Successful Decarbonisation Pathways in the Industry Sector need to consider short-term Measures

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Abstract:

The reduction on greenhouse gas (GHG) emissions is one of the major challenges the international society faces today. In its special report on global warming of 1.5°C, the IPCC (2018) highlights the impact of a changing environment on ecosystems and human civilization. Emission must reach net-zero by 2050. In addition, considerably reductions are required until 2030 to avoid an overshoot and limit the use of carbon dioxide removal (CDR). In this paper, we investigate a 1.5°C-mitigation pathway for the industry sector with emphasis on the energy demand. We apply policy measures such as regulatory law, economic incentives and new technologies to reach the emission reduction described by the IPCC special report. We investigate eight countries which together account for 76% of the final energy consumption in the EU28 industry sector. We find that the targets are achievable from a technical point of view, with emission reductions by 45% until 2030 and 90% until 2050. These reductions rely strongly on decarbonized electricity supply, regulatory action or subsidies and carbon capture and storage of process-related emissions. However, the necessary measures are very aggressive and realization seems unlikely in the near future.

Keywords: Industry, Fuel switch, GHG-emissions, Decarbonisation

1 Introduction/Motivation

The reduction on greenhouse gas (GHG) emissions is one of the major challenges the international society faces today. In its special report on global warming of 1.5°C, the IPCC (2018) highlights the impact of a changing environment on ecosystems and human civilization. Among the effects of 1.5°C global warming compared to 2°C is a reduction of extreme heatwaves, precipitation events and droughts, loss of food production and several other detrimental impacts. Additionally, the report provides mitigation pathways that are expected to meet the requirements to limit global warming. While estimates on the remaining carbon budget are subject to large uncertainties, a high confidence is expressed for the need to reach zero emissions by the middle of the century, following a linear decline.

The scenarios analysed by the IPCC rely on integrated assessment models (IAMs) that focus on the supply side, with the demand side treated as scenario assumptions, with additional sectoral models applied. Thus, the specific measures to achieve the targeted reductions are not detailed. The proposed actions include material efficiency/ activity reduction, energy efficiency, electrification, use of biomass and hydrogen, innovative process technologies and carbon capture and storage (CCS). Energy efficiency alone is not sufficient to limit global warming to 2°C (Aden et al. 2018); as the IPCC special report highlighted; a significantly less ambitious target than 1.5°C. Innovative processes in the steel (Arens et al. 2017, Allwood 2016), glass and cement (Bataille et al. 2018) and chemicals (Lechtenböhmer et al. 2016) are of high importance for deep emission cuts in the long term. However, they are not available for fast emission reduction until 2030.

In this paper, we investigate a 1.5°C-mitigation pathway for the industry sector. We apply policy measures such as regulatory law, economic incentives and new technologies to reach the emission reduction described by the IPCC special report. We aim to add detail to the demand side of emission reduction effort, especially regarding the measures effective until 2030. We want to answer two specific questions. First, what measures are able to achieve the emission reductions (until 2030 and 2050) compatible with 1.5°C scenarios? Second, what is the contribution of different technology fields (steam generation, process-related emissions and industrial furnaces)? We answer these questions for eight countries[1] which together account for 76% of the final energy consumption in the EU28 industry sector.

The paper is structured as follows. Section 2 presents literature on the applied model and describes the investigated scenarios. Section 3 presents the results. Section 4 discusses the results and concludes.

[1] Germany, France, United Kingdom, Italy, The Netherlands, Spain, Poland, Sweden

2 Method and Data

We apply the method of scenario analysis to investigate, how the emission reductions described by the IPCC may be achieved. Therefore, the presented measures and assumptions (activity of subsectors, economic development, technology availability and others) are selected among many possibilities. The scenarios are designed to highlight specific aspects of the energy system and are incomplete, regarding both possible measures and the development of framework data. The target scenarios (‘Regulatory’ and ‘Incentives’) in particular include strong assumptions. Their results should therefore be interpreted as ‘if-then’ statement, not as determination or prognosis (Dieckhoff et al. 2014). However, we claim that the scenario definition and the model interactions are consistent with current knowledge. The model FORECAST is too complex to present here, but several publications on the individual mechanics have been published. The most important exogenous scenario assumptions (industrial activity and energy carrier prices) are presented shortly. The focus of this article is, however, the measures designed to facilitate fast emission reduction.

2.1 Model

The bottom-up simulation Model FORECAST is used to calculate the impacts of measures specifically designed to achieve the emission reductions compatible with a 1.5°C-pathway. FORECAST consists of multiple parts, dealing with the residential (Elsland et al. 2013), industry (Fleiter et al. 2018) and tertiary sector. In this case, only the industry part is used. It includes several interacting technology fields that are targeted by the investigated measures: energy efficiency (Fleiter 2012), steam and hot water generation (Biere 2015), industrial furnaces (Rehfeldt et al. 2018) and innovative processes (Herbst et al. 2018).

