

Meta-analysis of industry sector transformation strategies in German, European and global deep decarbonisation scenarios

Sascha Samadi
Wuppertal Institute
Döppersberg 19
DE-42103 Wuppertal
Germany
sascha.samadi@wupperinst.org

Claus Barthel
Wuppertal Institute
Döppersberg 19
DE-42103 Wuppertal
Germany
claus.barthel@wupperinst.org

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Abstract

This paper analyses and compares industry sector transformation strategies as envisioned in recent German, European and global deep decarbonisation scenarios. The first part of the paper identifies and categorises ten key strategies for deep emission reductions in the industry sector. These ten key strategies are energy efficiency, direct electrification, use of climate-neutral hydrogen and/or synthetic fuels, use of biomass, use of CCS, use of CCU, increases in material efficiency, circular economy, material substitution and end-use demand reductions. The second part of the paper presents a meta-analysis of selected scenarios, focusing on the question of which scenario relies to what extent on the respective mitigation strategies. The key findings of the meta-analysis are discussed, with an emphasis on identifying those strategies that are commonly pursued in all or the vast majority of the scenarios and those strategies that are only pursued in a limited number of the scenarios. Possible reasons for differences in the choice of strategies are investigated. The paper concludes by deriving key insights from the analysis, including identifying the main uncertainties that are still apparent with regard to the future steps necessary to achieve deep emission reductions in the industry sector and how future research can address these uncertainties.

Introduction

It is likely that global total net CO₂ emissions will have to reach zero by around the year 2070 if the world is to achieve the Paris Agreement target of limiting the increase in global temperature relative to pre-industrial times to “well below 2 °C”. Limiting the temperature increase to 1.5 °C, which the Paris Agreement calls on nations to pursue, is likely to require global total net CO₂ emissions to reach zero even earlier – by around 2050 (IPCC 2018, p. 119). However, these target years for net-zero emissions are based on scenarios that, for the most part, rely heavily on so-called negative emission technologies in the second part of the century. These technologies include bioenergy use in combination with carbon capture and storage (BECCS) and direct air capture (DAC) of CO₂. There are widespread concerns about the feasibility of the large-scale future use of these types of negative emission technologies (Smith et al. 2016, Vaughan/Gough 2016), leading to the view that in order to have a good chance of achieving the Paris Agreement target range, global net CO₂ emissions will need to be reduced to zero (or close to zero) no later than the middle of the century. Consequently, in December 2019, all but one of the European Union member states endorsed the target of achieving climate neutrality in Europe by 2050, meaning that any GHG emissions will have to be compensated for within Europe by carbon storage options such as BECCS or afforestation.

This target is highly ambitious for all sectors of the economy but several reasons point to it being particularly ambitious for the industry sector. The industry sector includes a number of production processes widely considered to be “hard-to-abate”, mainly due to the occurrence of process emissions (e.g. in primary steel and cement production) and the use of carbon as a feedstock in the chemical industry. Furthermore, many types

of production and processing plants in the industry sector are characterised by long investment cycles, with technical lifetimes of 50 years or more (Rootzén/Johnsson 2013). Achieving climate neutrality by the middle of the century will, therefore, require early investment in new types of low carbon technologies and processes if significant stranded investments are to be avoided in the future. Finally, cost increases typically associated with the use of carbon-neutral technologies and processes cannot usually be recouped by companies, as international competition in the industry sector is high. It is, therefore, challenging for an individual country or even a world region to implement ambitious climate policies in the industry sector while other countries and world regions are not implementing similar policies.

For these reasons, there is an urgency to develop and discuss pathways that describe in technological detail how industry as a whole, or individual industry sectors, can reach climate neutrality by the middle of the century. Indeed, in recent years a large number of studies have focused on the industry sector's role in achieving significant CO₂ emission reductions or climate neutrality (e.g. ETH/EPFL 2018, Material Economics 2019, McKinsey 2018, Agora Energiewende/Wuppertal Institute 2019, Climate Strategies 2019, E3G 2019, High-Level Group on Energy-intensive Industries 2019, IEA 2019).

This paper performs a meta-analysis of industry sector developments in selected global, European and German mid-century mitigation scenarios. The aim of the paper is to provide an overview of the strategies available for achieving deep emission reductions in the industry sector and to identify and discuss key similarities and differences between the scenarios in terms of their choice of mitigation strategies. Based on this analysis, the paper aims to identify the main remaining uncertainties in respect of the steps needed to achieve deep emission reductions in the industry sector and how future research could address these uncertainties.

