 C
3 Biogas assumed to be twice as expensive as natural gas
4 Excluding steel, including high temperature heat used in chemical processes other than ammonia and ethylene (~10%)

SOURCE: Nottingham energy, Expert Interview, IEA Bioenergy taskforce, UK 2050 Pathway, NREL, DOE

Decarbonization options for ammonia production

Ammo-nia produc-tion

2.6 Mt/y



Alternative options	Cost estimate 2015[1] Yearly costs, EUR/t ammonia	Reduction potential MtCO2/yr	Decarboni-zation Cost EUR/tCO2	Assessment of potential 🟢 High 🟡 Medium 🔴 Low
Natural gas + CCS	CAPEX 56 OPEX 190 CCS 10-50 295	Carbon reductions 3.6 Remaining CO2 1.0	10-40	🟡 Relies on development of CCS infrastructure. Limited extra capex investment needed
H2 on site[1]	CAPEX 200 OPEX 554 754	Carbon reductions 4.6 Remaining CO2 0	280	🔴 The required large continuous supply of sustainable electricity can be difficult to obtain, depending on the site location. Large capex investment incl. nitrogen capture plant
H2 from external source[1]	CAPEX 45 OPEX 712 757	Carbon reductions 4.6 Remaining CO2 0	280	🟡 Enough sustainable hydrogen should be available and transported to the site. Capex investment incl. nitrogen capture plant required
Autothermal reforming + CCS	CAPEX 83 OPEX 190 CCS 50 323	Carbon reductions 4.6 Remaining CO2 0	44	🟡 Full decarbonisation possible, but depends on development of CCS infrastructure. Autothermal reforming requires retrofix
Natural gas	OPEX 190 CAPEX 56 245	Carbon reductions 0 Remaining CO2 4.6		

Partially (~1.5MtCO2) already captured and used to make downstream products (e.g. melamine, urea, beverages)

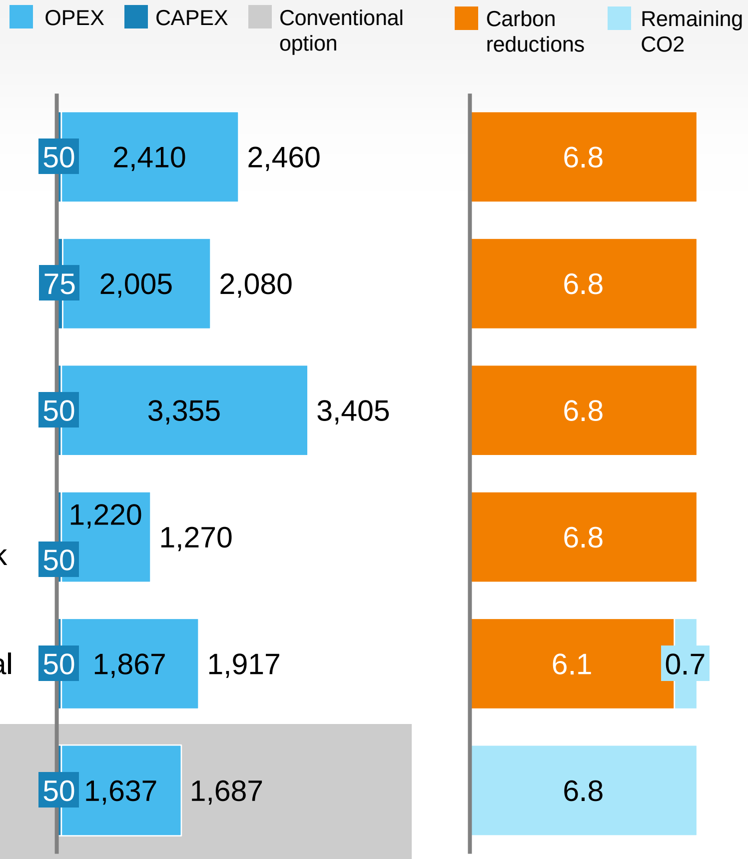
NOTE: Assumed 50 EUR/MWh electricity, 24.4 EUR/MWh gas, 100 EUR/MWh hydrogen

[1] Electrolyzer assumed at 900 EUR/tH2 per year, running at a ~50-55% capacity and with 65% efficiency; Additional Capex assumed for production of nitrogen, that comes from SMR in conventional option

[2] SMR Capex costs assumed ~1.5 bln EUR for a 600 kt/yr plant with 50 yr lifetime. Costs of autothermal reforming assumed to be 150% of capex of standard SMR. SMR assumed 28 GJ/t and 2 GJ/t for Haber-Bosch process. Electrolyser assumed to use 38 GJ/t NH3 electricity, and cost 500 EUR/t H2 per year, so EUR 88/t NH3/yr, so 1 bln for a 600 kt NH3 plant with a lifetime of 20 years. CCS costs assumed 50EUR/t NH3, but depending on specific site set-up this can be lower

