Workshop report on Heavy Industry in Climate Change Mitigation Scenarios

Deliverable 4.4

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1 Introduction

1.1 Objective

Achieving the Paris climate goals (keeping global average temperature increase to well below 2 °C and pursue efforts to limit to 1.5 °C since preindustrial levels) requires efforts in all sectors worldwide. The literature assessing transformation pathways towards meeting these upper-boundary of the Paris climate goals (Clarke et al., 2014; IPCC, 2018) shows a near complete decarbonisation of the energy system by 2050. Much of the anticipated mitigation potential to meeting the Paris goals is ascribed to the power sector, with many system models elaborating on the various options in this sector. Other sectors, however, are described in much lesser detail by these system models. This is also structurally recognized in science, policy and in the corporate environment, which are simultaneously calling for an greater integrative long-term perspective that includes industry (Ruby et al., 2018; Weber et al., 2018).

To understand the transformative challenges for the energy- intensive industries, a broader overview of our current understanding of industry decarbonization and perspectives towards 2050 is needed. As a starting point we have collected a broad range of recently published quantified perspectives on industry decarbonization with an outlook towards 2050. We have selected studies that have been created to advise the private sector and policy makers on possible decarbonisation strategies for industry specifically. Based on this collection of published roadmaps on industry, we have selected and invited authors and users of these roadmaps to join a discussion on industry decarbonization perspectives. The workshop, hosted on March 27th 2019 at the PBL Netherlands Environmental Assessment Agency, intended to start a dialogue with private and research representatives on the considered available potential for transformative change in and among key material processing industry sectors (e.g. steel, cement, pulp and paper and the chemical industry, referred to as 'the industry' from here onwards) and the applied practices for scenario-building in this field.

1.2 Methodology

1.2.1 Roadmap analysis

1.2.1.1 Roadmap selection

To build a corpus of current European industry decarbonization perspectives towards 2050, we have systematically collected and analysed several industry roadmaps and explorative studies by academia and (national) research institutes between the 2010-2018 period (Schneider et al., 2017; Van Sluisveld et al., 2018). The studies have been collected through querying Google search, Google Scholar, Scopus and by inquiring the REINVENT consortium partners for relevant literature. The studies have been manually checked for eligibility, e.g. by examining whether assumptions and implications had been consistently quantified and reported over the considered timeline.

1.2.1.2 Scenario selection

From the admissible studies we have mainly focused on the perspectives that either included the following aspects in a long-term perspective:

- *(Full) industry decarbonization*: All studies that attempt to align the industry sector with the Paris Climate Agreement objectives are considered eligible for assessment. This leads to various interpretations, ranging from either aligning to (1) economy-wide emission reduction objectives (e.g. such as the 80%-95% emission reduction ambition for EU) or a more specific (2) zero-carbon objective for a (sub)industry sector.

- *Maximum available mitigation potential*: In the absence of an integrated mitigation objective, we assume that the presented roadmap describes the maximal achievable mitigation potential.

See Annex 1 for the full list of analysed studies.

1.2.2 Expert elicitation

To complement the perspectives as reported in literature and structure the dialogue we have elicited several opinions for key industry sectors using a Delphi-like method. The Delphi method is developed as a method for structuring a group assessment process so that the process is effective in allowing a group of individuals to evaluate a complex problem. The Delphi method was considered appropriate as it is a stepwise method to (1) draw out individual contributions of information and knowledge, (2) evaluate group views and (3) review the individual contribution (De Smedt et al., 2013).

We have reinterpreted the guidelines for the Delphi method in such a way that we drew on individual expert opinions on industrial decarbonization using an online survey tool, prior to inviting all identified experts to the stakeholder workshop, during which results were discussed in more detail. The results of the expert elicitation as well as the literature review have been used as the prime focal point for discussions during the workshop. In a follow-up step we synthesized the outcomes of the elicitation, literature review and the discussions of the workshop and requested the partaking experts to revise or verify their positions.

Moreover, the Delphi method was also considered suitable as it does not strive for representativity in sampling, but for the highest possible degree of expertise. This feature allows to focus on the quality of an expert group, and not the quantity (Darkow and von der Gracht, 2013). The Delphi method proves to be particularly effective in mitigating (1) group think and (2) the overrepresentation of one specific (dominant) actor.

1.2.2.1 Expert selection

As expert elicitations typically include multiple experts to capture diversity of knowledge, background, and opinion (Colson and Cooke, 2018), we have applied several approaches to identify relevant participants to the workshop:

- **Sourcing from prominent publications:** We have approached lead authors of key industry policy assessment studies and sectoral roadmaps describing decarbonization pathways available to European industry. Based on their publication records or their expertise in developing decarbonization pathways or roadmaps for industry, we have identified relevant modelling frameworks and decarbonization pathway experts.

- **Sourcing from the REINVENT consortium network:** We have utilized the knowledge and established connections from REINVENT consortium partners by querying their networks for relevant expertise. For example, we have queried Prof. Dr. Lars Nilsson (Lund University) for general industry and steel sector experts, Prof. Dr. Ernst Worrell (Utrecht University) for plastics and paper experts and Prof. Dr. Stefan Lechtenböhmer (Wuppertal Institute) for plastic and steel expertise. Via this route, we have identified relevant industry stakeholders with climate and energy portfolios at their companies. Due to the heterogenous nature of industry (usually represented by a large number of various corporate entities) we opted to elicit mainly business associations of the selected industries.

- **Self-selection of experts:** We have applied snowball sampling by inviting selected stakeholders to recommend other important people in the field. Next to boosting the numbers of experts involved, this method also functions as a self-selection mechanism. If relevant actors are pointed out by more individuals, this validates the expert's relevance to the topic.

In total this brought together 22 participants, of which 12 external (with 2 participating via teleconferencing software) and 10 internal to the REINVENT project (See Table 1 for an overview or Annex 2 for names and affiliation).

Table 1 - Distribution of experts and represented climate change mitigations scenarios across industries

	Externals	REINVENT	Model Studies [Models]
Industry expert*1	6	8	31 [12]
Iron & Steel	1	0	22 [6]
Cement	1	0	17 [3]
Chemical industry	1	0	28 [10]
Pulp & paper	1	1	22 [6]
Food	0	1	7 [4]

*1 industry expert refers here to participants with in-depth knowledge on multiple industry sectors and without a specific affiliation to an industry.

1.2.2.2 Elicitation method

As input to the workshop we elicited the present expert opinion on industry decarbonization strategies. The aim of this exercise has been to stocktake the various long-term sectoral perspectives, assumed challenges and possible interlinkages between the manufacturing industries.

To compare results between quantitative roadmaps and the available expert knowledge, we have designed an elicitation protocol that can draw (1) quantitative results and (2) provide directionality of future change in the industry. The survey consisted of 2 sections of questions, asking about (1) expected (general) trends in production volume, energy demand and CO_2 emissions and (2) the considered low-carbon solution strategies in the experts' sector. See Annex 3 for the full set of survey questions.

The survey was performed by using the Qualtrics online software tool, allowing experts to self-complete in their own time. To reduce the time needed the fill in the survey, we predominantly asked for indications of change over time (e.g. relative growth over time, or ranking questions). Although such questions do not allow to provide in-depth detail of the considered decarbonization pathway assumed by the participant, they are preferred over “open questions” as they can be compared to the analysed roadmap studies and other expert responses (standardized output).

To limit non-response, we have allowed experts to self-identify themselves as either a general industry expert or a specific subsector expert. Although the questionnaires are similar for either route, it allowed the participant to indicate whether their answers are more generic (fast route) or specific (more time consuming) to a certain industry, with the option to loop back at the end to re-take the questionnaire for another subsector if needed.

To limit (cognitive) biases (Morgan, 2014), we allowed the participating experts to provide a lower, mean and/or upper limit of their expected value for questions of relative change (% change per year). This allowed to provide a range of possible development, in case no single point estimate could be made. Secondly, we provided a visual aid by including a figure that showed the effects of various values over time (See Annex 3 for the survey outline).

2 Workshop proceedings

2.1 Introduction: General context

In the opening address, several researchers affiliated to the REINVENT consortium introduced the ambitions, on-going research and boundaries of the REINVENT project to all the participants of the workshop. Prof. Dr. Lars Nilsson (Lund University and REINVENT project leader) explained the extended value chain perspective (from primary extraction to end-of life and recycling, transcending the boundaries of one industry or domain) in the REINVENT project. The core objective of the project is to study plausible pathways towards European industry decarbonization by 2050, limiting the scope to the top 5 most energy intensive industries (steel, plastics, pulp & paper, meat and dairy).

In a subsequent presentation, Prof. Dr. Detlef van Vuuren (PBL) elaborated on the science and policy behind the need for industry decarbonisation. To remain in line with the Paris Climate Agreement, the global community requires to limit global warming to well below 2°C to 1.5°C compared to pre-industrial levels. As temperature increase is linearly correlated to total cumulative carbon emissions emitted to the atmosphere, a remaining available global carbon budget to be divided over regions, sectors and time can be determined. Integrated Assessment Modelling studies (as available in e.g. the assessment reports by the United Nations Intergovernmental Panel on Climate Change, see e.g. Clarke et al. (2014); IPCC (2018)) describe possible routes towards meeting the Paris Climate Agreement. Although a variety of pathways exist, the corpus on mitigation pathways generally tends to point towards the use of back-stop technologies as a cost-effective measure to meeting climate goals, such as a large reliance on negative emission technologies or carbon sinks. However, with a large share of residual emissions expected to remain unabated in various sectors, more detailed knowledge on how these can transform or how loops on carbon emissions can be closed is therefore considered relevant in discussions about decarbonization.

This call for more knowledge on remaining carbon emissions was underscored by Dr. Mariësse van Sluisveld (PBL). In her presentation she showed an increasing trend (see Figure 1) for studies on industry decarbonization, with notable examples found in the IPCC special report on meeting the 1.5°C (IPCC, 2018) and the call for input on the upcoming new long term strategy towards 2050 by the European Union (EC, 2018).

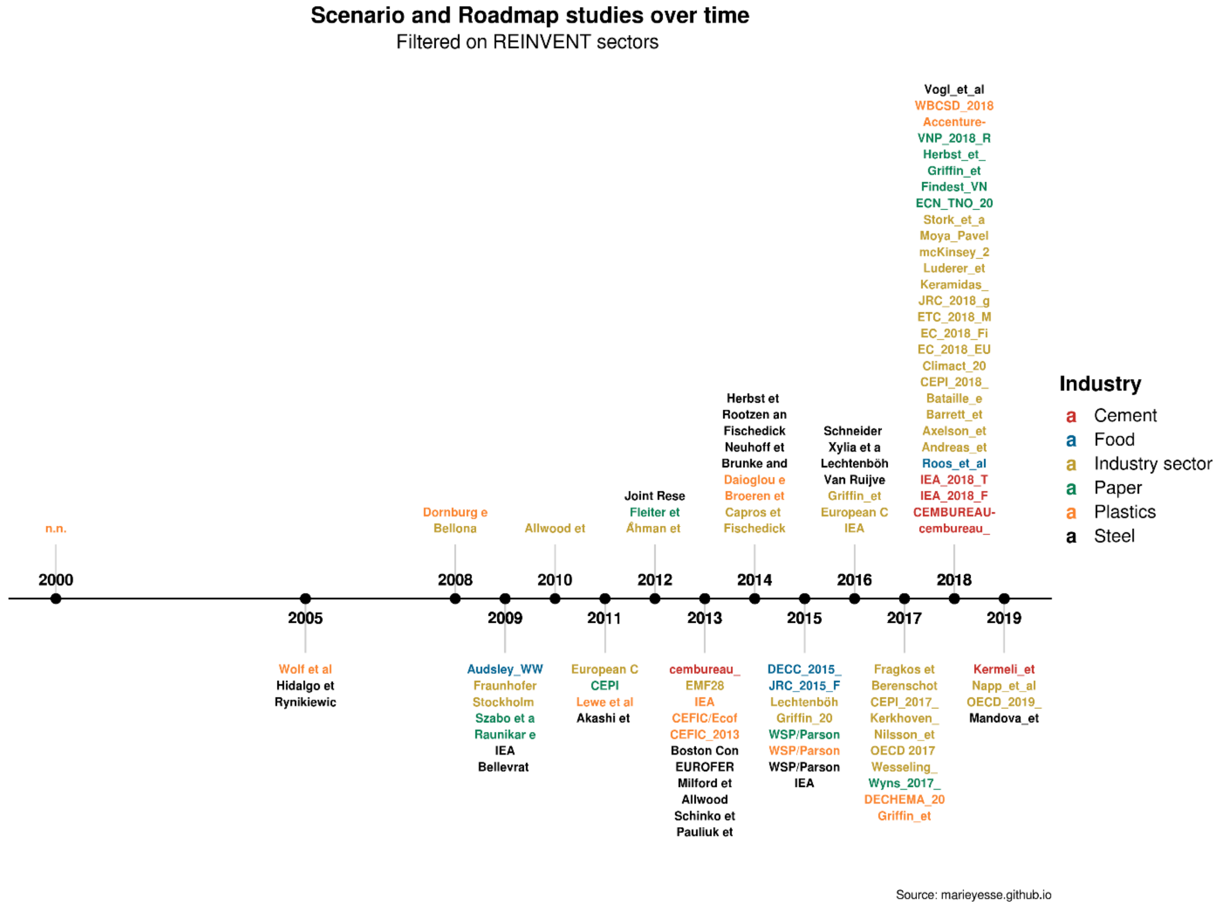


Figure 1 - Overview of industry roadmaps, the sector they are representing and their publication year.

See annex 1, Table 4 for more detailed information about the included studies.