2.2 Scenario definition

Three scenarios have been defined. The ‘Reference’ scenario assumes a development without increased ambition and measures to achieve strong emission reductions. It serves as baseline. The “Regulatory” scenario introduces strong regulatory measures and achieves the desired emission reductions. The “Incentives” scenario utilizes subsidies and price signals to achieve the emission reductions. The targets are defined as emission reduction by 45% until 2030 and 95% until 2050 (compared to 2010), with the inclusion of limited CCS. These conditions are best in line with P2-scenarios (IPCC 2018). For the purpose of this analysis, we assume that the overall targets have to be achieved by all sectors similarly (i.e. no other sector overachieves the goals in a way to help others substantially).

2.2.1 Measures

The measures modelled in the scenarios are (Table 1):

Changed investment behavior: Observations of investment decisions in energy efficiency measures (Moya, Pardo 2013) suggest that they depend not only on economic feasibility but also largely on risk assessment, expressed in requirements for payback periods of 2-4 years. In the 'Reference' scenario, this threshold persists, allowing only niche-diffusion of energy efficiency measures with high payback periods (Figure 1). In the 'Regulatory' and 'Incentives' scenarios, very high payback periods are accepted, leading to considerable energy efficiency improvements.

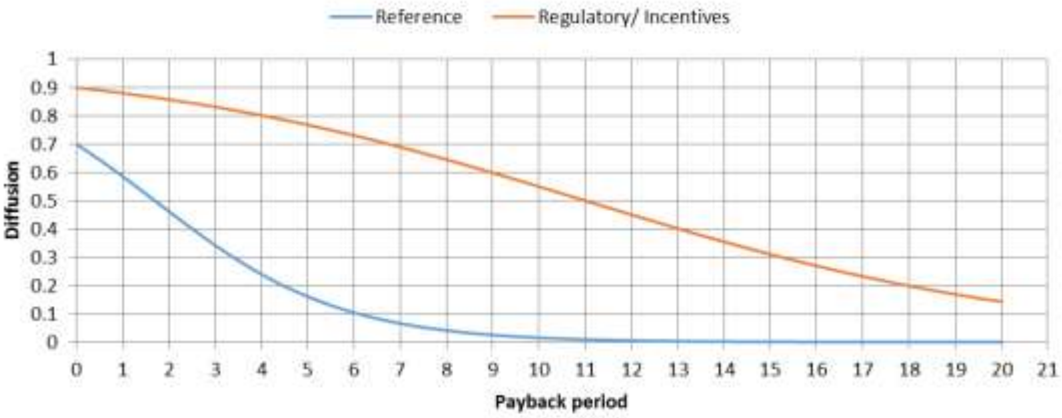

Figure 1: Diffusion of energy efficiency options over payback period

No new fossil-fired installations ('Regulatory' scenario): Starting in 2020, newly built steam generation is not allowed to run on fossil fuels. Existing installations may continue operation.

Increased replacement of old installations: Between 2020 and 2030, the average lifetime used to determine the replacement of steam generation is reduced to 75%. This applies to all technologies and increases stock turnover.

Gradual increase of electricity and biomass use: Starting in 2020, technically feasible fuel switch options are introduced (based on Rehfeldt et al. 2019). This includes the replacement of pulverized coal injection (PCI) with biomass in blast furnaces and sinter plants (both 40% of energy demand in 2030), increased use of biomass in lime and clinker production (up to 100% in 2030) and higher share of electric heating in container and flat glass production (50% in 2030).

Diffusion of innovative processes: Starting in 2030, radical process changes become available and diffuse into the market. They replace existing processes and make up for the majority of production in 2050. The processes include: hydrogen and electricity-based steel production[2] (replacing the primary steel route), low-carbon cement production (completely replacing Portland-cement production until 2050), full-electric glass furnaces and hydrogen based ammonia and ethylene production (replacing conventional production until 2050).

[2] Technology mix of hydrogen direct reduction, electrolysis and hydrogen plasma processes.

RE-gas: Starting in 2030, an increasing share of renewable gas is mixed into the natural gas supply. By 2050, the remaining gas use is to 95% carbon free.

Subsidies for biomass and electric steam generation ('Incentives' scenario): Starting in 2020, steam generation technologies that use biomass and electricity are subsidized, making their heat generation costs competitive with fossil technologies. Especially for electricity-based systems, the subsidies are substantial (~50% of electricity price).