SOURCE: National Inventory Report 2016, expert interview

Decarbonization options for ethylene production



Ethylene production

4 Mt/y

Assessment of potential: 🟢 High 🟡 Medium 🔴 Low

Alternative options	**Cost estimate 2015[2]** Yearly costs, EUR/t ethylene: CAPEX	OPEX	Total	**Reduction potential[3]** MtCO2/yr: Carbon reductions	Remaining CO2	**Decarbonization Cost** EUR/tCO2	**Assessment of potential**	
Hydrogen	50	2,410	2,460	6.8		454	🟡	High feedstock cost. Furnaces can be retrofitted. Only energy decarbonized, fuel gases not used and need alternative
Electric	75	2,005	2,080	6.8		231	🔴	Development of electric furnaces needed. New furnaces require capex investment. Only energy decarbonized, fuel gasses not used and need alternative
Biofuel as feedstock	50	3,355	3,405	6.8		1,008	🟡	Large amount of feedstock needed. Same facility can be used as for naphtha feedstock. Both energy and feedstock decarbonized
Bio-ethanol as feedstock	50	1,220	1,270	6.8		(245)	🔴	Large amounts of feedstock needed. Only produces ethylene, production other products needs different process
Ethylene Conventional + CCS	50	1,867	1,917	6.1	0.7	145	🟡	Carbon capture price depends on production process, can be high for lower CO2 concentration emissions
Naphtha feedstock[1]	50	1,637	1,687		6.8			

NOTE In both cost and CO2 reduction potential, the production of other HVCs that are produced together with ethylene are included. Carbon emissions are 1.7 t CO2/t ethylene

NOTE Assumed 50 EUR/MWh electricity, 24.4 EUR/MWh gas, 100 EUR/MWh renewable hydrogen

[1] In conventional setup, assumed gas consumption of 26.5 GJ/t ethylene and power consumption of 2.7 GJ/t ethylene. Cost of gas for fuel set to 0, as residual gasses are used. Carbon intensity of power assumed 0.14 kg CO2/MJ. 3.3 t Naphtha per t ethylene assumed, with a price of 400 EUR/t naphtha. Capex at 1.5 bln EUR for 600 kt/yr with 50 year lifetime

[2] Capex is assumed same for all options, except for electric furnaces which is assumed more expensive as it is still under development. Hydrogen and electricity need assumed same in terms of PJ as gas need in conventional setup. Biofuel assumed to be biodiesel costing 0.73 EUR/l, with need of 4t biofuel/t ethylene

[3] Only direct emissions included. Emissions of feedstock are not included

SOURCE: Petrochemicals Europe, European biomass association, SRI Ethylene report 2009, Ecofys international biodiesel markets 2012, expert interview, team analysis

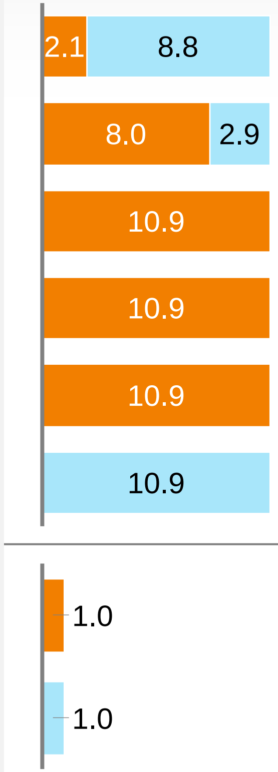
Decarbonization options for steel production

Alternative options | **Cost estimate 2015** Yearly costs, EUR/t steel | **Reduction potential** MtCO2/yr | **Assessment of potential**