The studies, covering a broad selection of sectoral roadmaps or industry decarbonization pathways, showed different rates of change in terms of their decarbonization (emission reductions compared to 2018) and energy efficiency (final energy demand reductions since 2018) improvement by 2050 (see Figure 2). Although not all studies adhered to the same end-point (synchronising with the EU full economy target, full decarbonization, or in line with the Paris Agreement), some sectors were depicted to reach decarbonization as soon as 2040 (pulp and paper), while the bulk of scenarios depicted emission reductions between 50-100% without clear mitigation profiles that favour a particular route. The result called for gaining broader insights on ´best available knowledge´ on representing industry and industry decarbonization options, but also how such a wealth of scenarios can help support strategic planning towards 2050 in industry.

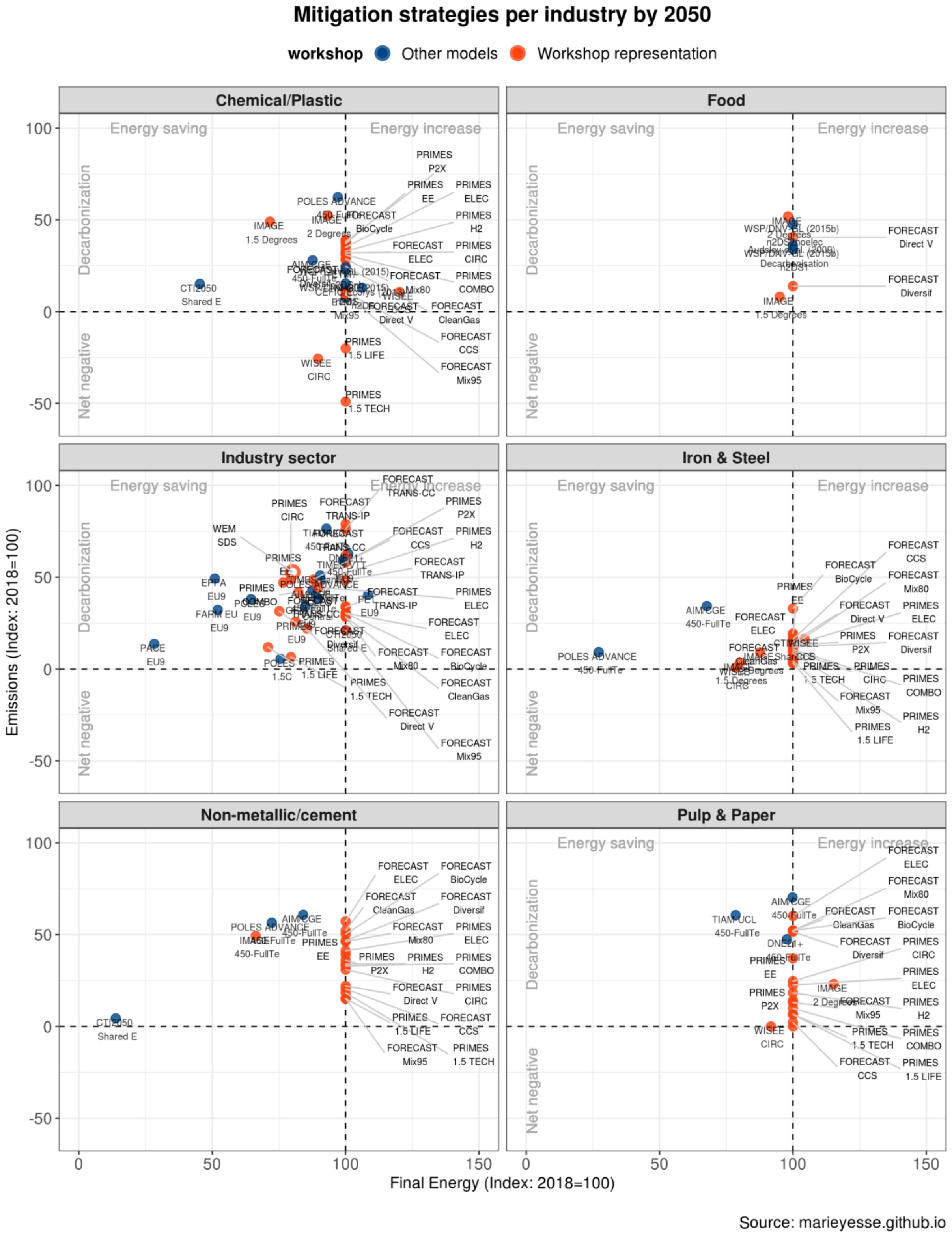


Figure 2 – Change in energy use and emissions per industry sector, 2018-2050

Studies represented at the workshop are shown in red. Two data points go off-screen in the Pulp & Paper sector as a result of biogenic carbon capture and storage. PRIMES and FORECAST studies as reported in EC (2018) and Hartner et al. (2019) did not include information on final energy use with a reference to a start year and have been fixed to 100. The WEM SDS value presents the outcome in the year 2040 (open circle symbol).

2.2 Session 1: Round table discussion on "Key technologies and strategies for a low-carbon EU future, plausible rates of change and missing areas of analysis

In the first session of the workshop, the various representatives behind some of the industry decarbonization studies were invited to the stage to shortly elaborate on their computational model framework to create a level playing field for discussion. The presenters had been instructed to focus on their representation of industry and their identification of decarbonization options. For a summary of session 1, see Section 2.3.

2.2.1 The IMAGE model (global)

Harmen Sytze de Boer (PBL) presented the industry representation in the IMAGE[1] model. The IMAGE model is a global Integrated Assessment Model describing energy demand and supply, with various interactions between society, the biosphere and the climate system. Industry is a submodel of the energy model, covering the key energy-intensive industries such as steel, cement, non-energy, pulp & paper, and food processing. The technology detail varies among industry modules: the steel and cement modules represent explicit current and future production processes while non-energy, pulp & paper and food processing only represent the main energy demands and flows (see Figure 3). Cheaper technologies get a larger share in production capacity mix. Systemic inertia is accounted for via modelling stocks and lifetimes of production technologies.

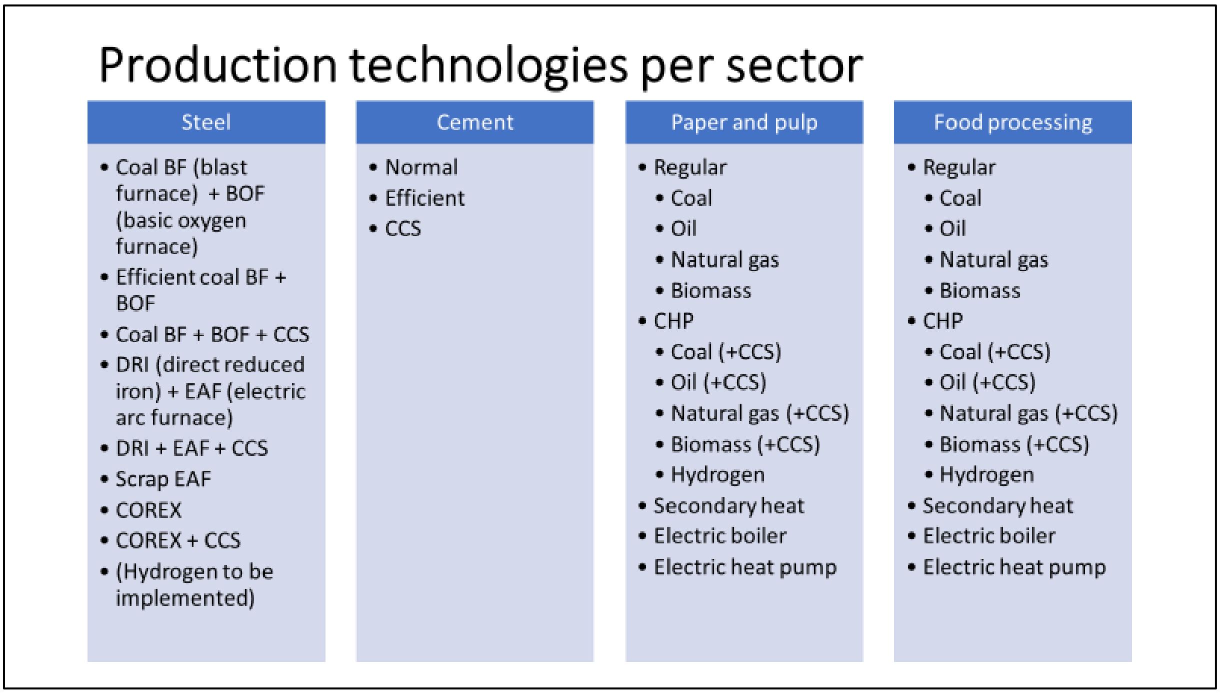


Figure 3 - Overview of the technologies included in the IMAGE model

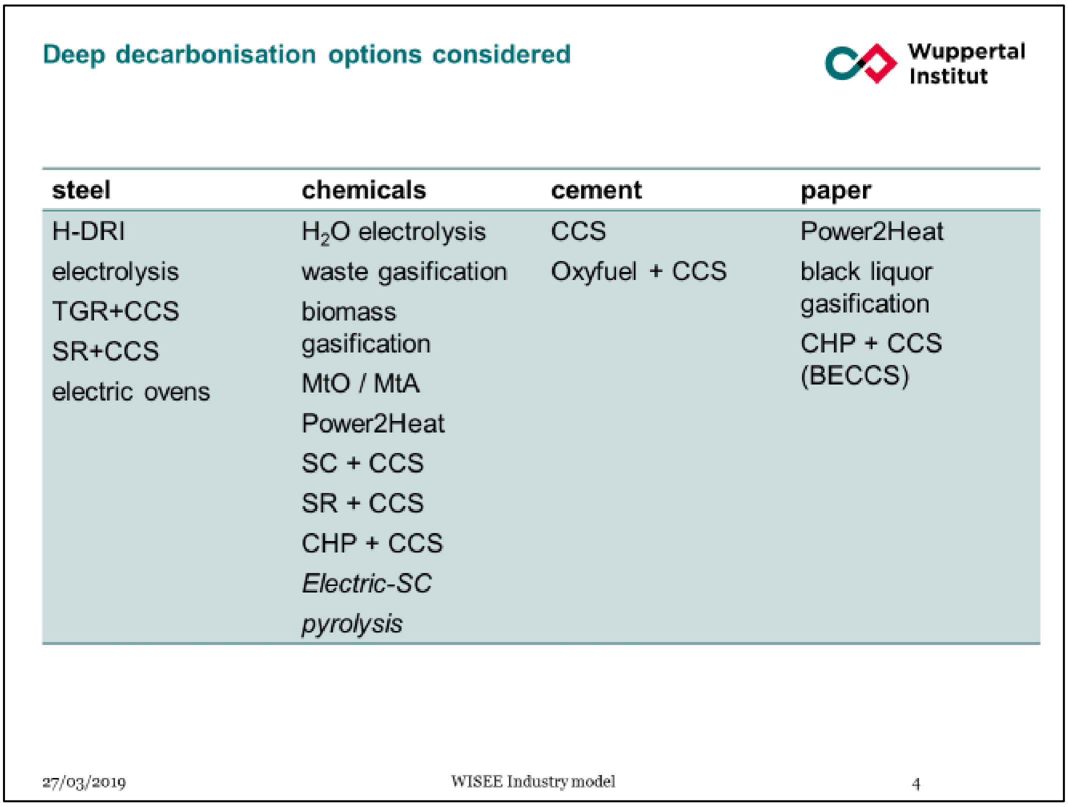
2.2.2 The WISEE model (EU)

Clemens Schneider (Wuppertal Institute) introduced the Wuppertal Institute System model architecture for Energy and Emission scenarios (WISEE). The WISEE model is a bottom-up simulation

[1] http://models.pbl.nl/image

model with detailed representation of energy system technologies but with a low degree of endogenization (scenarios are driven by manual input). The model has a particular high resolution on the German North-Rhine Westfalia area, while covering national perspectives for European Member States on a more aggregated level (Schneider et al., 2014). For industry, the WISEE model covers the value-chains of the iron and steel, (petro)chemical, pulp & paper, cement, non-ferrous, and non-metallic industries, with detailed information on production technologies.

The WISEE model accounts for current day and (low-carbon) breakthrough technologies for industry, encompassing options to enhance energy efficiency, switch to electricity-based technologies, new production methods, fuels and feedstocks and carbon capture and storage (see Figure 4).


Deep decarbonisation options considered

Wuppertal Institut

steel	chemicals	cement	paper
H-DRI	H_2O electrolysis	CCS	Power2Heat
electrolysis	waste gasification	Oxyfuel + CCS	black liquor gasification
TGR+CCS	biomass gasification		CHP + CCS (BECCS)
SR+CCS	MtO / MtA		
electric ovens	Power2Heat		
	SC + CCS		
	SR + CCS		
	CHP + CCS		
	Electric-SC		
	pyrolysis		

27/03/2019 WISEE Industry model 4

Figure 4 - Overview of the technologies included in the WISEE model

2.2.3 The Ensysi model (National)

Dr. Klara Schure (PBL) elaborated on the Dutch Energy System Simulation (Ensysi) model, an energy systems-dynamic simulation model. Despite a Dutch national focus, the Ensysi model encompasses exogenous multi-scale context settings to ensure supply and demand of energy are met throughout the Dutch economy. Cost parameters drive the internal decision mechanisms in the model – though context parameters are included to account for externalities, such as actor decisions, sectoral heterogeneity, technology availability and developments on various scales. The Ensysi model subdivides the industry sector in 8 subsectors, distinguishing mostly between the ETS and non-ETS industries, with the exception for specific metallurgic and chemical industries. The distinction allows for a more in-depth representation of energy demand and uses in industry, such as temperature grades for various manufacturing processes (see Figure 5).

Ensysi incorporates current and more innovative technological options within its decarbonization portfolio, such as more energy efficient capital stock, bio-based alternatives, carbon capture and storage and electrification, which are selected dynamically within the model based on merit. Softer factors, such as policy orientation and public perception, are also accounted for.