Identification of key strategies for achieving deep decarbonisation in the industry sector

As Figure 1 illustrates, we identify ten strategies that can make relevant contributions to achieving deep emission reductions in the industry sector in the future. We classify these ten strategies into the following four overarching categories:

- Climate-neutral energy carriers
- Carbon capture
- Reduction in demand for primary materials
- Energy efficiency

We will briefly outline and discuss these strategies, before analysing their respective roles in selected energy scenarios in the following section.

DIRECT ELECTRIFICATION

The direct electrification strategy aims to replace the use of fossil fuels with the direct use of electricity. Provided that the electricity comes from low or zero carbon sources, CO₂ emissions can be significantly reduced or completely avoided. This strategy plays an important role in ambitious mitigation scenarios and is pursued in combination with a significant expansion of low or zero CO₂ electricity generation. In the IEA's B2DS scenario (IEA 2017), for example, the share of electricity in overall final energy demand doubles from 18 % in 2014 to 35 % in 2050. Direct electrification is not only relevant in the transport sector (e-mobility) and in the building sector (e.g. via heat pumps), but also represents significant CO₂ reduction potential in the industry sector (Lechtenböhrer et al. 2016; Schüwer/Schneider 2018). Across all industries, but especially in the chemical industry, the generation of low to high temperature heat can largely be converted to using electricity via so-called power-to-heat systems. Both electric and electrode boilers, as

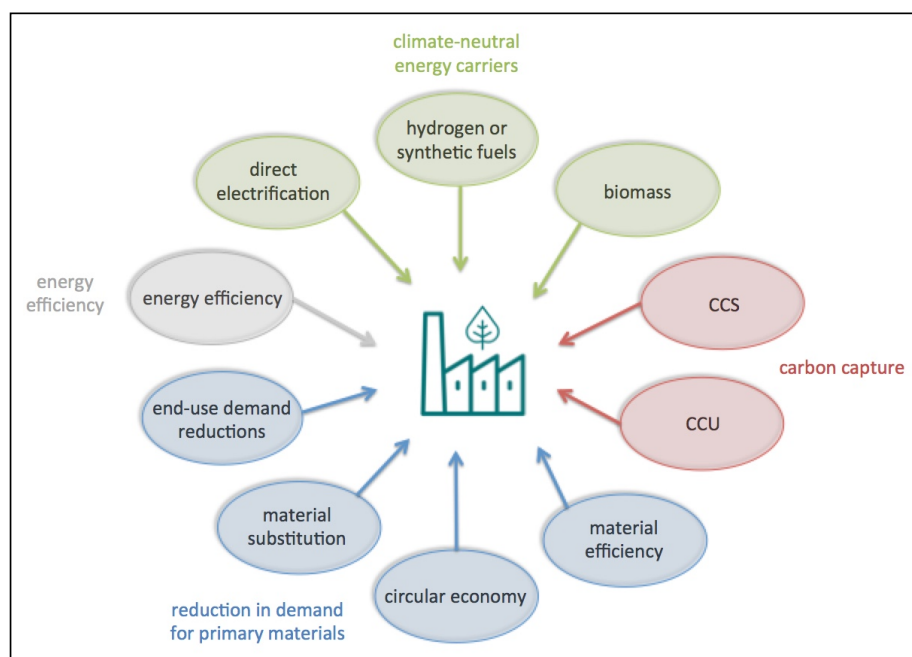


Figure 1. Ten key strategies that can make a significant contribution to achieving climate neutrality in industry.

well as high temperature heat pumps, are suitable for this purpose. Furthermore, plants such as electric steam crackers and electrified calciners can be used to provide electricity-based high temperature heat to produce base chemicals or cement.

HYDROGEN AND/OR SYNTHETIC FUELS

Climate-neutral hydrogen is expected to play an important role in achieving deep emission reductions in the basic materials industry. Hydrogen could be used, for example, in so-called direct reduction plants to achieve climate-neutral primary steel production (Vogl/Åhman/Nilsson 2018). Hydrogen could also be used in large volumes in future in the chemical industry as a feedstock, especially if the emission-intensive production of olefins and aromatics in steam crackers is replaced by alternative processes based on methanol (Agora Energiewende/Wuppertal Institute 2019). The chemical recycling of plastics would also require hydrogen as a feedstock. In addition, climate-neutral synthetic fuels based on hydrogen could play a future role in the industrial sector, either as energy carriers or as feedstock.