Cost estimate legend: OPEX, CAPEX, Conventional option

Reduction potential legend: Carbon reductions, Remaining CO2

Assessment legend: 🟢 High, 🟡 Medium, 🔴 Low

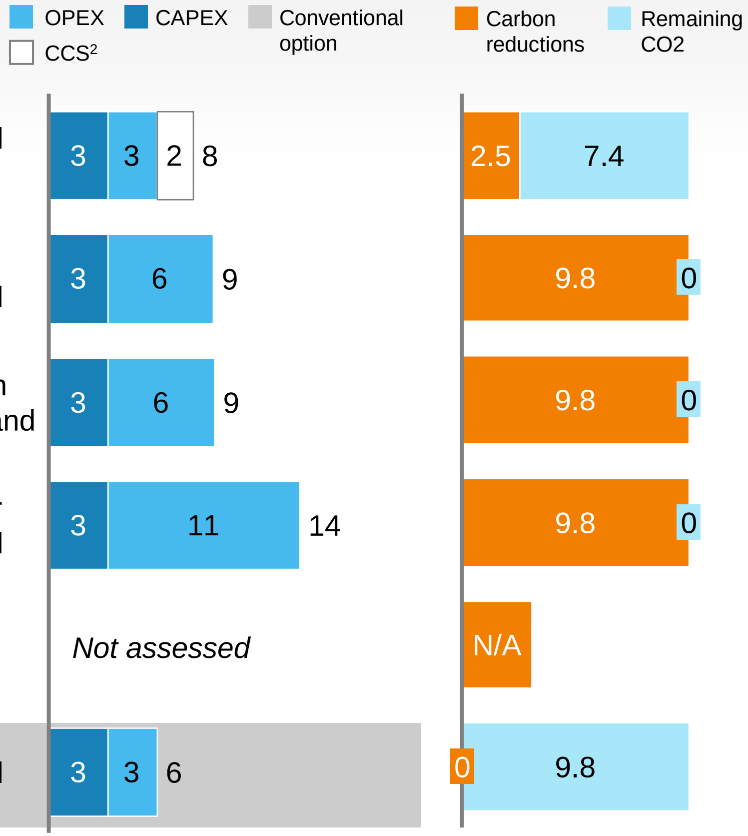


	Alternative options	Cost estimate 2015	Carbon reductions (MtCO2/yr)	Remaining CO2 (MtCO2/yr)	Assessment of potential
Change process: Integrated steel-making	Hisarna	*Exact business cases to be developed*	2.1	8.8	🟡 Hisarna makes application of CCS for decarbonization easier
	DRI-EAF Gas		8.0	2.9	🟡 High costs of iron ore pellets, but with significant carbon reductions
	DRI-EAF Bio		10.9		🟡 Biogas is limited in supply and significantly more expensive than gas
	DRI-EAF H2		10.9		🔴 Still under development and commodity costs are too high
	EAF		10.9		🟡 Scarce feedstock is the main hurdle which can be compensated for by DRI
	BF/BOF			10.9	🟡 Decarbonization possible with CCS
Steel rolling and coating	Electrification		1.0		🟢 Technology is ready, but not yet proven at scale in the steel industry
	Conventional			1.0	

SOURCE: National Inventory Report 2016, The final frontier; Decarbonising Europe’s energy intensive industries, S. Anderson; Future green steelmaking technologies, team analysis

Decarbonization options for petroleum refining

Petroleum refining



🟢 High 🟡 Medium 🔴 Low

Alternative options	**Cost estimate 2015[1]** Yearly costs, EUR/b crude oil				**Reduction potential[3]** MtCO2/yr		**Decarboni-zation Cost** EUR/tCO2	**Assessment of potential**
	CAPEX	OPEX	CCS[2]	Total	Carbon reductions	Remaining CO2		
Conventional + CCS	3	3	2	8	2.5	7.4	100[2]	🟡 Requires large CCS installation linked to many point emitters. No full decarbonisation possible, after 20-25% CC becomes very expensive
Biogas for heat demand	3	6		9	9.8	0	127	🔴 Biogas is limited in supply and significantly more expensive than gas. Process gases not used
Electrification of heat demand	3	6		9	9.8	0	132	🟡 Innovation needed. High fuel costs. Need to retrofit furnaces with electric heating. Process gasses not used
Hydrogen for heat demand	3	11		14	9.8	0	325	🟡 High fuel costs. Need to retrofit furnaces with hydrogen burners. Process gases not used
Bio refining	*Not assessed*				N/A		-	🔴 Large amounts of biomass feedstock needed. Complete rebuild of refineries required
Conventional	3	3		6	0	9.8	-	

Assumed 50 EUR/MWh electricity, 24.4 EUR/MWh gas, 100 EUR/MWh hydrogen

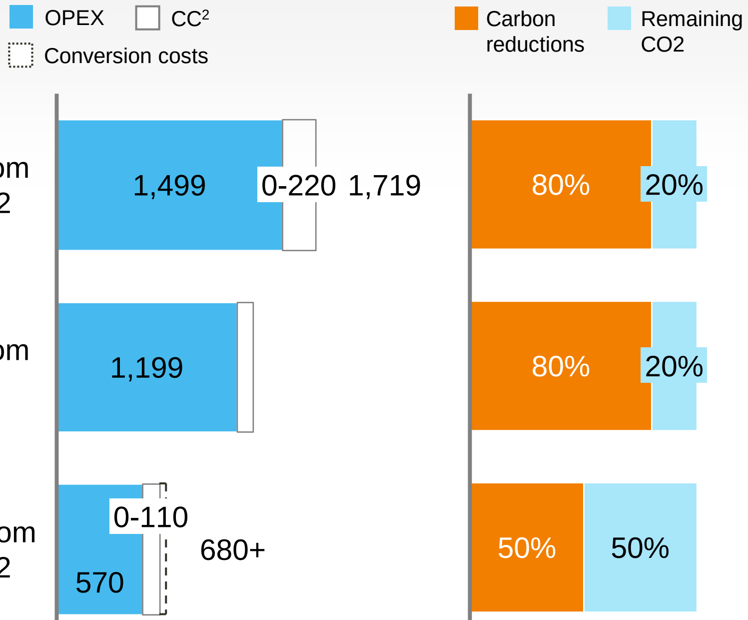
1 Feedstock (crude oil) excluded from OPEX costs. Assumed same heating efficiency for all fuels. For conventional option, excluded 35% of fuel cost, as refining gasses are used as fuel for 20-50% of heat demand. CAPEX based on new build costs of 25 thousand USD/bpd, lifetime of 20 years

2 CCS estimated to be 100 EUR/tCO2

3 Refining emissions excluding Machine Drive related emissions (~1.2 Mt CO2)

SOURCE: National Inventory Report 2016, The final frontier; Decarbonising Europe's energy intensive industries, team analysis

Decarbonization options – Deepdive CCU



● High ● Medium ● Low

	Alternative options	Cost estimate 2015[1] Yearly costs, EUR/t output	Reduction potential % reduced per tCO_2 input in conversion[3]	Decarboni-zation Cost EUR/tCO_2	Assessment of potential
CCU	Methane from CO2 and H2	1,499 0-220 1,719	80% 20%	625	● Large amount of expensive hydrogen needed per tCH4
	Methane from CO and H2	1,199	80% 20%	397	● Large amount of expensive hydrogen needed per tCH4
	Methanol from CO2 and H2	0-110 680+ 570	50% 50%	454	● Large amount of expensive hydrogen needed per t methanol. High pressure needed for conversion, not all CO_2 converted in process
	Others	E.g. CO2 as feedstock for ethanol (Lanzatech) polyols, urea or calcium carbonate			● Large number of CCU technologies in development worldwide: >250 Time of CO_2 lock-in depends on compound, e.g. urea as fertilizer emits CO_2 when used