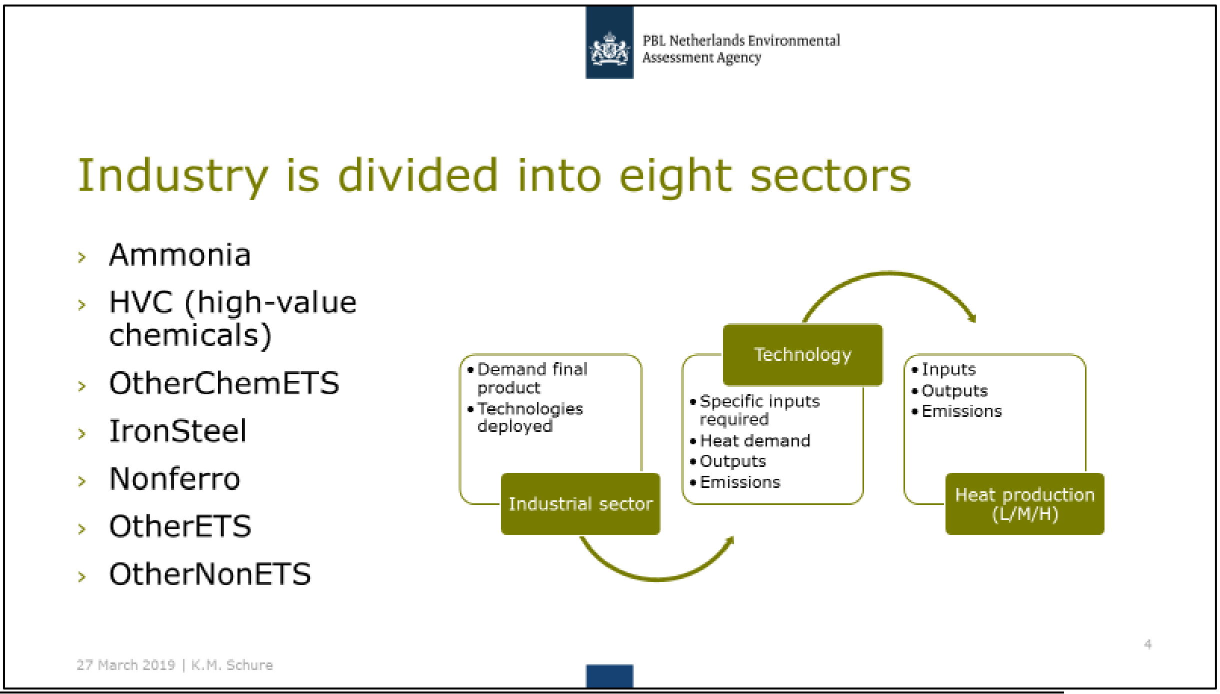


Figure 5 – The sectoral breakdown of industry in the Ensysi model

2.2.4 The FORECAST model (EU)

Dr. Andrea Herbst (Fraunhofer-ISI) presented the FORECAST[2] model via Zoom, during which she elaborated on the scale and level of detail included in the model. FORECAST is a technology-rich bottom-up simulation modelling system, providing information on a EU Member State level. For industry specifically, the FORECAST model includes 5 sub-modules that in total represent the production routes of about 70 represented intermediates (Fleiter et al., 2018). The sub-modules, covering basic materials processes, space heating / cooling, electric motor systems, furnaces, steam and hot water systems, are able to represent industry specific but also common shared technologies and processes. The FORECAST model also pays specific attention to the various temperature grades involved in the many production processes that have been taken into consideration. The level of detail is dependent on data availability, leading to the representation of either process steps (e.g. burning of clinker) to full production lines (e.g. for paper).

Each industry represented in FORECAST represents 70 processes and technologies and 200 mitigation options, which include a broad suite of options (see Figure 6). These options are either currently available or are expected to become available soon (technologies classified with a Technology Readiness Level (TRL) greater than 5). The mitigation options include energy and material efficiency improvements, fuel and feedstock switching, process innovations, both incremental as well as more

[2] https://www.forecast-model.eu/forecast-en/index.php

fundamental new processes and CCS. Diffusion of technologies depends on physical implementation boundaries and the payback time.

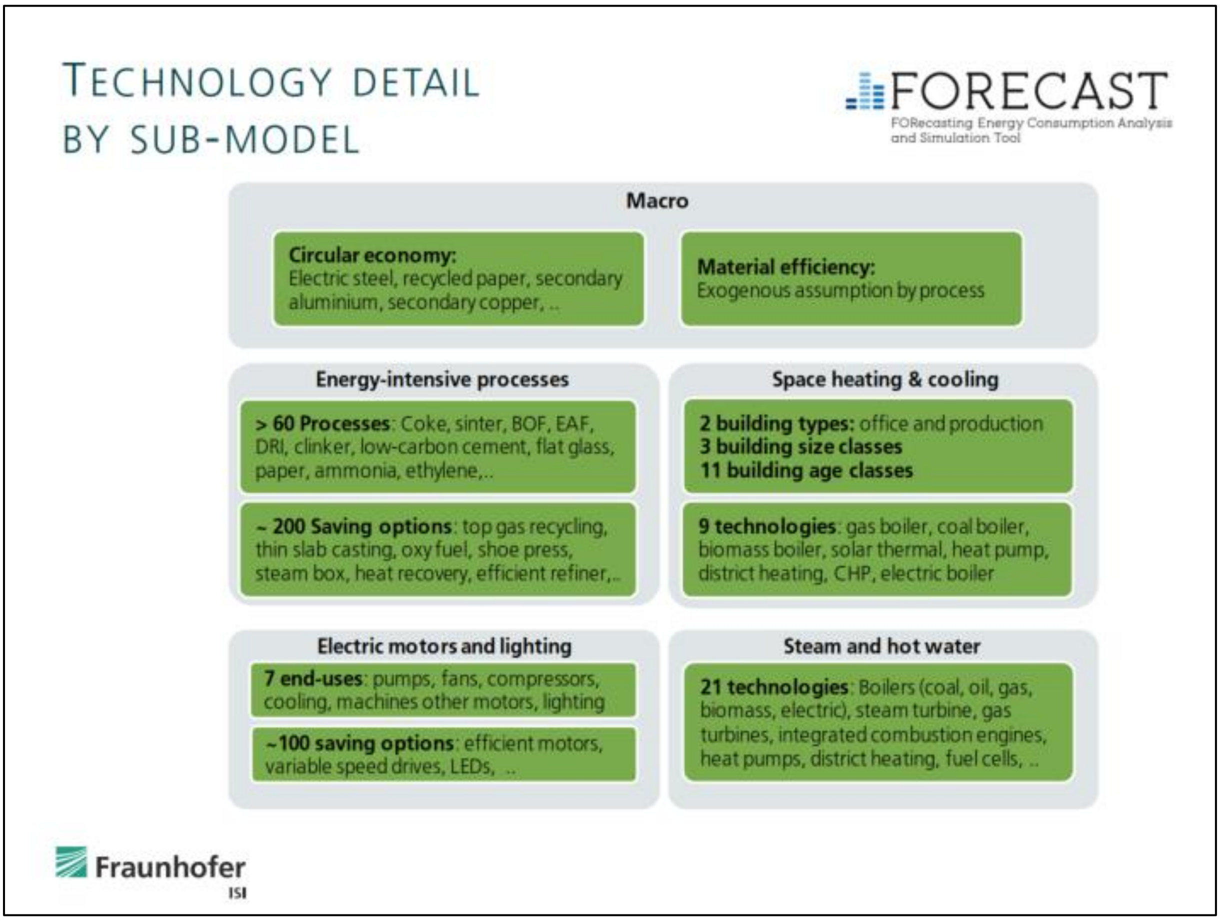


Figure 6 - Overview of the technologies included in the FORECAST model

2.2.5 The PRIMES model (EU)

Dr. Panagiotis Fragkos introduced the PRIMES[3] model to the participants of the workshop. The PRIMES model utilizes a systems-dynamic bottom-up energy system approach, providing depictions of systems change on a country-level resolution for the European Union and neighbouring countries. The industrial model in PRIMES consists of 10 sectors which are split into 31 different sub-sectors (see Figure 7). Each sub-sector includes a series of industrial processes and energy uses that are industry specific and have specific techno-economic assumptions. As a result, the PRIMES model is able to represent more than 200 types of energy process technologies (E3Modelling, 2018), putting special focus on energy-intensive industrial sectors, like iron and steel, non-ferrous metals, paper and pulp, chemicals and cement. Technology development and uptake in the production mix depends highly on costs, including both investment and operation and maintenance costs. Systemic inertia is represented in PRIMES via modelling stocks and lifetimes of production technologies.

The recently enhanced version of PRIMES[4] includes a very detailed industrial model with a high resolution split of industrial consumption by sector and type of industrial process and now includes

[3] http://e3modelling.gr/modelling-tools/primes/

[4] Used in the Impact Assessment of the EC Clean planet for all strategy, https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf

possibility of using hydrogen and synthetic fuels directly, extended possibilities of electrification and the possible emergence of non-fossil hydrocarbon feedstock in the chemicals. The main options to decarbonise industry in the PRIMES model include energy and material efficiency, fuel and feedstock substitution (i.e. electrification, biofuels, hydrogen, clean synthetic gas), circular economy, incremental and radical technology innovations and CC(U)S options.

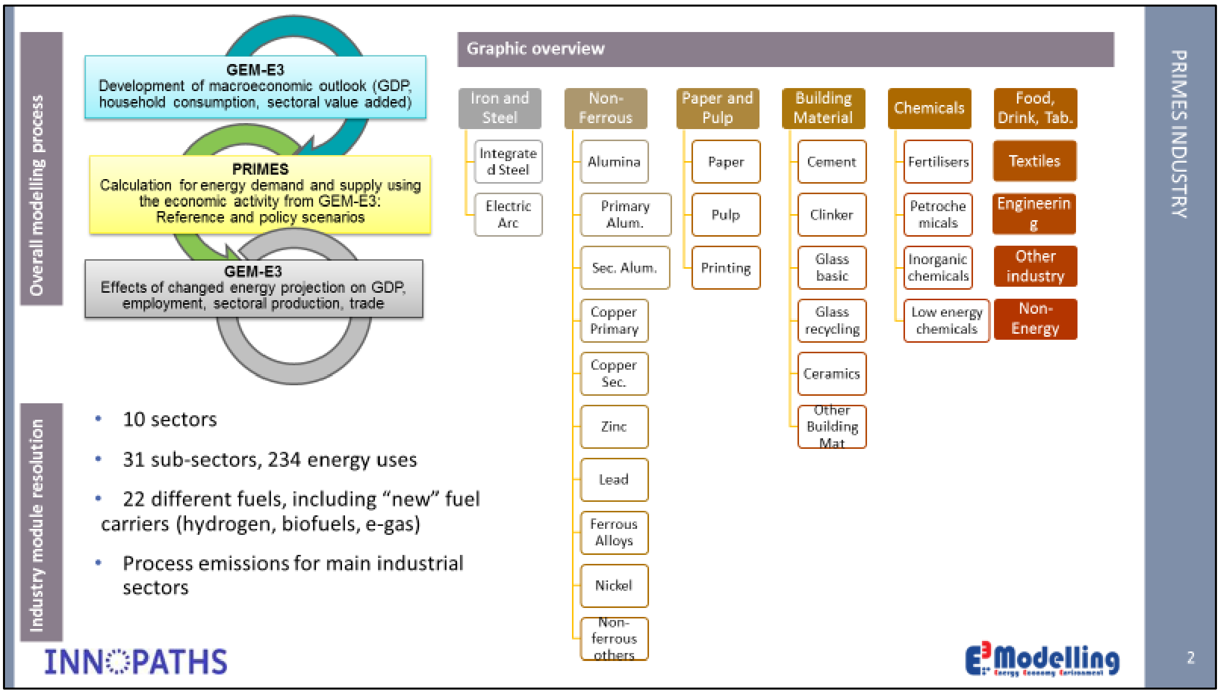


Figure 7 – The production processes and the sectoral breakdown of industry in the PRIMES model

2.2.6 The World Energy Model (Global)

Dr. Andreas Schröder (IEA) introduced the World Energy Model (WEM)[5] to the participants of the workshop. The World Energy Model is a global energy system simulation model, representing detailed sectoral and regional energy demand and supply dynamics. The industry sector representation in the WEM model covers 6 industrial subsectors in detail and a representation of various underlying production processes (see Figure 8). Several industry specific processes are captured within the subsectors, and others encompass more common shared technologies (such as industrial electric motors). For more detailed information on process routes and industry activity levels the WEM model also communicates with the Energy Technologies Policies group at IEA.

The WEM model includes various industry mitigation options. Energy-efficiency takes shape by adopting more energy-saving technologies, for which the choice is determined by the payback period and the penetration potential. Material efficiency is also accounted for through options such as lifetime extension, product design, the use of secondary material use and recycling.