BIOMASS

Reductions in CO₂ emissions can also be achieved by replacing fossil energy sources with biomass. Important potential areas of use for biomass in industry are the provision of heat (Jordan et al. 2019) and as feedstock for the basic chemical industry (Fiorentino/Ripa/Ulgiati 2017). Future applications may also include the use of biomass in combination with CCS in industrial plants to achieve negative emissions (BECCS) or the use of relatively small quantities of biomass as a climate-neutral carbon supplier in hydrogen-based steel production. However, it should be noted that in individual regions, as well as globally, the sustainable biomass potential is limited and there is high uncertainty about its available volume (Roth/Riegel/Batteiger 2018).

ENERGY EFFICIENCY

Increasing energy efficiency is an important complementary strategy for deep CO₂ emission reductions in industry. Realising energy efficiency potentials in cross-sectional technologies, such as engines and pumps, as well as in processes specific to individual sectors, can reduce the burden on other mitigations strategies (Boulamanti/Moya 2017). However, it should be noted that although replacing old existing plants can lead to significant efficiency improvements, especially in the basic materials industry, such replacements should only be made if they do not lead to the long-term lock-in of emission-intensive processes.

CCS

The strategy of carbon capture and storage (CCS) refers to the capture and permanent storage of energy or process-related CO₂ emissions. In principle, CCS technology can be used in a variety of industrial plants. However, in terms of economic efficiency, those industrial plants in which relatively large quantities of CO₂ accrue in high concentrations are particularly suitable for the use of CCS. These include ethanol and ammonia production plants, as well as the steam reformers used for natural gas-based hydrogen production (Bains/Psarras/Wilcox 2017). The chemical industry's steam crackers and industrial plants for the production of electricity and heat are also large point sources of CO₂ emissions and could be equipped with

CCS. For all the above-mentioned processes, climate neutral non-CCS alternatives are either available or under development (based, for example, on the use of hydrogen or direct electrification); however, CCS may be indispensable for achieving deep emission reductions in cement production (IEA 2018, Farfan/Fasihi/Breyer 2019).

CCU

In the CO₂ capture and utilisation (CCU) process, CO₂ is separated from industrial processes and used as a raw material in other sectors and products. As with CCS, CO₂ capture is conceivable at large point sources of CO₂ emissions, e.g. in the steel, chemical and cement sectors. Potential CCU applications include synthetic fuels and organic chemistry products (for example plastics and carbon-containing fertilisers), which will continue to depend on carbon even in a climate-neutral world (Farfan/Fasihi/Breyer 2019). Furthermore, as alkaline minerals can absorb CO₂, there may be potential to store significant quantities of CO₂ in a long-lasting product used in construction (RWTH Aachen 2018). By using CO₂ in other products, the need to establish CCS infrastructure (CO₂ pipeline network and CO₂ storage) could be avoided or at least reduced. However, unless the fossil carbon used in new products can be continuously recycled (via chemical recycling, for example) or eventually permanently stored, CO₂ emissions will accrue at the end of the lifetime of the products.

MATERIAL EFFICIENCY

The strategy of increasing material efficiency involves performing the functions that materials serve with less material input. If successful, this strategy can reduce the demand for basic material production. The goal of increased material efficiency can be achieved in different ways:

Avoiding material losses in the manufacturing process

Material losses from the production of basic materials to the finished product are estimated to be about one tenth of all paper, one quarter of all steel and as much as two fifths of all aluminium (Milford et al. 2011). These material losses, which require energy-intensive recycling, could be reduced by various means including adjustments to manufacturing processes and changes in the design of individual components (Milford et al. 2011).

Reducing the material intensity of products

Carruth et al. (2011) show that optimising design and production processes could result in many products being around one third lighter, without sacrificing performance. In the construction sector, many of the required static properties of components could be manufactured using considerably less material input.

Intensifying the use of products

Intensifying product use is about providing the same level of service using fewer products; for example, by designing buildings to save space, making equipment multifunctional or increasing the usage rates of products through shared use (e.g. car sharing). In addition, longer useful lives of products – which could be achieved, for example, by better focus on repairs – could reduce the demand for new goods and, accordingly, the

production volumes and emissions of basic industries (Allwood/Cullen 2012).

CIRCULAR ECONOMY

Steps towards a circular economy, in the sense of reusing to the greatest possible extent materials already produced (and used), could make a considerable contribution to reducing future CO₂ emissions in primary industries. According to an analysis by Material Economics (2018), 75 % of the demand for steel, 50 % of the demand for aluminium and 56 % of the demand for plastics in Europe could be met by recycled materials by 2050. Such closing of material cycles would considerably reduce CO₂ emissions and require significantly less energy than the primary production of basic materials (Damgaard/Larsen/Christensen 2009). However, realising high recycling rates will require product design changes, an adequate disassembly of products at the end of their service life and improved recycling logistics.