NOTE: Assumed 50 EUR/MWh electricity, 24.4 EUR/MWh gas, 100 EUR/MWh hydrogen

[1] Electrolyzer assumed at 900 EUR/tH2 per year, running at a ~50-55% capacity and with 65% efficiency

[2] CC costs for CO2 depend on where to apply CCU, e.g. pure CO2 can be captured from ammonia production, whereas capturing CO2 from refineries can cost around 80-100EUR / tCO2

[3] Process does not convert 100% of CO2, but the remainder of CO2 can be recycled into the same process against same operational costs

SOURCE: National Inventory Report 2016, expert interview

Decarbonization options – Deepdive plastic recycling

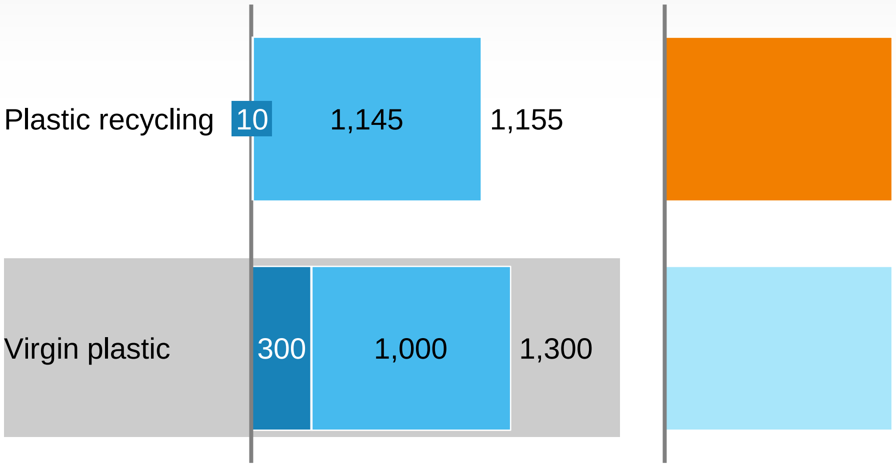
PRELIMINARY ASSESSMENT

Alternative options | **Cost estimate 2015** Yearly costs, EUR/t output | **Reduction potential** % per tCO2 put in | **Decarbonization Cost** EUR/tCO2 | **Assessment of potential**

🟦 OPEX
🟦 CAPEX
⬜ Conventional option
🟧 Carbon reductions
🟦 Remaining CO2

🟢 High 🟡 Medium 🔴 Low

Circular economy: plastic recycling



Decarbonization Cost: ~650[1]

Assessment of potential: 🟢

- Technology available and more cost effective than virgin plastic. However, assumed as additional costs for CO_2 reduction, since recycling is most likely executed by a different company than plastic producers, so no direct business case comparison
- Business case different for other types of plastic; cost and potential dependant on quality of recycled plastic mix
- Assumes all transport & logistics run on renewable energy

NOTE: Assumed 50 EUR/MWh electricity, 24.4 EUR/MWh gas, 100 EUR/MWh hydrogen

[1] All Opex and Capex assumed to be additional versus Virgin Plastic base case, since probably not executed by same company