[5] https://www.iea.org/weo/weomodel/

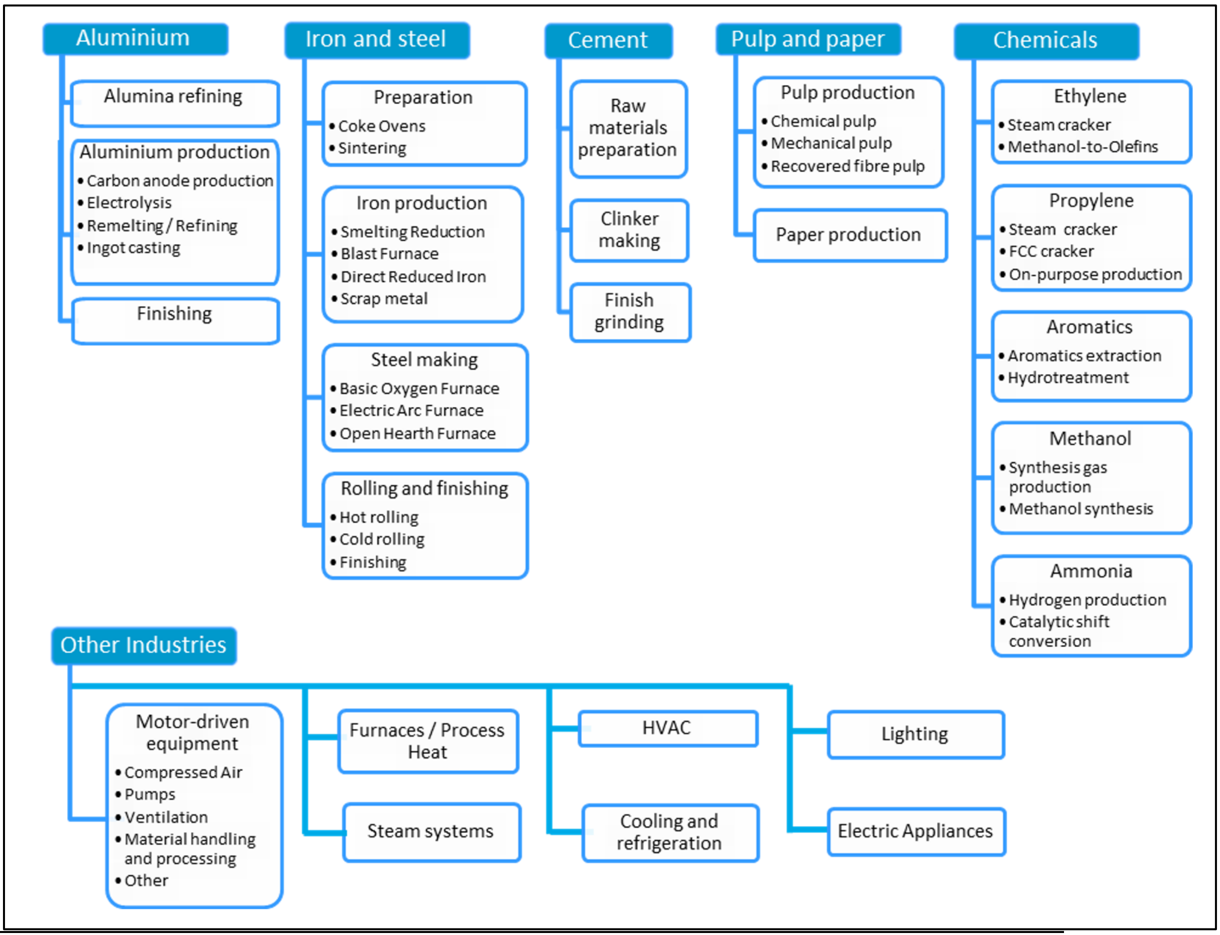


Figure 8 – The sectoral breakdown of industry in the WEM model

2.2.7 The Chemical Industry Transition Tool (National & sectoral)

Michiel Stork (Navigant) introduced the Chemical Industry Transition Tool (CITT)[6] to the workshop participants, used for producing the roadmap for the Dutch chemical industry association (VNCI) (Stork et al., 2018). The CITT model is a detailed chemical industry simulation tool taking all direct and indirect emissions of the Dutch chemical industry into consideration – including the emissions related to the end-of-life of their products. The model can represent various deep decarbonization pathways, used to explore three different extreme pathways (closing loop and biomass, electrification and efficiency, and CCS, see Figure 9 for available measures), and, subsequently, two more balanced combination pathways.

[6] Details on CITT and the assumptions used are reported in the annexes of https://www.vnci.nl/Content/Files/file/Downloads/VNCI_Routekaart-2050.pdf

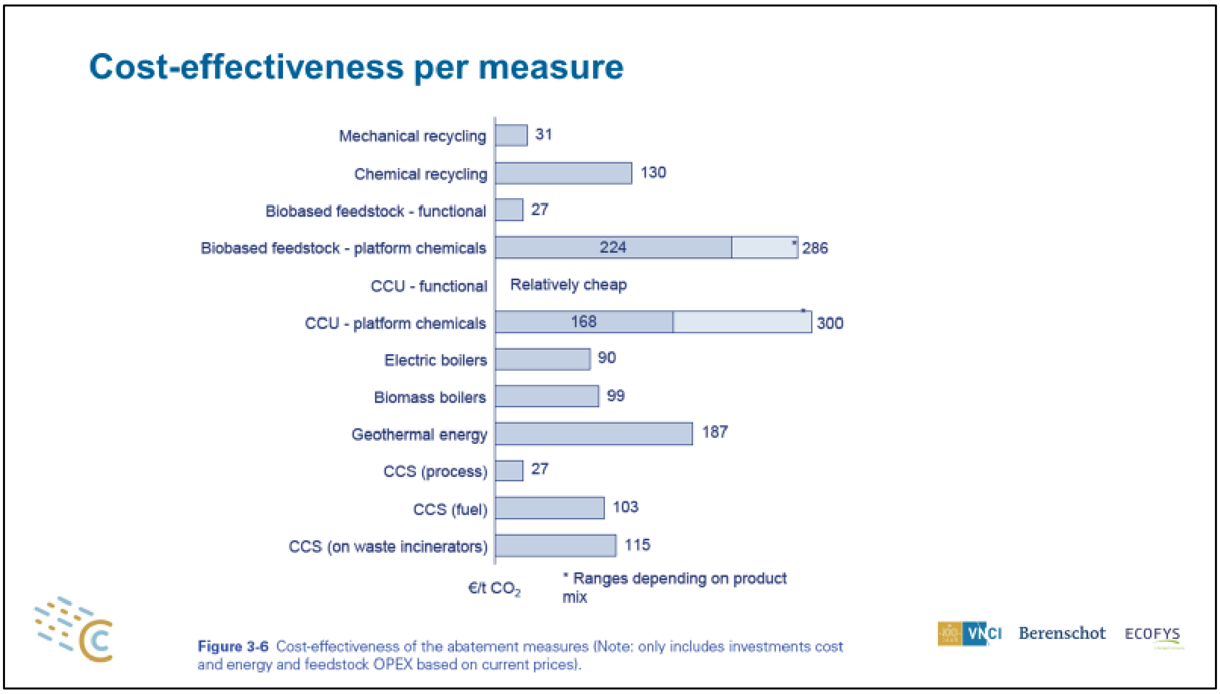


Figure 9 – Overview of decarbonization measures included in the CITT model and their assumed cost-effectiveness

2.2.8 The SmInd Model (National)

Andrej Guminski (FfE) presented the Sector Model for Industry (SmInd) to the participants of the workshop. The SmInd model is a German bottom-up stock-and-flow model, representing 22 industrial processes, which is part of the broader FfE energy system modelling framework. SmInd includes both industry specific as well as cross sectional technologies. As such SmInd can be used to quantify the effect of 105 decarbonization measures in the industry branches food and tobacco, paper, iron and steel, basic chemicals, glass and ceramics, non-metallic minerals and non-ferrous metals, as well as improvements on 30 cross-sectoral technologies (Guminski et al., 2019; Hübner and von Roon, 2019).

The SmInd model takes various decarbonization options into consideration, such as efficiency improvement, fuel switching, electrification CCS/U and process substitution. Deployment of technological change is decided upon the level of included bottom-up detail for each industry (see Figure 10), the process specificity to the industry and the types of (low-carbon) options encompassed in the model.

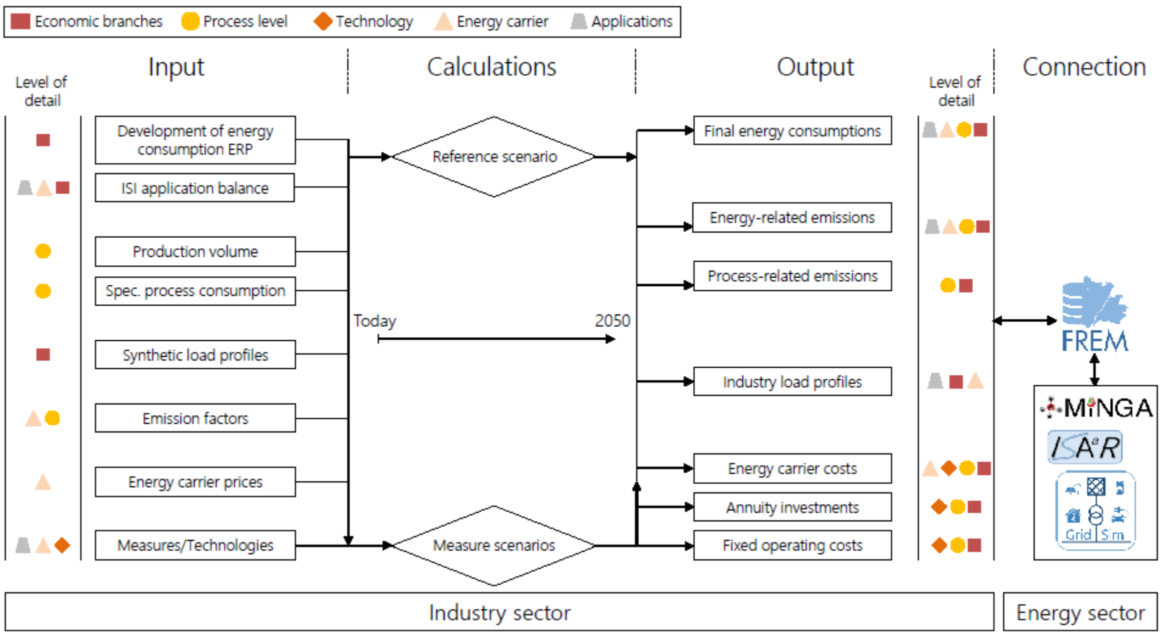


Figure 10 – Overview of the SmInd operational framework (source: Hübner and von Roon (2019))

2.3 Summary to session 1

The workshop underscored the availability of a wide range of computational modelling frameworks in the field of industry decarbonization (see Table 2). Differences occur in terms of solution strategies, spatial and technological representation, number of represented industry sectors, degree of system integration and the level of included detail. Overall, the selected computational models include a more cost-effective and technology-oriented solution structure, broadly covering a similar representation of mitigation strategies albeit at different degrees of representation (See Table 3). Options related to material demand, cross-sectoral linkages and 'green management' are generally less dynamically represented in the modelling frameworks. Linking back to Figure 2, computational modelling frameworks that include a more detailed representation or system coverage do not necessarily translate to representing more decarbonization potential for industry sectors.

Table 2 - Overview of models and their (industry) coverage

	IMAGE	WISEE	Ensysi	FORECAST	PRIMES	WEM	CITT	SmInd
Host institute	PBL	Wuppertal Institute	PBL	Fraunhofer-ISI	E3-Modelling	IEA	Navigant	FfE
Model Focus*1	IAM	ESM	ESM	Industry model	ESM	ESM	Industry model	Industry model
Spatial coverage	Global	EU	National	EU	EU & Member State	Global	National	National
Temporal scale	1971-2100	2015-2050	2010-2050	2008-2050	2010-2070	1971-2040 (2050)	20105-2050	2015-2050
Type *2	Simulation	Simulation	simulation	Simulation	Intertemporal Optimization	Simulation	Simulation	simulation
Foresight *3	Myopic	Myopic	Myopic	Myopic	Perfect Foresight	Myopic	Myopic	Myopic
Industry sectors	6	10	8	9	31	6	1	14
Industrial processes/products	12	100		>70	200			22
Decision making	Techno-economic	Multi-dimensional	Techno-economic	Techno-economic	Techno-economic	Techno-economic	Techno-economic	Techno-economic
Used data sources	Public/ IEA proprietary	Public/Proprietary	Public	Public / Proprietary	Public	IEA internal, proprietary + public	Public / Proprietary	Public

*1 IAM: Integrated Assessment Model (thorough representation of energy-economy-environment linkages), ESM: Energy System Model (thorough representation of energy-economy linkages), and Industry model (thorough representation of one or more industry sector(s))

*2: Simulation stands for computations using modelling output as new input with each timestep until the pre-set number of iterations have been met, (inter)temporal optimization represent a technique that seeks an optimal pathways towards an objective.

*3: Foresight indicates the level of anticipation of the future: Myopic indicates no information on the future and therefore no anticipation, Perfect foresight indicates information on future developments and cordially anticipation

Table 3 - Overview of models and their portfolio of decarbonization options included

Area	Main strategy	Sub-strategy	IMAGE	WISEE	Ensysi	FORECAST	PRIMES	WEM	CITT	SmInd	
											0 = no representation
Energy	Electrical energy efficiency		1	1	1	1	1	1	1	1	1 = Detailed endogenous representation
	Thermal energy efficiency		2	1	1	1	1	1	1	1	2 = Generic endogenous representation
	Fuel substitution	Biofuels	1	1	1	1	1	1	1	1	3 = Ad-hoc / exogenous
		Hydrogen	1	1	1	1	1	1	1	1	
		Other	1	1	1	1	1	1	1	1	
	Electrification	Direct	1	1	1	1	1	1	1	1	
		Indirect *1	0	1	1	1	1	1	1	1	
Process	Low-carbon processes		1	1	1	1	1	1	1	1	
	Feedstock substitution		3	1	1	1	1	1	1	0	
	CC(U)S - process emissions		2	1	1	1	1	0	1	1	
	CC(U)S - energy-related emissions		2	1	1	1	1	1	1	1	
	CC(U)S - waste incineration		0	2	1	0	2	0	1	0	
Material	Material efficient processes		3	3	1	2	1	3	1	0	
	Delayed / life extension		3	3	0	2	1	3	0	0	
	Recycling	Mechanical	2	1	0	1	1	3	1	0	
	Recycling	Chemical	2	1	0	1	1	3	1	0	
	Demand reduction		3	3	3	2	1	3	1	0	
Interrelated	Industrial Symbiosis		2*2	2*2	3	3	3	3	0	0	
Non-technical	Financial decision factors*3		3	3	2	1	2	0	1	1	
	Actor behaviour		3	3	2	1	2	0	0	0	

***1 Indirect electrification implies the generation of fuels that are subsequently used for carbon neutral power or material generation (e.g. Power-to-X)**

***2 Mostly limited to the exchange of Blast Furnace Slag from the Steel to the Cement sector**

***3 e.g. Different Return-on-Investment Rates**

2.4 Session 2: Round table discussion on "Lining up with the EU 2050 long-term strategy ambitions: what long-term (technology) perspectives are considered by industry"

Prior to the workshop all the participants had been invited to provide information on their expectations for future industry developments under stringent climate constraints. Experts had been invited to provide quantitative indication of long-term developments for three key indicators, amongst which are (1) CO_2 emissions, (2) total final energy consumption and (3) production volume. In a subsequent step, the experts were invited to rank a list of pre-defined mitigation strategies in the order of importance over time. The experts could self-identify themselves as an generalist industry expert or a specific subsector expert.