Table 1: Emission reduction measures

Scenario	**Technology field**	**Measures** until 2030	**Measures** after 2030
Reference	All	ETS certificate price stable	ETS certificate price -> 85 EUR/tCO_2
	Energy efficiency	None	None
	Steam and hot water generation	None	None
	Industrial furnaces	None	None
	Innovative processes	None	None
	Targets	**None**	**None**
Regulatory	All	ETS certificate price-> 100 EUR/tCO_2	ETS certificate price -> 200 EUR/tCO_2
	Energy efficiency	Changed investment behavior	
	Steam and hot water generation	From 2020: no new fossil-fired installations Between 2020 and 2030: increased replacement of old installations	
	Industrial furnaces	Gradual increase of electricity and biomass use	Increased fuel switch speed
	Innovative processes	-	Diffusion of innovative processes, RE-gas
	Targets	**-45%**	**-95%**
Incentives	All	ETS certificate price-> 100 EUR/tCO_2	ETS certificate price -> 200 EUR/tCO_2
	Energy efficiency	Changed investment behavior	
	Steam and hot water generation	From 2020: subsidies for biomass and electric steam generation Between 2020 and 2030: increased replacement of old installations	
	Industrial furnaces	Subsidies for electricity use in furnaces	
		-	Increased fuel switch speed
	Innovative processes	-	Diffusion of innovative processes, RE-gas
	Targets	**-45%**	**-95%**

Subsidies for electricity use in furnaces ('Incentives' scenario): Starting in 2020, the electricity price is subsidized with 7.4 EUR/GJ for the use in industrial furnaces. This level of support equals the one in steam generation.

Increased fuel switch speed: Starting in 2030, industrial furnaces are questioned frequently in terms of their fuel use, due to price signals and innovative processes becoming available. This leads to higher replacement and fuel switch rates. In subsectors with strong diffusion of innovative processes (iron and steel, glass, chemical industry), the mean time to consider fuel switch decreases from 10 years to 2 years.

ETS certificate price: The EU ETS remains in effect in all scenarios. It is extended to all industry subsectors (e.g. engineering, others). The certificate prices increase moderately in the

'Reference' scenario only after 2030 but strongly in the target scenarios. In those, hard coal faces an effective price increase of 300% due to certificate prices of 200 EUR/tCO_2 (natural gas 75%) after 2040 (Table 2).

Table 2: EU ETS certificate prices

Scenario	**Unit**	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Reference	EUR/t	15	8	20	23	25	38	50	68	85
Incentives	EUR/t	15	8	50	75	100	150	200	200	200
Regulatory	EUR/t	15	8	50	75	100	150	200	200	200

CCS of process emissions: In 2010, direct process related emissions account for about 30 Mt. This alone exceeds the allowed emissions in a 95% scenario in 2050. Therefore, carbon capture and storage (CCS) is applied to selected processes (clinker and lime burning, carbon black production). It is modelled as technical measure, but the process emissions of these processes may in principle be offset by any CDR mechanism, for example afforestation. Technical measures to avoid these process emissions in the first place are not included in the scenarios.

2.2.2 Energy carrier prices

The energy carrier prices (Figure 2, Table 8) are exogenous model input for each modelled country. To provide a general overview, we present the unweighted average for selected energy carriers here.

The most relevant energy carriers are electricity, fuel oil, hard coal, natural gas and biomass. Electricity historically has high prices compared to fuel and becomes more expensive until 2020 (128% of 2010 prices). Until 2050, the electricity price decreases to 112% of its 2010 level. Fuel oil prices increase strongly, reaching 220% of their 2010 level in 2030 and 260% in 2050. In the 'Regulatory' scenario, biomass reaches availability limitations. In an iterative process, the prices have been adjusted to reflect higher supply costs (e.g. transport costs for import from outside the EU). They reach 260% of their 2010 levels in 2050. In the other scenarios, the biomass price increases moderately to 140% of the 2010 level in 2050. The estimates assume a sustainable biomass potential for the EU28 industry sector of 100 Mt, which is only approached in the 'Regulatory' scenario.