SOURCE: National Inventory Report 2016, expert interview

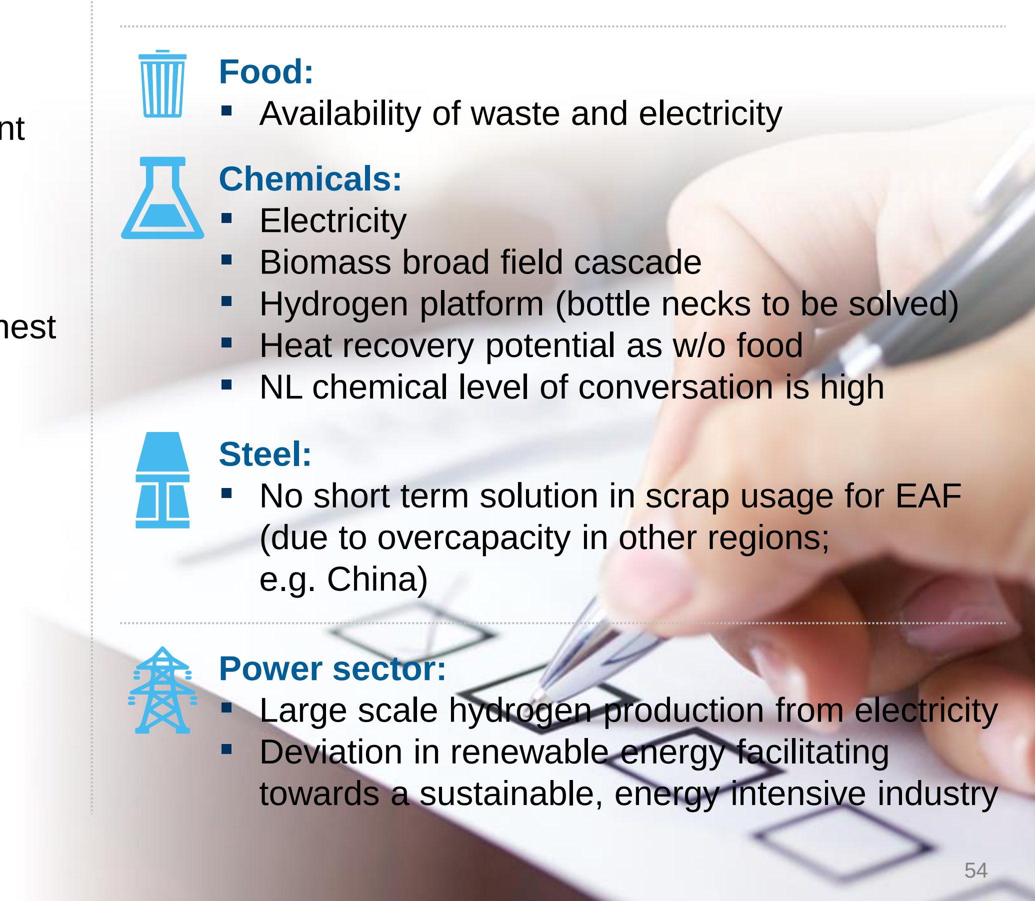
Contents

Main insights of VEMW workshop 24 January 2017

Overarching take-aways

- Industry to take a leading role in accelerating the energy transition in the Netherlands
- Decarbonization options should play into the strengths of the Netherlands
- Major opportunity expected at cross-linkages between sectors (e.g., use of waste streams as feedstock)
- Industry facilitating further increase of intermittent renewables through demand side management
- Certain decarbonization options can have significant impact in multiple sectors (e.g., electrification)
- Emissions reduction options have to be evaluated along the complete (cross-border) value chain
- Use of feedstock (e.g., hydrogen, biomass) for highest value applications (cascading)

Individual remarks



Connection:
- Biomass chemicals – balanced drain
- Gas policy not holistic enough (e.g. biomass spec.)
- Potential of cross sectoral collaboration (heat, CO)
- Enable shift in industry & energy sector

Food:
- Availability of waste and electricity

Chemicals:
- Electricity
- Biomass broad field cascade
- Hydrogen platform (bottle necks to be solved)
- Heat recovery potential as w/o food
- NL chemical level of conversation is high

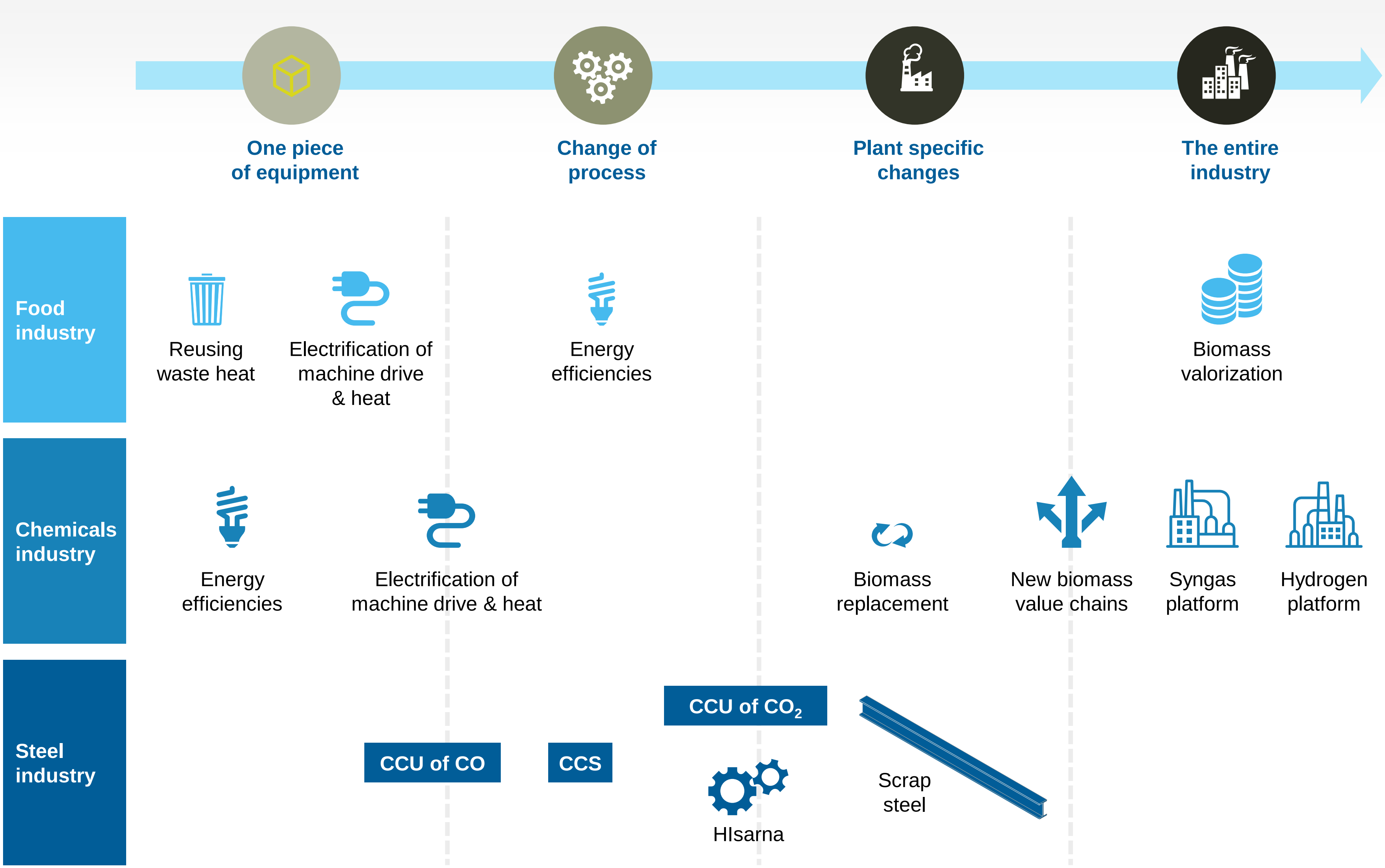
Steel:
- No short term solution in scrap usage for EAF (due to overcapacity in other regions; e.g. China)