2.4.1 Expert elicitation outcomes

2.4.1.1 EU Industry development perspectives towards 2050

As shown in Figure 11, wide ranges of future developments are taken into consideration among experts and models for all key indicators, regardless of the sector. Remarkable is the general wide range of solutions for CO_2 emissions by 2050, implying that industry decarbonization is not unanimously interpreted as a full sectoral decarbonization (i.e. by representing an alignment to a 80% reduction target for the economy as a whole, thus assuming the availability of offsets elsewhere). For the chemical sector, subsector experts are shown to be more in consensus on required CO_2 emission reductions under stringent climate targets than the other experts or models.

For the other parameters, final energy consumption and production volume, the literature and experts are showing a wide range of possible future development for various industries. Total energy use or production volume can both decline and grow for the depicted industries in Figure 11, although the literature shows a general decline for the iron & steel and cement industry (see Annex 5 for a full picture). The diverging responses are underscoring the different expectations about the availability of low-carbon electricity supply, efficiency improvements and other means of decarbonizing industry as discussed in the next paragraph.

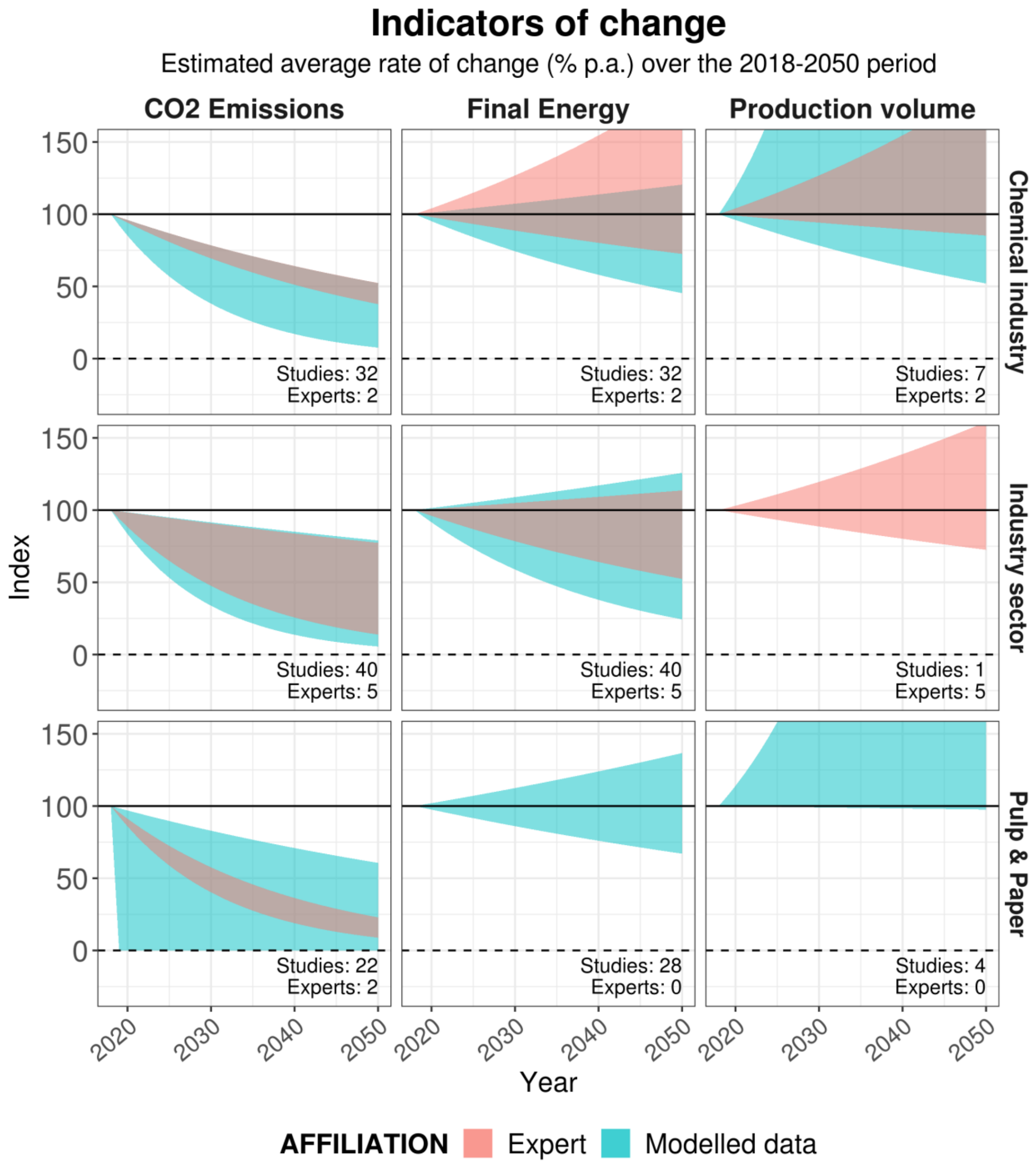


Figure 11 – Changes in emissions, energy and production volume according to experts and models

Average annual rate of change (% p.a.) over the 2018-2050 period by quantitative modelling studies and experts, depicted over a timeline. The pulp & paper expert values are extracted from the NL (VNP, 2018b) and EU (CEPI, 2011) roadmap.

2.4.1.2 Industry decarbonization strategies

For the second part of the expert elicitation the participating experts were asked to rank a pre-defined list of options in the order of their assumed importance over time. As shown in Figure 12, by sorting the list on ranking levels we see that by 2030 both the generic industry as subsector industry experts agree on the important role for (1) material efficiency, (2) thermal efficiency, (3) electrification, (4) fuel substitution and (5) energy efficiency. Other options, such as CCS/CCU, novel low-carbon production processes and industry symbiosis are considered to not play a major role (yet) in industry decarbonization activities by 2030.

By 2050 some of the focus areas shift position and different strategic considerations become apparent among the expert categories. Overall the experts, responding to the survey but also at the venue, agree on the role of (1) electrification and (2) hydrogen as important elements to a decarbonization strategy by 2050. Some deviations in perspective have become visible on the role of CCS/CCU and fuel switching (ranked higher by the chemical industry experts and emphasized during the workshop by the steel industry experts) and novel low-carbon production processes and efficiency measures (ranked higher by the generalist industry experts). "Other" measures are also addressed by the chemical industry experts (see Annex 6 for the comments).

In both periods, industrial symbiosis (industry coupling) is ranked on the lowest level. Despite commented on as an option with potential (see next section), its likelihood of active implementation is questioned.

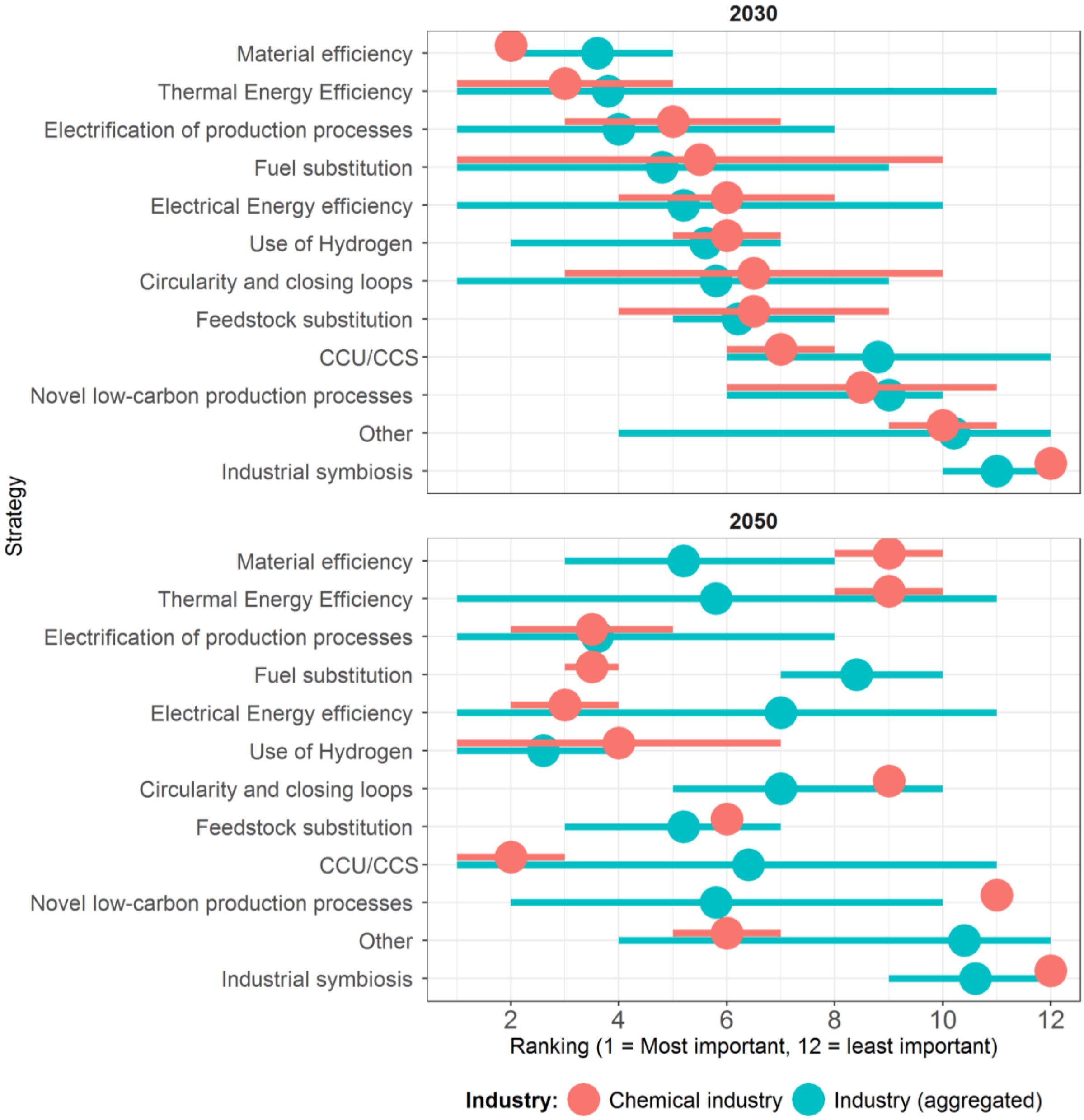


Figure 12 - Depiction of the provided ranking on low-carbon strategies given by each expert over time.

The solid line in the figure represents the full range of covered perspective, while the big dot represents the mean for each strategy and subset of experts. Number of industry experts was 5 and the chemical industry was 2.

2.4.2 Stakeholder discussion

During the second session of the workshop, the industry stakeholders had been invited to elaborate on the perspective of their sector and emphasize the key opportunities and challenges. The session assumed an unstructured dialogue, allowing a conversation to be taken place. Given several common aspects, the dialogues have been grouped in core topics[7]:

Novel low-carbon technologies

Novel disruptive technologies have been mentioned to be already operational in some sectors, but are only available at a small scale. To upscale these technologies it would require major investments in new equipment and infrastructure which is considered a major barrier (doubling to quintupling the total investment costs, resulting in 5-10 times more expensive products thus endangering the competitive advantage on the market) (*chemical, paper industry*). Secondly, promoting the adoption of a technology via subsidies requires the availability of such benefits over longer terms. Although it depends on the total amount of heat or electricity required for the manufacturing process, phasing out a subsidy for e.g. CHP plants may drive factories to not choose CHP again (*paper industry*).

Process integration/industrial symbiosis:

Despite the low assigned importance of industry coupling (industrial symbiosis, see Figure 12) for either time window, an overall interest was expressed for this measure. Sectoral coupling is considered to become more important over time, but current innovations in that direction are still at the development phase and will take several decades to mature (*chemical industry*). Moreover, local conditions will also be considered decisive for the role of industrial symbiosis in industry decarbonization: "*if possible it would have a high priority, but if logistics don't allow it, it would have a low priority*" (*paper industry*). Cement and chemical industries are not commonly grouped together, but often cement and steel plants are in close vicinity to each other (*steel industry)* allowing potential exchange of flows (waste heat, by-products) or business opportunities (e.g. hydrogen plant). Clustering is a natural factor in building factories. So crosslinking is already quite established (*steel industry*). Lack of trust and transparency in a long-term commitment of stakeholders is a recognized barrier, despite successful examples elsewhere (such as in Sweden (Hybrit), Korea and Japan) (*steel industry*). Training people to see opportunities, setting clear goals, having (governmental) support and establishing transparency could help this option forward. Other considered barriers are regulative of nature, as found for e.g. transporting waste flows or by-products beyond country borders (*paper industry*). Renewable energy technology subsidies also prevent the adoption of measures to repurpose e.g. by-product gasses as a source for energy generation (*steel industry*). By removing such barriers, it could facilitate better process integration and advance industry value chains into becoming their more sustainable counterpart.

Industry coupling options that had been mentioned were CO_2 from fermentation; use of process gases, carbon cascading; using more carbon from biomass/waste (e.g. waste-to-chemicals, as demonstrated by Enerkem in Rotterdam); smart use of existing assets (option possibly available to ethanol); using carbon monoxide from cement in the chemical industry (*chemical industry*).

[7] Sector specific comments are indicated with brackets and italicized text.