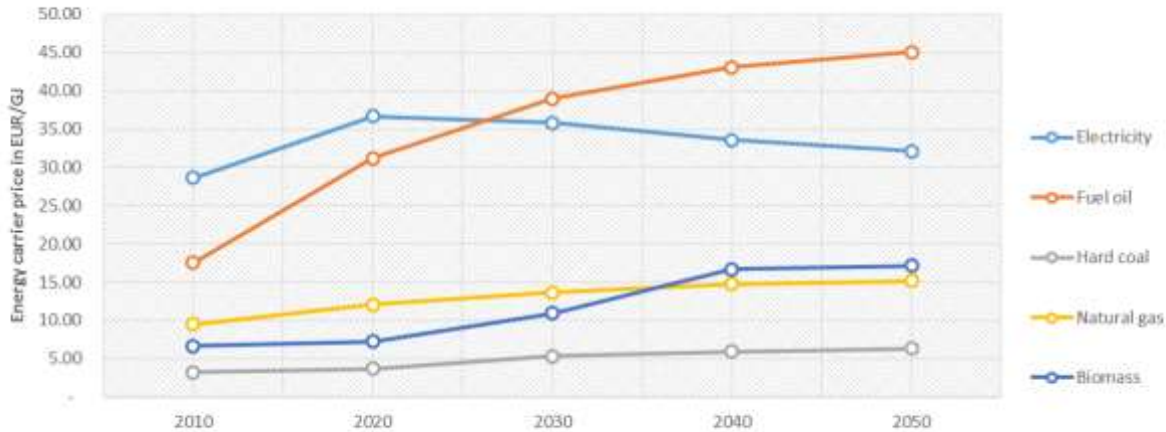

Figure 2: Selected energy carrier prices (unweighted average of all analysed countries), 'Regulatory' scenario

2.2.3 Energy and emission balance

The scenarios base on the Eurostat energy balance (Eurostat 2018) and calibrate to 2015. The energy carriers are aggregated from the Eurostat definitions, the subsectors equal those of Eurostat (with the exception of iron and steel, which additionally includes coke ovens and blast furnaces). The emissions are the product of the resulting final energy demand and the fuel-specific emission factors (Table 3). In addition to energy-related emissions, process emissions are included in the results (e.g. calcination in cement production).

Table 3: Emission factors for fuels (based from Jurich 2016)

Energy carrier	**Emission factor**	
	tCO_2/GJ	g/kWh
Light fuel oil	0.07	266
Hard coal	0.09	338
Coke	0.11	389
Lignite	0.11	403
Natural gas	0.06	202
Petroleum coke	0.10	364
Heavy fuel oil	0.08	281
Derived gases	0.06	216
Stack gas	0.26	936
Waste	0.05	166
Biomass	-	-

2.2.4 Electricity supply

Since fuel switch to low-emission electricity is a reduction option for industry, the applied generation technology and its emissions are important assumptions. We assume a similarly ambitious decarbonisation scenario for the supply side (Table 4), with an average reduction of 45% (in terms of electricity emission factor) until 2030 and 90% until 2050. These reductions allow the industry sector to mitigate CO_2 by switching to electricity before 2030. We balance the emissions of electricity production in the industry sector to avoid hiding emissions from increased electricity demand in the supply sector.

Table 4: Emission factors of electricity production

Country	**Unit**	**2010**	**2030**	**2050**
France	g/kWh	95	50	7
Germany	g/kWh	550	252	36
Italy	g/kWh	407	205	29
Netherlands	g/kWh	460	220	32
Poland	g/kWh	1038	529	76
Spain	g/kWh	355	202	29
Sweden	g/kWh	20	14	4
United Kingdom	g/kWh	509	259	36

2.2.5 Industrial activity and macroeconomic framework

Industrial production on country and process level is a major input. It was collected via a variety of data sources including PRODCOM, UN commodity production database, US geological survey, UNFCCC, and industry organisations (World steel association, CEPI, Cembureau, Eurochlor, etc.). The macroeconomic framework data for the model-based analysis stem from the European Reference Scenario 2016 (European Commission 2016) and remain the same across all scenarios.

Emission reduction pathways need to consider material efficiency in production and consumption. Compared to the ‘Reference’ scenario, several energy intensive products are produced in smaller quantity in the target scenarios (Table 5). These include ammonia (-25%), ethylene (-20%), steel (-20%), container glass (-10%) and cement (-20%) (Table 5).

Table 5: Industrial activity of selected products in Mt (example for Germany)

Scenario	Subsector	Product	2010	2030	2050
Reference	Chemical industry	Ammonia	2.68	2.98	3.16
Reference	Chemical industry	Ethylene	5.06	5.90	6.64
Reference	Iron and steel	Steel	43.83	46.22	44.36
Reference	Iron and steel	Steel products	38.10	39.58	37.99
Reference	Non-ferrous metals	Aluminium	1.01	1.16	1.16
Reference	Non-metallic mineral products	Cement	29.89	35.28	33.77
Reference	Non-metallic mineral products	Container glass	4.69	4.43	3.44
Reference	Non-metallic mineral products	Flat glass	2.26	2.17	2.00
Reference	Paper and printing	Paper	23.06	20.34	18.96
Regulatory	Chemical industry	Ammonia	2.68	2.66	2.37
Regulatory	Chemical industry	Ethylene	5.06	5.40	5.31
Regulatory	Iron and steel	Steel	43.83	43.10	35.29
Regulatory	Iron and steel	Steel products	38.10	37.31	32.68
Regulatory	Non-ferrous metals	Aluminium	1.01	1.15	1.13
Regulatory	Non-metallic mineral products	Cement	29.89	32.26	27.02
Regulatory	Non-metallic mineral products	Container glass	4.69	4.24	3.10
Regulatory	Non-metallic mineral products	Flat glass	2.26	2.17	2.00
Regulatory	Paper and printing	Paper	23.06	20.34	18.96
Incentives	Chemical industry	Ammonia	2.68	2.66	2.37
Incentives	Chemical industry	Ethylene	5.06	5.40	5.31
Incentives	Iron and steel	Steel	43.83	43.10	35.29
Incentives	Iron and steel	Steel products	38.10	37.31	32.68
Incentives	Non-ferrous metals	Aluminium	1.01	1.15	1.13
Incentives	Non-metallic mineral products	Cement	29.89	32.26	27.02
Incentives	Non-metallic mineral products	Container glass	4.69	4.24	3.10
Incentives	Non-metallic mineral products	Flat glass	2.26	2.17	2.00
Incentives	Paper and printing	Paper	23.06	20.34	18.96