Power sector:
- Large scale hydrogen production from electricity
- Deviation in renewable energy facilitating towards a sustainable, energy intensive industry

SOURCE : VEMW workshop 24 January 2017

DRAFT

Minimum scale of change



One piece of equipment

Change of process

Plant specific changes

The entire industry

Food industry

Reusing waste heat

Electrification of machine drive & heat

Energy efficiencies

Biomass valorization

Chemicals industry

Energy efficiencies

Electrification of machine drive & heat

Biomass replacement

New biomass value chains

Syngas platform

Hydrogen platform

Steel industry

CCU of CO

CCS

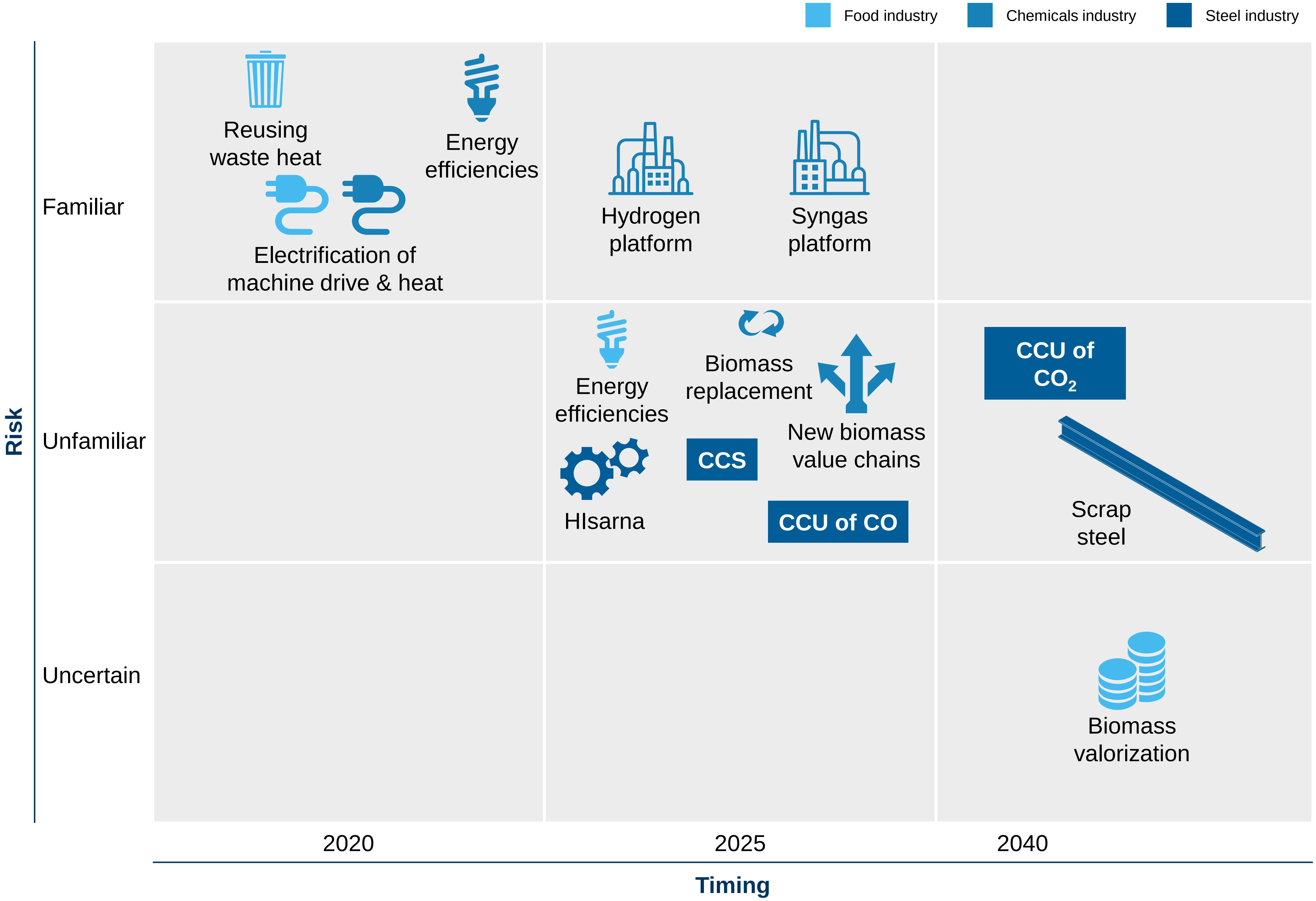
CCU of CO_2

HIsarna