Potential wild cards

Keeping carbon in the loop is considered important, particularly in the plastics industry, implying an important role for circularity and the circular economy. The aspects of circularity are however not well covered in long-term perspectives until now. Secondly, upgrading (waste) heat and steam are considered the next frontiers of development, with low-hanging fruits in various industries (*chemical industry*). Geothermal energy is considered an interesting alternative heat source, especially in combination with heat pumps (*paper industry*). However, as industrial heat pump development is mostly taking place in Asia, this option is not seen as likely to be implemented in Europe soon.

3 Discussion and conclusions

At this workshop we have brought together various experts in modelling pathways of change for manufacturing industries as well as industry stakeholders with in-depth knowledge on transformative change in their specific fields. The objective of the workshop has been to draw specific knowledge on the state-of-art of planning for decarbonization and likely directions of (1) theoretic and (2) actual change to greening the industry.

Roadmaps are considered useful instruments to structuring complex problems, prioritizing action and reaching consensus for long-term change

Roadmaps have proven to be an important instrument to look at the implementation and the role of technologies, and how stakeholders fit in. It is also a systematic approach to track made progress of defined key indicators (such as emissions, energy, investment, scaling effects). Roadmaps set the context and allow for basic analysis of a transition towards a new end state, consider the barriers and enabling factors. Stakeholder engagement is considered key. However, at the same time, the cross-comparison of the range of available assessment tools also indicated that much of the focus is on technical change and transforming production processes. Downstream processes and socio-material elements are less explicitly captured in the analytical tools used to assess the decarbonisation potential in industry.

A wide variety of industrial change interpretations co-exist due to the heterogeneity of value chains and many uncertainties in anticipated long-term policies, markets, demand developments and commitments

The analysed interpretations of long-term change are versatile, in both models as expert opinions, covering a wide spectrum of future industry developments. This underscored that strategies will depend on local circumstances, such as the availability of carbon free electricity and CO_2 storage options *(steel industry)* and the development of markets, with high growth expected in Asia and the USA (*chemical industry*). The uptake of clean processes and technologies was also mostly assumed to be driven by economic considerations, e.g. fuel substitution, electrification and hydrogen will depend on future commodity prices (*paper industry*). The economic hurdles were considered higher than the technological ones.

Industrial (bulk) processes are relatively well covered in interpretations of future change, although value chains, circularity and options for process integration find more limited representation.

More broader discussion focused on underexplored areas of research, such as more specific plant and value chain investments and linking options. Secondly, social change was mentioned as a more effective option for societal change than technological change within e.g. the steel sector. The sector-specific models were considered to be more suitable to reflect the effects of changing products, demand, and fuel use for specific steps in the value chain. However, it was mentioned during the workshop that it is not a good idea to include full Life Cycle Analysis (LCA) methods in energy models. (Global) integrated assessment models were considered too aggregated to include the level of necessary detail on this level of representation. Subsequently, instead of making models more detailed, it was also mentioned to simplify the applied models as to allow for more easy agreement among stakeholders and association members.

3.1 Future steps

The workshop provided the insight that it is difficult to rank technologies, as perspectives vary from country to country, and across business activities. A regional perspective would require a lengthy discussion with association members in order to come to an agreement on a ranking (*paper industry*) Regardless of this, the result of the ranking exercise was considered interesting, and further development was encouraged in the direction of more specific spatial views and interactions.

Secondly, more in-depth comparison of models and scenarios was recommended between the modellers, to enable mutual learning and shared knowledge creation across the various modelling frameworks. Particularly for underexplored areas of futures research, such as quantifying system effects for up and downstream industry emissions (scope 3), feedstock emissions, demand-side measures and the adoption of CCU in industry.

4 Acknowledgements

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Annex 1: Selected Roadmap studies

Table 4 – Represented studies and their classification in Figure 1

Study title	Year of publication	Prepared by	Focus	Field
Vision 2020 Chemical Industry of The Future Technology Roadmap for Materials	2000	n.n.	Plastics	Other
Technological prospects and CO2Â emission trading analyses in the iron and steel industry: A global model	2005	Hidalgo et al.	Steel	Academic/Research
Techno-economic Feasibility of Large-scale Production of Bio-based Polymers in Europe	2005	Wolf et al.	Plastics	Academic/Research
The climate change challenge and transitions for radical changes in the European steel industry	2005	Rynikiewicz	Steel	Other
Scenario Projections for Future Market Potentials of Biobased Bulk Chemicals	2008	Dornburg et al.	Plastics	(Inter)Governmental
How to Combat Global Warming - An ambitious but necessary approach to reduce greenhouse gas emissions	2008	Bellona	Industry sector	NGO
Energy Technology Transitions for Industry	2009	IEA	Steel	(Inter)Governmental
A world model of the pulp and paper industry: Demand, energy consumption and emission scenarios to 2030	2009	Szabo et al.	Paper	Academic/Research
Global outlook for wood and forests with the bioenergy demand implied by scenarios of the Intergovernmental Panel on Climate Change	2009	Raunikar et al.	Paper	Academic/Research
Introducing carbon constraint in the steel sector: ULCOS scenarios and economic modeling	2009	Bellevrat and Menanteau	Steel	Other
ADAM 2-degree scenario for Europe â€“ policies and impacts	2009	Fraunhofer ISI et al.	Industry sector	Other
Europeâ€™s Share of the Climate Challenge - Domestic Actions and International Obligations to Protect the Planet	2009	Stockholm Environment Institute	Industry sector	Other
Audsley_WWF_2009_How_low_can_we_go_food.pdf	2009	Audsley_WW	Food	NGO
Options for Achieving a 50% Cut in Industrial Carbon Emissions by 2050	2010	Allwood et al.	Industry sector	Academic/Research
The Forest Fibre Industry - 2050 Roadmap to a low-carbon bio-economy	2011	CEPI	Paper	Business & Trade Assocation
A projection for global CO2Â emissions from the industrial sector through 2030 based on activity level and technology changes	2011	Akashi et al.	Steel	Academic/Research
Chemical Manufacturers: The Search for Sustainable Growth	2011	Lewe et al.	Plastics	Consultancy
Energy Roadmap 2050	2011	European Commission	Industry sector	(Inter)Governmental
Prospective Scenarios on Energy Efficiency and CO2 Emissions in the EU Iron & Steel Industry	2012	Joint Research Centre	Steel	(Inter)Governmental
Decarbonising industry in Sweden - an assessment of possibilities and policy needs	2012	AÌŠhman et al.	Industry sector	Academic/Research
Energy efficiency in the German pulp and paper industry e A model-based assessment of saving potentials	2012	Fleiter et al.	Paper	Academic/Research
Steel's contribution to a low-carbon Europe 2050	2013	Boston Consulting Group/VDEh	Steel	Consultancy
A Steel Roadmap for a Low-Carbon Europe 2050	2013	EUROFER	Steel	Business & Trade Assocation

Technology Roadmap - Energy and GHG Reductions in the Chemical Industry via Catalytic Processes	2013	IEA	Plastics	(Inter)Governmental
European chemistry for growth - Unlocking a competitive, low carbon and energy efficient future	2013	CEFIC/Ecofys	Plastics	Business & Trade Assocation
The Roles of Energy and Material Efficiency in Meeting Steel Industry CO2Targets	2013	Milford et al.	Steel	Academic/Research
Transitions to material efficiency in the UK steel economy	2013	Allwood	Steel	(Inter)Governmental
Switching to carbon-free production processes: Implications for carbon leakage and border carbon adjustment	2013	Schinko et al.	Steel	Academic/Research
The Steel Scrap Age	2013	Pauliuk et al.	Steel	Other
The EMF28 Study on Scenarios for Transforming the European Energy System	2013	EMF28	Industry sector	Academic/Research
CEFIC_2013_Energy-Roadmap-The Report-European-chemistry-for-growth.pdf	2013	CEFIC_2013	Plastics	Business & Trade Assocation
cembureau_2013_2050_roadmap_cement_ lowcarboneconomy_2013-09-01.pdf	2013	cembureau_	Cement	Business & Trade Assocation
A plant-specific bottom-up approach for assessing the cost-effective energy conservation potential and its ability to compensate rising energy-related costs in the German iron and steel industry	2014	Brunke and Blesl	Steel	Academic/Research
Forecasting global developments in the basic chemical industry for environmental policy analysis	2014	Broeren et al.	Plastics	Academic/Research
Energy demand and emissions of the non-energy sector	2014	Daioglou et al	Plastics	Other
Carbon Control and Competitiveness Post 2020: The Steel Report	2014	Neuhoff et al.	Steel	Other
Techno-economic evaluation of innovative steel production technologies	2014	Fischedick et al.	Steel	Academic/Research
Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change	2014	Fischedick and Roy	Industry sector	(Inter)Governmental
CO2 emissions abatement in the Nordic carbon-intensive industry - An end-game in sight?	2014	Rootzen and Johnsson	Steel	Academic/Research
Modelling recycling and material efficiency trends in the European steel industry	2014	Herbst et al.	Steel	Academic/Research
European decarbonisation pathways under alternative technological and policy choices: A multi-model analysis	2014	Capros et al.	Industry sector	Academic/Research
Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 - Iron and Steel	2015	WSP/Parsons Brinckerhoff/DNV GL	Steel	(Inter)Governmental
Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 - Chemicals	2015	WSP/Parsons Brinckerhoff/DNV GL	Plastics	(Inter)Governmental
Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 - Pulp and Paper	2015	WSP/Parsons Brinckerhoff/DNV GL	Paper	Other
Energy Technology Perspectives 2015 - Mobilising Innovation to Accelerate Climate Action	2015	IEA	Steel	(Inter)Governmental
Re-Industrialisation and Low-Carbon Economyâ€"Can They Go Together? Results from Stakeholder-Based Scenarios for Energy-Intensive Industries in the German State of **North Rhine Westphalia**	2015	LechtenbÃ¶hmer et al.	Industry sector	Academic/Research
DECC_2015_Food_and_Drink_Report.pdf	2015	DECC_2015_	Food	(Inter)Governmental

Griffin_2015_Radical_change_in_energy_intensive_UK_industry.pdf	2015	Griffin_20	Industry sector	Other
JRC_2015_Food_sector_and_energy3.pdf	2015	JRC_2015_F	Food	(Inter)Governmental
Long-term model-based projections of energy use and CO2emissions from the global steel and cement industries	2016	Van Ruijven et al	Steel	Academic/Research
Decarbonising the energy intensive basic materials industry through electrification - Implications for future EU electricity demand	2016	LechtenbÃ¶hmer et al.	Steel	Academic/Research
Worldwide resource efficient steel production	2016	Xylia et al.	Steel	Academic/Research
Industrial site energy integration â€" the sleeping giant of energy efficiency? Identifying site specific potentials for vertical integrated production at the example of German steel production	2016	Schneider and LechtenbÃ¶hmer	Steel	Academic/Research
Energy Technology Perspectives 2016 â€" Towards Sustainable Urban Energy Systems	2016	IEA	Industry sector	(Inter)Governmental
EU Reference Scenario 2016 - Energy, transport and GHG emissions - Trends to 2050	2016	European Commission	Industry sector	(Inter)Governmental
Griffin_et_al_2016_Industry_.pdf	2016	Griffin_et	Industry sector	Academic/Research
Energy system impacts and policy implications of the European Intended Nationally Determined Contribution and low-carbon pathway to 2050	2017	Fragkos et al.	Industry sector	Academic/Research
Berenschot_2017_Electrification-in-the-Dutch-process-industry-final-report-DEF_LR_nice_Tech_Overview_in_supplinfo.pdf	2017	Berenschot	Industry sector	Consultancy
CEPI_2017_Ivesting_in_Europe_for_industry_transformation_roadmap_2050_v07_printable_version.pdf	2017	CEPI_2017_	Industry sector	Business & Trade Assocation
DECHEMA_2017_Technology_study_Low_carbon_energy_and_feedstock_for_the_European_chemical_industry.pdf	2017	DECHEMA_20	Plastics	Other
Griffin_et_al_2017_Opportunities_for_energy_demand_and_carbon_emissions_reduction_in_the_chemical_sectorn.pdf	2017	Griffin_et	Plastics	Academic/Research
Kerkhoven_et_al_2017_De toekomst van de Nederlandse Energie-intensieve Industrie - Het Verhaal.pdf	2017	Kerkhoven_	Industry sector	Academic/Research
Nilsson_et_al_2017_Industrial_ policy_for_well_below_2_degrees_Celsius-2.pdf	2017	Nilsson_et	Industry sector	Academic/Research
OECD 2017 IEA - Energy Technology Perspectives 2017.pdf	2017	OECD 2017	Industry sector	(Inter)Governmental
Wesseling_et_al_2017_The_transition_of_energy_intensive_processing_industries_towards_deep_decarbonization_characteristics_and_implications_for_future_research.pdf	2017	Wesseling_	Industry sector	Academic/Research
Wyns_2017_A_Mapping_of_EU_industryial_and_onnovation_policy.pdf	2017	Wyns_2017_	Paper	Other
Accenture-2018_Taking_the_EU_chemical_industry_into_the_Circular_economy_CEFIC-Report-Exec-Summary.pdf	2018	Accenture-	Plastics	Business & Trade Assocation
Andreas_et_al_2018_Bellona_Guide_to_decarbonization_Industry-Report-final.pdf	2018	Andreas_et	Industry sector	Academic/Research
Axelson_et_al_2018_Breaking_Through_Industrial_Low-CO2_Technologies_on_the_Horizon_IES_13072018_0.pdf	2018	Axelson_et	Industry sector	Academic/Research
Barrett_et_al_2018_Industrial_energy_materials_and_products_UK_decarbonisation_challenges_and_opportinties_socio-technical_analysis.pdf	2018	Barrett_et	Industry sector	Academic/Research
Bataille_et_al_2018_A_review_of_tech_and_policy_deep_decarbonization_Pathway_options_for_making_energy_intensive_industry_production_consistent_with_the_Paris_Agreement.pdf	2018	Bataille_e	Industry sector	Academic/Research
cembureau_2018_The_Role_of_CEMENT_in_the_2050_low_carbon_economy.pdf	2018	cembureau_	Cement	Business & Trade Assocation
CEMBUREAU-2018_BUILDING-CARBON-NEUTRALITY-IN-EUROPE_WEB_PBP.pdf	2018	CEMBUREAU-	Cement	Business & Trade Assocation