3 Results

With the reference year of 2010, the base emissions, towards which the targeted reductions are calculated, amount to 874 Mt (Figure 3). Of those, 426 Mt are energy-related emissions excluding electricity generation (i.e. fuels), 120 Mt process-related emissions and 328 Mt of electricity (balanced with the respective emission factor in generation). Process emissions include only those of production, not product use. Emissions from fuel is mainly caused in industrial furnaces (207 Mt) and steam generation (166 Mt). (Indirect) Emissions from electricity are caused by demand of cross-cutting technologies (224 Mt) and special electricity uses, e.g. aluminium production in the Hall-Héroult process (55 Mt). In 2010, there is little use of electricity in furnaces, steam generation and space heating, and thus small indirect emissions (25 Mt).

According to the target reductions of 45% reduction in 2030 and 95% reduction in 2050 compared to 2010, the allowed emissions remaining are 480 Mt in 2030 and 44 Mt in 2050.

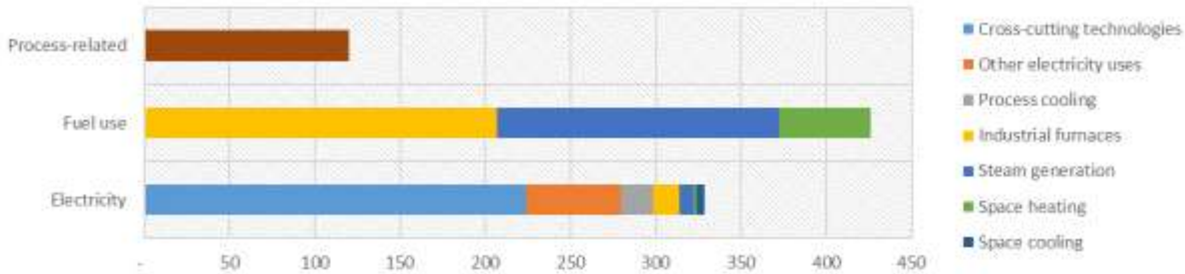

Figure 3: GHG-emissions in base year 2010 by source category and application

By 2030, the remaining emissions amount to 614 Mt in ‘Reference’, 512 Mt in ‘Incentives’ and 469 in ‘Regulatory’ (Figure 4). The target values are reached in the ‘Regulatory’ scenario, ‘Incentives’ trails by 30 Mt. Especially the determined use of biomass (380 TWh) instead of (still quite emission intensive, Table 6) electricity constitutes the advantage of the ‘Regulatory’ scenario. Of this total, 325 Mt, 209 Mt and 203 Mt are fuel-related in ‘Reference’, ‘Incentives’ and ‘Regulatory’, respectively. There are 126 Mt process-related emissions in ‘Reference’ and 107 Mt in both target scenarios. Finally, 163 Mt, 200 Mt and 164 Mt are caused by electricity consumption. Emissions from fuel is still mainly caused in industrial furnaces (187 Mt, 131 Mt, 112 Mt) and steam generation (113 Mt, 63 Mt, 69 Mt). Emissions from electricity are caused by demand of cross-cutting technologies (108 Mt, 100 Mt, 100 Mt) and special electricity uses, e.g. aluminium production in the Hall-Héroult process (26 Mt in all scenarios). The deployment of CCS in selected processes begins in 2030 (4 Mt captured in ‘Incentives’, 5 Mt captured in ‘Regulatory’).