Scrap steel

SOURCE : VEMW workshop 24 January 2017

Portfolio of initiatives on industrial decarbonization opportunities



🟦 Food industry
🟦 Chemicals industry
🟦 Steel industry

Risk

Familiar

Unfamiliar

Uncertain

Reusing waste heat

Energy efficiencies

Electrification of machine drive & heat

Hydrogen platform

Syngas platform

Energy efficiencies

Biomass replacement

New biomass value chains

HIsarna

CCS

CCU of CO

CCU of CO_2

Scrap steel

Biomass valorization

2020

2025

2040

Timing

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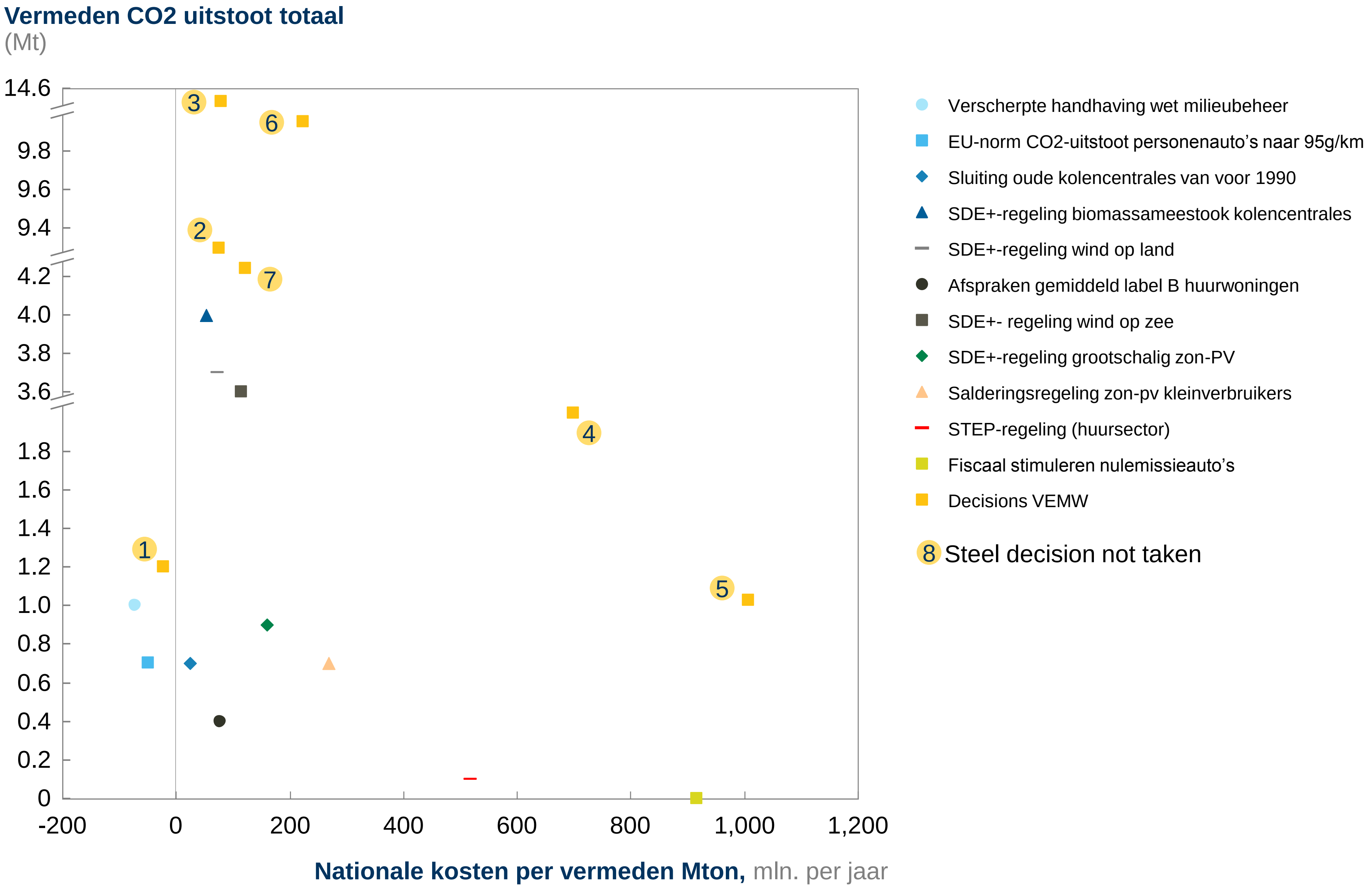
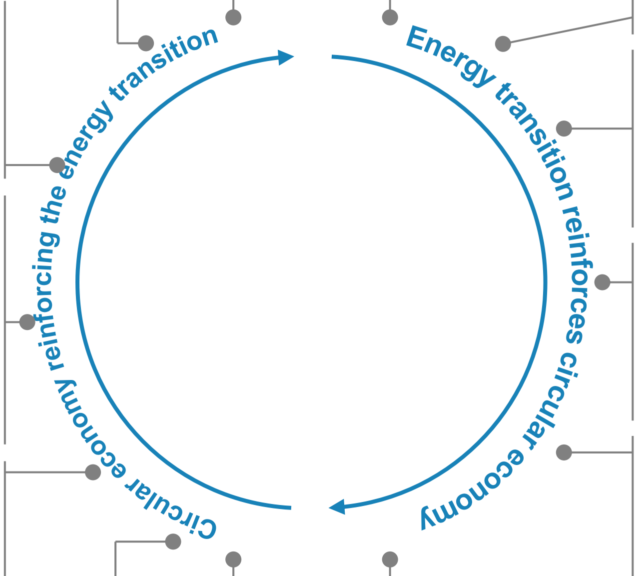
CO2-reductie vs cost efficiency of existing measures