MATERIAL SUBSTITUTION

In some areas, substituting materials is a conceivable option for reducing the emission intensity of individual products or services. One example is the use of timber for the partial replacement of concrete and steel in the construction of buildings, leading to lower life cycle emissions (Tetty et al. 2019; Skullestad et al. 2016). Other possible areas of application for material substitution include the use of bio-based natural insulating materials instead of conventional insulating materials and a gradual move towards lightweight construction. There are, however, limits to material substitution, which include restrictions to the availability of sustainable timber/other crops and the inability of lower carbon materials to act as adequate substitutes for some applications.

END-USE DEMAND REDUCTIONS

The demand for industrial products, including for energy-intensive basic materials, could be reduced relative to a business-as-usual scenario through deliberate reductions by end users in their demand for goods and services (Kainuma et al. 2013). The volume of new building construction, for example, could be reduced if people were satisfied with smaller per-capita living space. A decrease in car ownership and distance per person travelled by car could not only reduce steel demand for car manufacturing but could also limit the need for transport infrastructure.

Relevance of each key strategy in selected scenarios

This section analyses and compares the extent to which the emission reduction strategies presented in the previous section are followed in selected climate protection scenarios for Germany, Europe and the world.¹ For each of these three geographical areas, two to three studies were selected and up to two scenarios were analysed from each study. The following four criteria had to be met for a study and scenario to be included in this analysis:

- The study was released in 2017 or later.
- The study's scenarios provide sufficient quantitative detail to analyse the role of specific mitigation strategies in the industry sector.
- The study's scenarios describe developments up to at least the year 2050.
- The scenarios describe ambitious CO₂ emission reductions. This criterion is defined here as at least a 95 % reduction in total CO₂ emissions by 2050 relative to 1990 for Germany and Europe and at least a 50 % reduction in corresponding emissions globally.²

Table 1 shows the seven studies and ten scenarios included in the following meta-analysis, as they fulfil all four criteria. While there may be additional studies and scenarios that fulfil these criteria, the scenarios selected from the well-known studies listed in Table 1 can be considered to constitute a reasonable sample size for the intended analysis.

The seven selected studies and their ten scenarios will be briefly introduced before analysing each scenario's reliance on the differentiated mitigation strategies in the industry sector.

The study "Resource-Efficient Pathways towards Greenhouse-Gas-Neutrality" was developed by the German Environment Agency (Umweltbundesamt, UBA) and published in 2019. It consists of six different scenarios that all describe a reduction in Germany's GHG emissions of at least 95 % by 2050 (relative to 1990), while also attempting to significantly improve resource efficiency. In this meta-analysis we include two of these scenarios: The GreenEe1 scenario, which focuses to a greater degree than the study's other scenarios on technological solutions, and the GreenSupreme scenario, which is the most ambitious of the study's scenarios achieving fast emission reductions by combining technological transformation with lifestyle changes.

The study "dena Study Integrated Energy Transition" was published by the German Energy Agency (Deutsche Energie-Agentur, dena) in 2018 and was developed in cooperation with stakeholders from politics, society and science. It contains four mitigation scenarios, two achieving an 80 % GHG emission reduction by 2050 (relative to 1990) and two achieving a 95 % emission reduction. The two more ambitious scenarios are included in this paper's meta-analysis. They differ mainly in respect to how strongly they pursue the direct electrification strategy, with the EL95 scenario maximising the use of this strategy and the TM95 scenario applying a more balanced combination of mitigation strategies.

"Climate Paths for Germany" was published in early 2018 by the Federation of German Industries (Bundesverband der Deutschen Industrie, BDI). The study contains two mitigation scenarios that aim to show how the German mid-century emission reductions target range in place at that time (80 % to

1. Due to a lack of sufficiently detailed data in the studies, an appropriate comparison of energy efficiency improvements in the scenarios is not possible. Therefore, the meta-analysis only contains nine of the ten strategies differentiated above.

2. For Germany and Europe, a reduction of at least 95 % is targeted here, as both Germany and the majority of EU countries have recently set the target of achieving climate neutrality by the year 2050. Consequently, GHG emission reductions by 2050 should be close to 100 %, with negative emission technologies in Europe or abroad used to compensate for any excess emission levels by 2050. The global target mentioned here is based on findings from the IPCC's Special Report on 1.5 °C warming (IPCC 2018). This report suggests that globally CO₂ emissions will need to be about 50 % lower by 2050 compared to 1990 for it to be likely for global warming to be kept well below 2 °C, the minimum target set by the Paris Agreement.