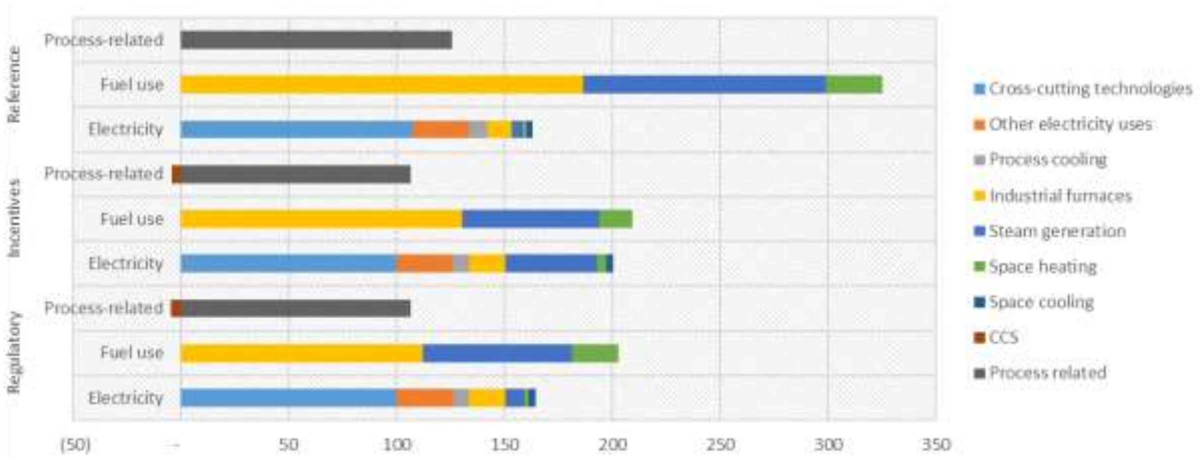

Figure 4: GHG-emissions in 2030 by source category and application

In 2050, the remaining emissions amount to 436 Mt in ‘Reference’, 81 Mt in ‘Incentives’ and 79 in ‘Regulatory’ (Figure 5). The target values are not achieved, but in reach. The use of biomass in the ‘Regulatory’ scenario recedes in favour of now strongly decarbonized electricity (200 TWh). There remain 284 Mt, 26 Mt and 33 Mt of fuel-related emissions in ‘Reference’, ‘Incentives’ and ‘Regulatory’, respectively. Additionally, 128 Mt process-related emissions in ‘Reference’ and 53 Mt in both target scenarios persist. Finally, 24 Mt, 33 Mt and 26 Mt are caused by electricity consumption. Emissions from fuel is still mainly caused in industrial furnaces (164 Mt, 10 Mt, 11 Mt) and steam generation (109 Mt, 16 Mt, 21 Mt). Emissions from electricity are caused by demand of cross-cutting technologies (15 Mt, 14 Mt, 14 Mt) and special electricity uses, e.g. aluminium production in the Hall-Héroult process (4 Mt in all scenarios). To account for persisting process-related emissions, CCS is widely deployed in selected processes (31 Mt captured in ‘Incentives’ and 32 Mt captured in ‘Regulatory’). The remaining gap of ~40 Mt in both scenarios could be closed with a complete decarbonisation of the electricity supply. However, the main challenge for the industry sector are process-related emissions of small sources, in which CCS is hard to implement both from a technical and economical point of view.

Table 6: Emission factors of heat and electricity generation

		Reference	Regulatory	Incentives
		g/kWh		
2010	Steam generation[1]	219		
	Industrial furnaces	314		
	Electricity generation[3]	427		
2030	Steam generation[1]	192	143	261
	Industrial furnaces	299	244	277
	Electricity generation[3]	212		
2050	Steam generation[1]	162	50	90
	Industrial furnaces[2]	267	62	53
	Electricity generation[3]	30		

1: Fuel-based share
2: After 2030 including hydrogen as feedstock
3: Average of countries weighted by consumption

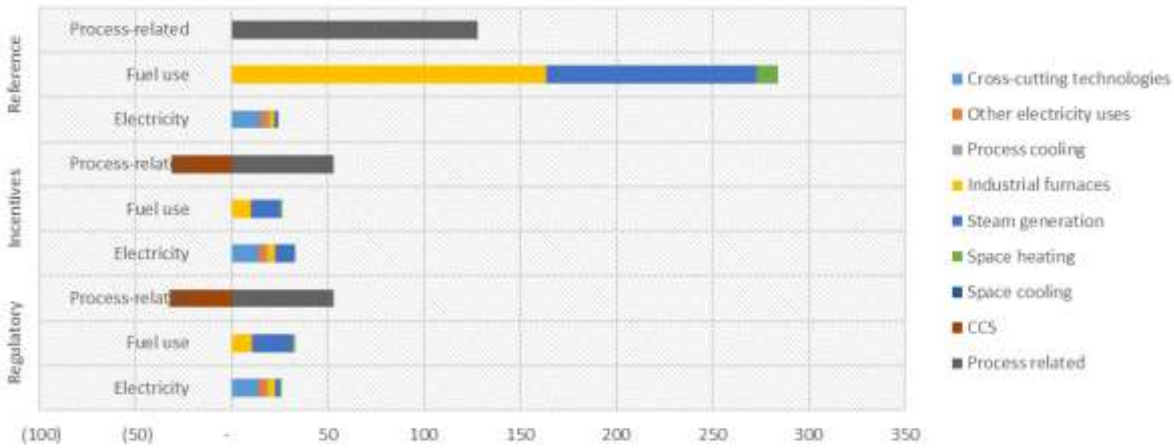

Figure 5: GHG-emissions in 2050 by source category and application

While the emissions from these processes are of limited importance in 2010 and even 2030, with a remaining emission target of 44 Mt in 2050, they become most relevant. For the investigated countries, they amount to 19 Mt (Table 7).