CEPI_2018_Sustainability_report_full_update.pdf	2018	CEPI_2018_	Industry sector	Business & Trade Assocation
Climact_2018_Net-zero-by-2050.pdf	2018	Climact_20	Industry sector	Other
EC_2018_EU_strategic_longterm_vision_roadmap_com_2018_733_analysis_in_support_en_0.pdf	2018	EC_2018_EU	Industry sector	(Inter)Governmental
EC_2018_Final_report_of_the_high_level_Panel_of_EU_decarbonization_pathways_initiative.pdf	2018	EC_2018_Fi	Industry sector	(Inter)Governmental
ECN_TNO_2018_Decarbonising+the+steam+supply+of+the+Dutch+paper+and+board+industry.pdf	2018	ECN_TNO_20	Paper	Consultancy
ETC_2018_Mission_Possible_Reaching_net-zero_carbon_emissions_from_harder-to-abate_sectors_by_mid-century.pdf	2018	ETC_2018_M	Industry sector	Other
Findest_VNP_2018_PPI-Breakthrough-Technology-Roadmap-i.s.m.-Findest.pdf	2018	Findest_VN	Paper	Business & Trade Assocation
Griffin_et_al_2018_Industrial_decarbonisation_of-the_PPI_sector_UK_perspective.pdf	2018	Griffin_et	Paper	Academic/Research
Herbst_et_al_2018_Issue Paper on low-carbon transition of EU industry by 2050.pdf	2018	Herbst_et_	Paper	Academic/Research
IEA_2018_FULL_TechnologyRoadmapLowCarbonTransitionintheCementIndustry.pdf	2018	IEA_2018_F	Cement	(Inter)Governmental
IEA_2018_TechnologyRoadmapLowCarbonTransitionintheCementIndustry.pdf	2018	IEA_2018_T	Cement	(Inter)Governmental
JRC_2018_geco_2018_energy-ghg_balances_20181213.pdf	2018	JRC_2018_g	Industry sector	(Inter)Governmental
Keramidas_et_al_2018_JRC_Global_ENergy_and_Climate_Outlook_2018_Sectoral_mitigation_options_towards_a_Low-emissions_economy.pdf	2018	Keramidas_	Industry sector	Academic/Research
Luderer_et_al_2018_Residual_fossil_CO2_emissions_15-2_pathways2.pdf	2018	Luderer_et	Industry sector	Academic/Research
mcKinsey_2018_Decarbonization-of-industrial-sectors-The-next-frontier.pdf	2018	mcKinsey_2	Industry sector	Consultancy
Moya_Pavel_2018_JRC_Energy_efficiency_and_GHG_emissions_prospective_scenarios_for_PPO.pdf	2018	Moya_Pavel	Industry sector	(Inter)Governmental
Roos_et_al_2018_less_meat_more_legumes_prospects_and_challenges_in_the_transition_toward_sustainable_diets_in_sweden.pdf	2018	Roos_et_al	Food	Academic/Research
Stork_et_al_2018_VNCI_Routekaart-2050.pdf	2018	Stork_et_a	Industry sector	Academic/Research
VNP_2018_Roadmap-VNP-95-procent-CO2-besparing.pdf	2018	VNP_2018_R	Paper	Business & Trade Assocation
Vogl_et_al_2018_Assessment_of_hydrogen_direct_reduction_for_Fossil-free_steelmaking.pdf	2018	Vogl_et_al	Steel	Academic/Research
WBCSD_2018_Chemical_Sector_SDG_Guide.pdf	2018	WBCSD_2018	Plastics	Other
Kermeli_et_al_2019_The_scope_for_better_industry_representation_in_long-term_energy_models_modeling_the_cement_industry.pdf	2019	Kermeli_et	Cement	Academic/Research
Mandova_et_al_2019_Achieving_carbon_neutral_iron_and_steelmaking_in_EU_through_the_deployment_of_bioenergy_with_CCS.pdf	2019	Mandova_et	Steel	Academic/Research
Napp_et_al_2019_role_of_advanced_demand-sector_technologies_and_energy_demand_reduction_in_achieving_ambitious_carbon_budgets.pdf	2019	Napp_et_al	Industry sector	Academic/Research
OECD_2019_Global Material Resources Outlook to 2060.pdf	2019	OECD_2019_	Industry sector	Other

Table 5 – Selected studies for quantitative analysis Future pathways and technological innovation assessments for industry

Industry	Study	Affiliation	Model	Spatial coverage	Focus	Time-frame	# Scen	GHG Target 2050
Industry (Generic)	D4.2, 2018	Research institute/Academia	IMAGE	Global	System	2050	2	1.5°C/ 2°C
	D4.2, 2018	Research institute	WISEE	EU		2050	2	-100%
	(IEA, 2018)	Intergovernmental organization	WEM	Global	System	2040	1	2°C
	EC, 2018	Research institute	FORECAST	EU	System		8	-80-100% / 1.5°C
	EC, 2018	Research institute	PRIMES	EU	System	2050	8	-80-100%/ 1.5°C
	Guminski et al. (2019)	Research institute	SmInd	DU	System	2050	1	- (Max electrification)
Cement sector	(OECD/IEA, 2018)	Intergovernmental organization	ETP	Global	Sectoral	2050	1	2°C
Plastic sector	(Stork et al., 2018)	Consulting firm	CITT	NL	System	2050	3	-95%
Pulp and paper	(VNP, 2018a)	Industry umbrella organization	none	NL	Sectoral	2050	1	-95%

Annex 2: Participants list

Stakeholder	Affiliation
1. Andrea Herbst	Fraunhofer-ISI (via Zoom)
2. Andrej Guminski	FFE (via Zoom)
3. Andreas Schroeder	IEA
4. Tiffany Vass	IEA (via Zoom)
5. Asa Ekdahl	World Steel Association
6. Corneel Lambregts	VNP
7. Jaeyong Choi	World Steel Association
8. Klara Schure	PBL
9. Michiel Stork	Navigant
10. Panagiotis Fragkos	E3 Modelling (via Zoom)
11. Pierre Barthelemy	CEFIC
12. Lars Nilsson	Lund University
13. Ekaterina Chertkovskaya	Lund University
14. Fredric Bauer	Lund University
15. Clemens Schneider	Wuppertal Institute
16. Katharina Knoop	Wuppertal Institute
17. Mathieu Saurat	Wuppertal Institute
18. Andries Hof	PBL
19. Harmen-Sytze de Boer	PBL
20. Detlef van Vuuren	PBL
21. Mariësse van Sluisveld	PBL
22. Bregje van Veelen	Durham University

Annex 3: Expert elicitation outline

Start of Block: Landing page

Intro

"Heavy industry in climate change mitigation scenarios" Wednesday March 27, 2019, The Hague, The Netherlands. Due to the increasing interest in the role and potential of industry in climate change mitigation there is an interest to evaluate the various presented decarbonization strategies for industry. In an unique endeavor we would like to discuss the breadth of perspective for various industry sectors. Prior to the stakeholder workshop, which is to be hosted by PBL Netherlands Environmental Assessment Agency, on Wednesday March 27th in The Hague, The Netherlands, we would like to elicit your expert opinion first on several key parameters of change to decarbonize the industry sector by 2050.

The survey consists of 2 sections of questions, asking about (1) expected (general) trends in production volume, energy demand and CO2 emissions and (2) the considered low-carbon solution strategies in your sector. We ask you to consider 2 scenarios per question:

Scenario name	Scenario description
'Business-as-usual'	Current practices are continued into the future, without concern for additional climate policies
'Decarbonization 2050'	The world is set out to remain aligned to the Paris Climate Agreement, which is represented by a fully decarbonized industry in 2050

The questionnaire will take up to 10-15 minutes to fill in. The results will be presented during the workshop on March 27th, 2019.

Thank you kindly in advance for filling in this questionnaire,

With kind regards, **Dr Mariësse van Sluisveld (PBL) Dr Andries Hof (PBL) Harmen-Sytze de Boer (PBL) Prof Dr Detlef van Vuuren (PBL) Clemens Schneider (Wuppertal Institute) Katharina Knoop (Wuppertal Institute) Prof Dr Stefan Lechtenböhmer (Wuppertal Institute) Prof Dr Lars Nilsson (Lund University)**

The REINVENT project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730053, see https://www.reinvent-project.eu for further information..

Page Break

OPENING **Personal information (for validation)**

Q1
Please indicate your name & affiliation:

- ○ Name (1) ____
- ○ Affiliation (2) ____

Q2
Please indicate which sector you are representing during this survey:
We assume that all answers in the remainder of the survey relate to the option chosen here.

If you are able to represent multiple industry sectors as indicated below, we would like to kindly ask to select one industry now and retake the survey for each other field of expertise (a link back will be provided at the end of the survey).

- ○ Steel industry (1)
- ○ Chemical industry (2)
- ○ Pulp and paper industry (3)
- ○ Cement industry (4)
- ○ Food (processing) industry (5)
- ○ Industry (aggregated) (6)

End of Block: Landing page

Start of Block: Stakeholders

SECTION 1
Inquiring on expected general trends

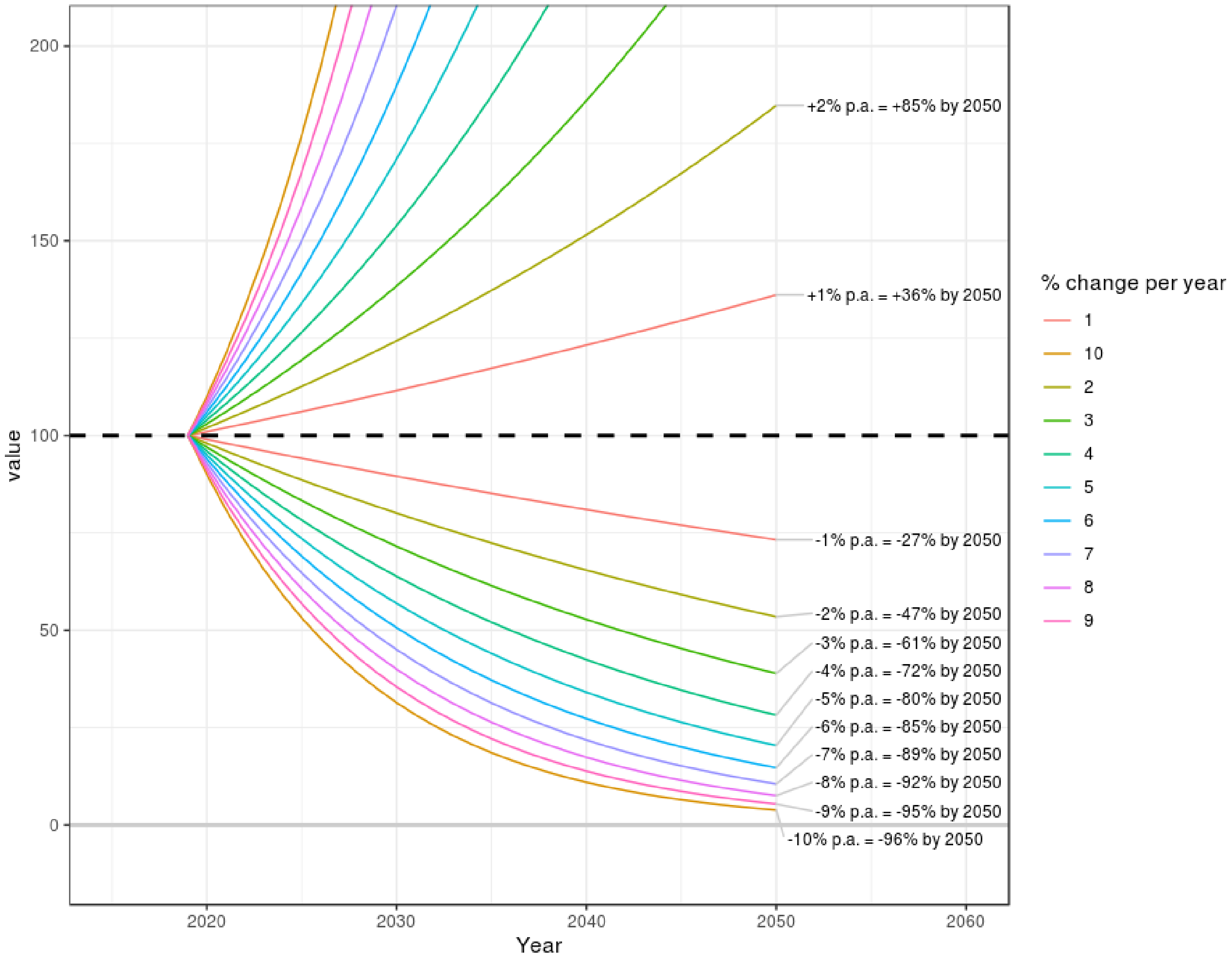
From this point onwards we are going to assume that all answers are provided in a European context, please specify when your estimate differs from this geographical boundary (each question will have a comment box beneath it).

INFO **The figure below shows the effect of different rates of annual change, all compared to 2019 levels.**

As indicated by the figure:

- a 1% annual decline leads to a total reduction of -27% by 2050,

- a 2% annual decline leads to a total reduction of -47% by 2050,
- etc.