SOURCE : Kostenefficientie CO2 reductiemaatregelen IBO 2016

The industry transition – how the circular economy transition and the energy transition interact and reinforce each other

How the circular economy and the energy transition reinforce each other



! Need to take into account embedded energy while thinking through energy efficiency measures

I Reduction of (primary) waste; decrease of raw materials use (e.g., building material wasted during construction)

II Switch to bio-based processes: lower temperature and pressure need; lowering energy usage

III Increase reuse and recycling: decrease of raw materials use, decrease of energy needed for extraction (and production, consumption)

IV Biotic circularity: increase us of bio-gas can decrease fossil gas usage

V Reduction of EOFL waste (loop)

A Energy efficiency improvements reduce fossil fuel extraction

B Switch to bio-refining helps reduce fossil feedstock inputs

D Switch to bio-gas increases demand for biogas (gasification)

E Application of CCU reduces raw materials input (fossil feedstock)

! Innovation/ industrial renewal

Where circular economy and energy transition measures can be misaligned

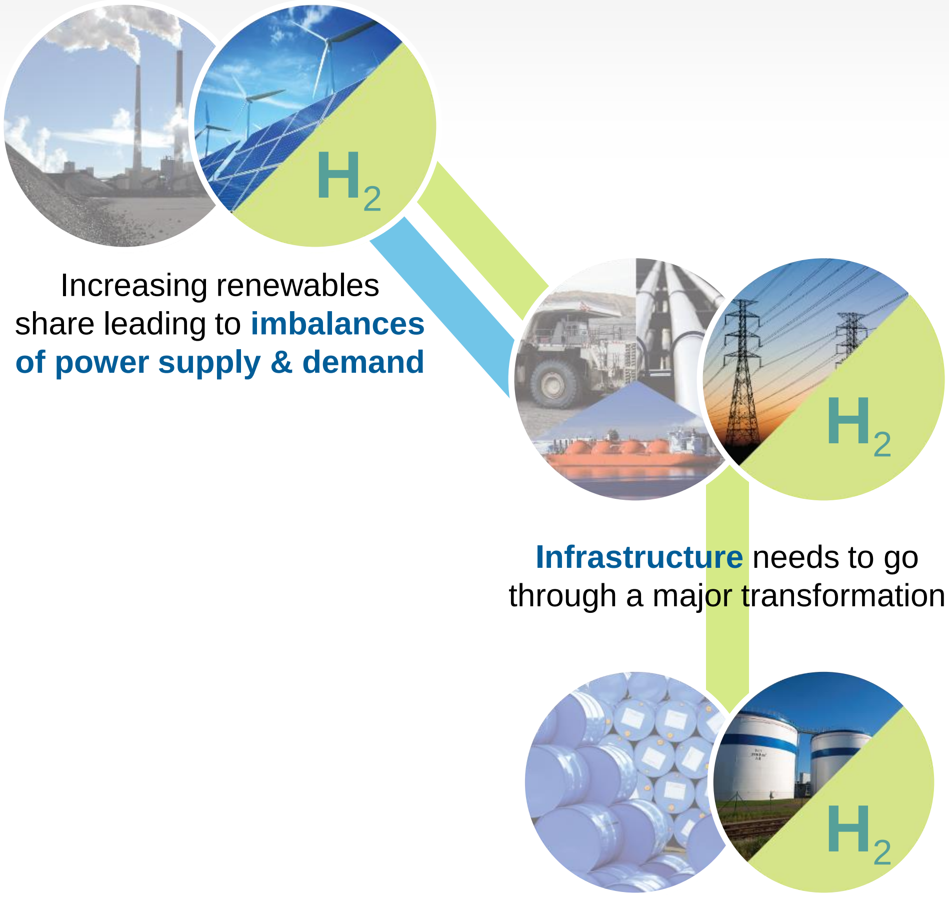
Circular economy →	← **Energy transition**
For each loop, energy is required	Improving insulation will require increased use of raw materials and embedded energy
Using bio-based plastics may require higher energy use	Large-scale application of solar (thin film) PV will lead to high waste production

SOURCE: Source

Hydrogen can help balance and buffer a renewable electricity based energy system

Energy vectors
🟦 Electricity
🟩 Hydrogen
Today
Future

As a source of energy **As the backbone of an energy system** **Advantage of hydrogen as an alternative carrier**



Increasing renewables share leading to **imbalances of power supply & demand**

Infrastructure needs to go through a major transformation

Global buffering capacity based on mostly fossil sources

Hydrogen can balance intermittent electricity generation

- Hydrogen can be formed by electrolysis at times of high electricity supply and low demand, and stored (e.g., in salt caverns) during times of low electricity supply and high demand

Hydrogen can use/build on existing fossil fuel infrastructure

- Hydrogen can, with modifications, be transported via the existing gas pipeline network

Hydrogen can be easier stored and transported than electricity

- Large scale storage of hydrogen is possible (e.g., seasonal storage)
- Transport of hydrogen is easier than electricity, as it can be shipped or transported via pipelines

SOURCE: Hydrogen Council