Table 7: Process-related emissions of processes without implementation of CCS

Process	**Emissions (MtCO2eq.)**
Ceramics, diverse	4.2
Zinc, primary	2.5
Poly ethylene	2.4
Aluminium, primary	2.2
Glass, diverse	2.1
Tiles, plates, refractories	1.9
Bricks	1.9
Soda ash	1.2
Electric arc furnace	0.6
Sum	18.9

Of special importance to reach the 2030 targets are fast emission reductions via fuel switch in steam generation. In 2015, hard coal-based systems are still the cheapest steam generation option; natural gas and biomass are competing. Electricity-based systems cannot compete. In the target scenarios, two approaches are modelled (Figure 6). The ‘Regulatory’ scenario bans fossil fuel-based steam generation after 2020 in new installations. This leaves biomass boilers as the most economical option, as the price of electricity remains considerably higher than most fuels in all scenarios (Table 8). However, he price for biomass increases due to potential restrictions and the overall heat production costs increase due to the ban on fossil fuel systems. The ‘Incentives’ scenario grants subsidies to electricity, making it the most attractive option after 2020.

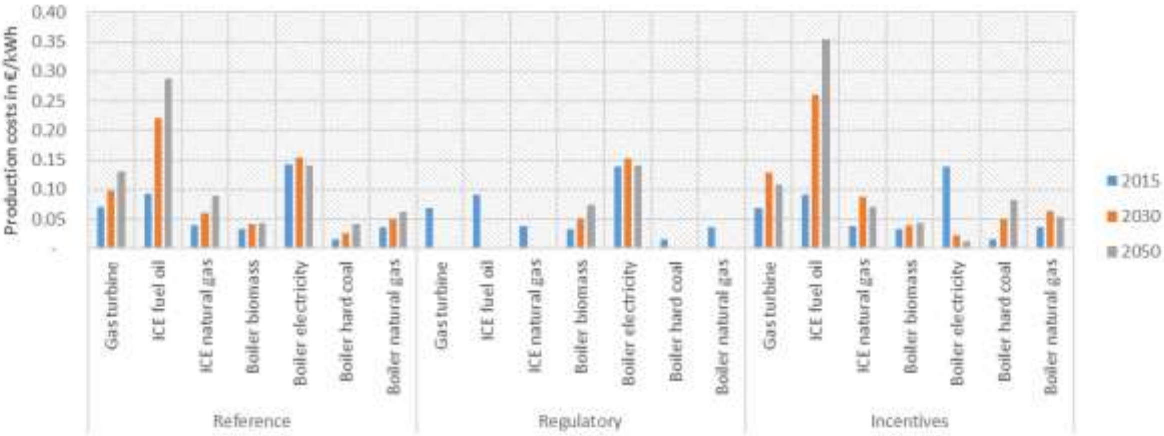

Figure 6: Heat production costs of selected technologies

4 Discussion and conclusion

The presented results suggest that, from a technical point of view, the targets associated with the 1.5°C scenarios of the IPCC are achievable for the industry sector of the selected countries. The overall emission reduction in the target scenarios reaches >40% in 2030 and >90% in 2050. The missing 5% in 2050 could be provided by additional CCS of process-related emissions in distributed processes or (as proposed by the IPCC) with negative emissions from afforestation. In the target scenarios, biomass use is limited to a level assumed sustainable and serves as bridging technology. It is gradually replaced by electricity after 2030.

However, the scenarios developed in this article include very aggressive measures to yield fast emission reductions until 2030 and deep reductions until 2050. Of special importance are two fields of action, which shall be discussed shortly.

First, process heat generation. In the “Incentives”-scenario, high subsidies for electric steam boiler allow a quick phase-out of fossil fuels. They lower the price of electricity to a level competitive with coal-based generation (Figure 6). Due to the high costs associated with such subsidies, it is unclear whether societies are willing or able to implement them. The “Regulatory”-scenario offers the alternative of a ban on new fossil steam generation. It is considerably more effective (50% emission reduction in steam generation systems until 2030 instead of 30%). However, it is equally unclear whether the associated increase in generation costs are economically sustainable for the industry. To enhance the effect of incentives or regulatory measures that push low-emission steam generation, early replacement of old installations is assumed during the 2020’s. This speeds up stock turnover and remove fossil installations from the generation portfolio until 2030. It must be expected that regulatory efforts to achieve early replacement face legal barriers. At the same time, softer approaches, e.g. via investment incentives might not achieve the desired effect. However, the shift in generation costs (subsidies and CO_2-price) included in the scenarios could trigger re-evaluation of reinvestments on its own. While this is not included in the model, the cost structure of large process heat installations (low capital intensity, high importance of energy costs) support this theory.