Q3
Please indicate the expected rate of change (in average annual change in %) for your sector for the following key indicators over the 2019-2050 period

(if your estimate deviates from EU, please indicate this in the comment box below)

Unit: in average annual change (%).
*A positive value (+) implies a **growth** and a negative value (-) implies **decline**.*

	Production volume			Total Final Energy Consumption			CO2 Emissions		
	MIN (1)	MEAN (2)	MAX (3)	MIN (1)	MEAN (2)	MAX (3)	MIN (1)	MEAN (2)	MAX (3)
Business-as-usual (1)									
Decarbonization 2050 (2)									

(Optional) **Comments: Please elaborate on your answer to help us understand your choices above.**

____

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____

SECTION 2 **Inquiring on overall importance of specific mitigation strategies (covering direct & indirect emissions)**

Q4

Please rank the technology-oriented solutions strategies to their medium-term (2030) **importance under a Decarbonization 2050 scenario for EU (rank 1 = most important, rank = 12 is least important)** *(If your estimate does not apply to an EU perspective, please specify this in the comment box below)*

(drag and drop)

______ **Electrical Energy efficiency** (e.g. retrofitting more efficient technology) (1)
______ **Thermal Energy Efficiency** (e.g. retrofitting more efficient heating technology) (2)
______ **Material efficiency** (Reducing embedded carbon, e.g. via product redesign) (7)
______ **Feedstock substitution** (using alternative raw materials, does not imply use of secondary materials) (3)
______ **Fuel substitution** (using alternative fuels, e.g. switching to natural gas, biomass, etc) (4)
______ **Electrification of production processes** (e.g. power-to-x, electrolysis, heat pumps, etc.) (5)
______ **Use of Hydrogen** (e.g. as fuel and/or feedstock) (12)
______ **CCU/CCS** (6)
______ **Novel low-carbon production processes** (radical change of existing infrastructure) (8)
______ **Circularity and closing loops** (Reducing indirect emissions, via e.g. mechanical and chemical recycling) (9)
______ **Industrial symbiosis** (industry clustering, or utilizing waste flows from one industry as resource in another industry, e.g. bio-refinery, etc.) (10)
______ **Other** (please specify below) (11)

(Optional)

Comments: Please elaborate on your answer to help us understand your choice.

Also use this box to address other technology-oriented mitigation strategies available to your sector that are not listed above.

____

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____

Q5 **Following Q4,** please provide example(s) of which specific technologies and/or developments have been considered for the top 5 medium-term (2030) mitigation strategies for your sector

(If your estimate does not apply to an EU perspective, please specify this in the comment box above)

Examples belonging to the strategy ...

- ◯ Ranked 1st: (1) ____
- ◯ Ranked 2nd: (2) ____
- ◯ Ranked 3rd: (3) ____
- ◯ Ranked 4th: (4) ____
- ◯ Ranked 5th: (5) ____

Q6

Please rank the technology-oriented solutions strategies to their long-term (2050) **importance under a Decarbonization 2050 scenario for EU (rank 1 = most important, rank = 12 is least important)** *(If your estimate does not apply to an EU perspective, please specify this in the comment box below)*

(drag and drop)

______ **Electrical Energy efficiency** (e.g. retrofitting more efficient technology) (1)
______ **Thermal Energy Efficiency** (e.g. retrofitting more efficient heating technology) (2)
______ **Material efficiency** (Reducing embedded carbon, e.g. via product redesign) (7)
______ **Feedstock substitution** (using alternative raw materials, e.g. biomass, does not include use of secondary materials) (3)
______ **Fuel substitution** (using alternative fuels, e.g. switching to natural gas, biomass, etc) (4)
______ **Electrification of production processes** (e.g. power-to-x, electrolysis, heat pumps, etc.) (5)
______ **Use of Hydrogen** (e.g. used as fuel and feedstock) (12)
______ **CCU/CCS** (6)
______ **Novel low-carbon production processes** (radical change of existing structures) (8)
______ **Circularity and closing loops** (Reducing indirect emissions, via e.g. mechanical and chemical recycling) (9)
______ **Industrial symbiosis** (industry clustering, or utilizing waste flows from one industry as resource in another industry, e.g. bio-refinery, etc.) (10)
______ **Other** (please specify below) (11)

(Optional) **Comments: Please elaborate on your answer to help us understand your choice. Also use this box to address other technology-oriented** mitigation strategies available to your sector that are not listed above.

____

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Q7

Following Q6, please provide example(s) of which specific technologies and/or **developments have been considered for the top 5** <u>long-term (2050)</u> mitigation strategies for your sector

(If your estimate does not apply to an EU perspective, please specify this in the comment box above)

Examples belonging to the strategy ...

○ Ranked 1st: (1) ____

○ Ranked 2nd: (2) ____

○ Ranked 3rd: (3) ____

○ Ranked 4th: (4) ____

○ Ranked 5th: (5) ____

Page Break

END **This is the end of the survey, after clicking the next button you will send your answers to Mariësse van Sluisveld [PBL Netherlands Environmental Assessment Agency, mariesse.vansluisveld@pbl.nl], who will analyse the results and present her findings during the stakeholder workshop as planned for Wednesday March 27th.**

Please feel free to include additional details or important elements that are currently not taken into consideration in this survey but are important topics for discussion on the day of the workshop.

(Optional) **Write here about further topics that you think should definitely be addressed while discussing industry transformations under a low-carbon strategy towards 2050:**

____

____

____

____

____

End of Block: Stakeholders

Annex 4: Workshop Agenda

Workshop on ‘Heavy industry in climate change mitigation scenarios’

WED. 27 MARCH 2019

BEZUIDENHOUTSEWEG 30, 2594 AV, DEN HAAG, THE NETHERLANDS

Final agenda

12:00-13:00	**Light lunch served**
13:00-13:05	**Welcome by chair of session & Introduction to REINVENT** *Lars Nilsson – Lund University*
13:05-13:15	**Introduction to climate change mitigation scenarios and the mitigation challenge for ‘hard to abate’ sectors.** *Detlef van Vuuren – PBL Netherlands Environmental Assessment Agency*
13:15-13:30	**Preliminary insights from a comparative analysis & survey on long-term industry decarbonization pathways** *Mariësse van Sluisveld – PBL Netherlands Environmental Assessment Agency*
13:30-15:00	**Session 1: Round table discussion on “Key technologies and strategies for a low-carbon EU future, plausible rates of change and missing areas of analysis”**
13:30-14:30	**Policy and technology assessment tools & methods:** - **IMAGE:** *Harmen Sytze de Boer - PBL Netherlands Environmental Assessment Agency* - **WISEE:** *Clemens Schneider – Wuppertal Institute* - **Ensysi:** *Klara Schure – PBL Netherlands Environmental Assessment Agency* - **FORECAST:** *Andrea Herbst - Fraunhofer ISI* - **PRIMES:** *Panagiotis Fragkos – E3-Modelling (Via Zoom)* - **IEA-WEM:** *Andreas Schröder – International Energy Agency* - **Chemical Industry Transition Tool:** *Michiel Stork – Navigant* - **FFE Industry Model:** *Andrej Guminski – Forschungsstelle für Energiewirtschaft (Zoom)*
14:30-15:00	**Discussion and reflections**
15:00-15:15	**Coffee break**
15:15-17:30	**Session 2: Round table discussion on “Lining up with the EU 2050 long-term strategy ambitions: what long-term (technology) perspectives are considered by industry”**
15:15-17:00	**Participating industries:** - **Steel industry:** *Asa Ekdahl & Jaeyong Choi – World Steel Association* - **Chemical industry:** ▪ *Pierre Barthelemy - European Chemical Industry Council (CEFIC)* - **Pulp & Paper industry:** ▪ *Corneel Lambregts - Royal Association of Dutch Paper and Paperboard (VNP)* - **Cement industry:** ▪ *Tiffany Vass – International Energy Agency (IEA-ETP, via Zoom)*
17:00-17:30	**Discussion and reflections**
17:30-17:45	**Wrap-up by chair**
17:45:18:45	**Networking drinks**

Annex 5: Full overview quantitative metrics on future industry change

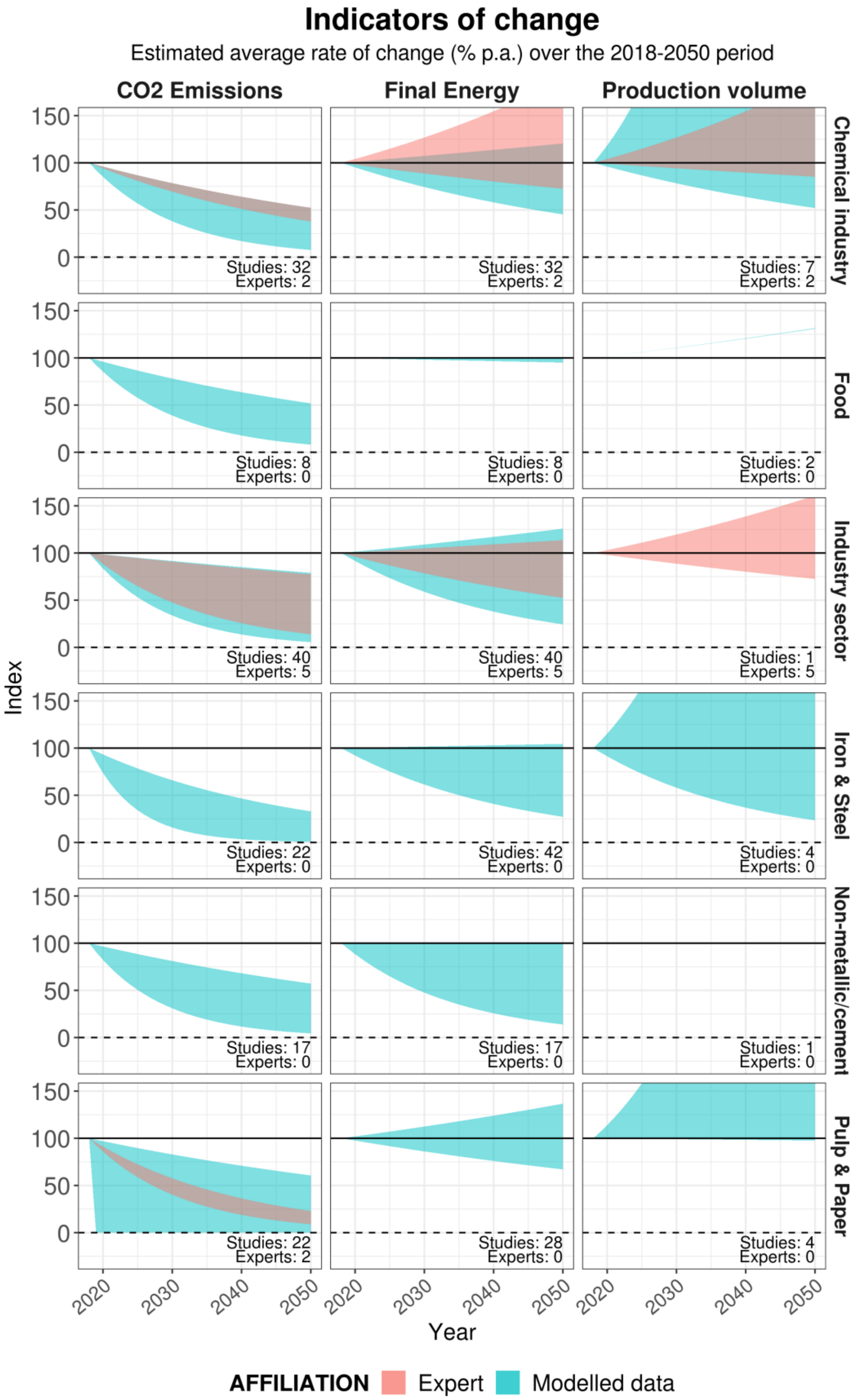

Figure 13 - Full overview of modelled rates of change and estimated rates of change by experts

Annex 6: Expert elicitation open question outcomes

Comments on ranking mitigation strategies towards 2030

Rank	Considered strategy	Expert affiliation
1	switch to natural gas	Chemical industry
	natural gas	Industry (aggregated)
	Increasing waste heat recovery and chp; top-pressure recovery turbines/ top gas recycling in iron and steel	Industry (aggregated)
2	further improvement of process efficiency/steam generation for chem. processes	Chemical industry
	retroffitting	Industry (aggregated)
	Switching to more efficient cement grinding technologies	Industry (aggregated)
3	further improvement of process efficiency	Chemical industry
	Increasing the proportion of waste used for thermal heat in cement sector	Industry (aggregated)
	electrification of industrial proceses	Industry (aggregated)
4	chemical recycling of plastics	Chemical industry
	improved material efficiency via product redesign	Industry (aggregated)
	Extending building lifetimes (particularly commercial buildings) to reduce need for new materials; increased recycling and reuse	Industry (aggregated)
5	chemical recycling of waste	Industry (aggregated)
	increasing use of bio-based feedstock	Chemical industry
	hydrogen use in furnaces	Industry (aggregated)
	Switching to biomass or renewable electricity feedstock in the chemicals sector	Industry (aggregated)

Comments on ranking mitigation strategies towards 2050

Rank	Considered strategy	Expert affiliation
1	widespread use of low carbon hydrogen	Chemical industry
	Increasing waste heat recovery and chp; top-pressure recovery turbines/ top gas recycling in iron and steel	Industry (aggregated)
2	electrification of large scale chemical processes	Chemical industry
	Using alternative binding materials in cement; DRI and HIsarna in iron and steel	Industry (aggregated)
3	CO2 as an alternative feedstock for chemical processes	Chemical industry
	Post-combustion capture in cement; conversion of steel works arising gases to chemicals and fuels	Industry (aggregated)
4	chemical recycling of waste, 2ndary raw materials	Chemical industry
	Use of hydrogen for chemical feedstocks; use of hydrogen to replace coal in iron and steel	Industry (aggregated)

5	Extending building lifetimes (particularly commercial buildings) to reduce need for new materials; increased recycling and reuse; improved building design and construction; reduced metal manufacturing losses	Industry (aggregated)

Final comments

Comment	Expert affiliation
Availability of abundant, affordable and low carbon electricity	Chemical industry
I would like to learn more about material efficiency and see examples at the workshop.	Industry (aggregated)
The short vs long term optimum. How to manage a transition rather than solely focusing on carbon targets...	Chemical industry