Second, industrial furnaces. The target scenarios include considerable fuel switch towards biomass and electricity in important processes (iron, cement and glass production) already until 2030. In the “Regulatory”-scenario, specific measures are selected to include only options technically available and deployable until then. In the “Incentives”-scenario, subsidies for electricity use in industrial furnaces are introduced. The former is more effective (70% reduction compared to 61%). In both cases, the fuel switch incurs additional costs. Additionally, the stranded investments associated with these changes are a risk, as after 2030, innovative processes completely based on hydrogen and electricity have to enter the market. As an example, blast furnaces are modelled to increase their share of biomass to 40% until 2030 (effectively replacing pulverized coal with e.g. charcoal). Until 2050, however, hydrogen- and electricity-based direct reduction replace blast furnaces in the primary route. While it seems possible that the investment in biomass-use pays off during 20 years of high CO_2-prices, the transition requires careful management on plant-level to limit capital loss. This is not represented in the used model.

We conclude that, while the emission reductions in line with 1.5°C global warming can be achieved with determined action in the industry sector, high risks and concerns about economical, political and social acceptability remain that are not reflected in our model approach. Critical points are the availability of clean electricity, early fuel switch until 2030 and the deployment of innovative, decarbonised production processes until 2050. The compensation of otherwise not avoidable emissions (via CCS or afforestation) is essential to achieve reductions beyond 85%, as the amount of process-related emissions alone surpasses the allowed emissions in 2050.

The proposed measures require determined implementation and are not common tools of market economies. Still, observations of the past question the ability of the free market to meet the challenges of climate change in due time. Many of the investigated measures are unlikely to be implemented as modelled. The achievability of emission reductions in line with 1.5°-scenarios in industry therefore seems to be merely a theoretically possibility.

Table 8: Selected energy carrier prices per country

Country	**Electricity**	**Fuel oil**	**Hard coal**	**Natural gas**	**Biomass[1]**
France					
2010	19.90	15.80	3.20	9.70	8.10
2020	33.00	27.60	3.70	12.20	8.80
2030	24.80	34.50	5.30	13.70	13.40
2040	23.90	38.10	5.90	14.80	20.38
2050	20.30	39.80	6.30	15.20	20.96
Germany					
2010	33.10	14.60	3.20	12.30	7.70
2020	55.60	24.50	3.70	12.90	8.30
2030	51.70	30.60	5.30	14.50	12.55
2040	45.00	33.80	5.90	15.60	19.09
2050	42.80	35.40	6.30	16.10	19.64
Italy					
2010	40.10	27.50	3.20	8.30	7.00
2020	51.20	46.80	3.70	11.30	7.60
2030	53.20	58.50	5.30	12.80	11.57
2040	46.90	64.60	5.90	13.90	17.59
2050	44.60	67.60	6.30	14.30	18.09
The Netherlands					
2010	27.10	19.20	3.20	9.00	6.20
2020	28.50	35.30	3.70	11.10	6.70
2030	31.70	44.10	5.30	12.70	10.30
2040	31.70	48.80	5.90	13.90	15.66
2050	31.20	51.00	6.30	14.30	16.11
Poland					
2010	27.40	16.40	3.20	9.00	4.40
2020	26.10	29.70	3.70	11.70	4.80
2030	30.40	37.20	5.30	13.20	7.19
2040	34.20	41.10	5.90	14.20	10.94
2050	33.40	43.00	6.30	14.60	11.25
Spain					
2010	30.40	15.90	3.20	8.10	5.20
2020	35.80	28.10	3.70	12.00	5.70
2030	31.90	35.10	5.30	13.50	8.60
2040	29.80	38.80	5.90	14.50	13.08
2050	28.70	40.60	6.30	14.90	13.46
Sweden					
2010	23.40	14.50	3.20	13.40	7.50
2020	18.20	28.50	3.70	14.20	8.10
2030	17.80	35.70	5.30	16.00	12.27
2040	18.00	39.40	5.90	17.30	18.66
2050	20.50	41.20	6.30	17.70	19.20
United Kingdom					
2010	27.80	16.50	3.20	6.30	7.20
2020	44.90	29.10	3.70	11.30	7.80
2030	45.10	36.40	5.30	12.80	11.85
2040	39.30	40.20	5.90	13.90	18.02
2050	35.30	42.10	6.30	14.30	18.53

1: Biomass prices from ‘Regulatory’ scenario, with price increase due to potential limitations

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