Table 1. Overview of the seven studies and ten scenarios included in the meta-analysis.

Institution and year of release	Study	Scenarios included in the meta-analysis	Change in GHG or CO ₂ emissions by 2050 (vs. 1990)	
			All sectors	Industry sector
GERMANY				
UBA 2019	Resource-Efficient Pathways towards Greenhouse-Gas-Neutrality	GreenEe1	-96 %	-95 %
		GreenSupreme	-97 %	-97 %
dena 2018	dena Study Integrated Energy Transition	TM95	-95 %	-91 %
		EL95	-95 %	-91 %
BDI 2018	Climate Paths for Germany	95 % path	-95 %	-95 %
EUROPE				
EC 2018	A Clean Planet for all – A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy	1.5TECH	-100 %	-92 %
		1.5LIFE	-100 %	-93 %
ECF 2018	Net-Zero by 2050: From Whether to How	Shared-efforts	-99 %	-92 %
WORLD				
IEA 2017	Energy Technology Perspectives 2017	B2DS	-78 %	-38 %
ETC 2018	Mission possible – Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century	Supply Side	-91 %	-74 %

95 % relative to 1990) can be achieved at relatively low cost. The more ambitious of the two scenarios (the 95 % path) was selected for the meta-analysis.

The study “A Clean Planet for all” was published by the European Commission in 2018. It was undertaken to inform the Commission’s mid-century, long-term low greenhouse gas emissions development strategy; the Paris Agreement invited all parties to draw up and communicate such a strategy by 2020. The study develops eight main mid-century mitigation scenarios, which differ in terms of their key mitigation strategies and their 2050 emission reduction targets. The meta-analysis includes the study’s two most ambitious scenarios, both of which achieve climate-neutrality by 2050. While the 1.5TECH scenario focuses strongly on technological solutions to achieve climate-neutrality, the 1.5LIFE scenario assumes lifestyle changes which allow the intensity of the technological solutions to be eased.

Published in 2018 by the European Climate Foundation (ECF), “Net-Zero by 2050: From Whether to How” used a newly-developed simulation model of European emissions and the mitigation options available now and in the future to derive possible pathways for reaching net-zero GHG emissions. A number of European research institutes and environmental NGOs cooperated to develop more than 10 different scenarios to achieve near-zero emissions. From these scenarios, three typical scenarios were selected and presented in the report and, of these, the “Shared-efforts” scenario is the best documented and is, therefore, included in the meta-analysis.

The study “Energy Technology Perspectives 2017” was published in 2017 by the International Energy Agency (IEA). In the same way as previous publications in this series, the study focuses on the technological transformation required in the energy system in the coming decades to meet global climate targets. One of the two scenarios (2DS) aims to limit the rise in global temperature to below 2 °C, while the more ambitious scenario (B2DS) aims to meet the “well below 2 °C” target of the Paris Agreement. The latter, more ambitious scenario is included in the meta-analysis.

Finally, “Mission possible – Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century” was published in 2018 by the Energy Transitions Commission, which consists of energy producers, energy users, equipment suppliers, investors, non-profit organisations and academics from the developed and developing world. The study explores ways of achieving net-zero CO₂ emissions globally by 2060 and puts a special focus on the so-called harder-to-abate sectors, including the heavy industry sectors of cement, steel and chemicals. The study describes two illustrative pathways. Of these two pathways, the Supply Side decarbonisation pathway is much better documented in the study and is, therefore, included in the meta-analysis.

It should be noted that the exact definition of the industry sector and its final energy demand differ to some extent between the analysed scenarios. However, these differences are not considered to alter the key results of the meta-analysis.

CLIMATE-NEUTRAL ENERGY CARRIERS

Direct electrification

Direct electrification in the industry sector is a key mitigation strategy in many of the analysed scenarios (see Table 2). The share of electricity in final energy demand increases considerably in most of the analysed scenarios, with all but three reaching electricity shares of between 39 % and 69 % by 2050. The increase is only more moderate in the IEA’s B2DS scenario and the two German scenarios, TM95 and 95 % path. There could be two reasons why some German scenarios foresee only a moderate increase in the role of electricity in the industry sector’s final energy demand. Firstly, electricity prices could be expected to remain relatively high in Germany in the future compared to many other regions of the world, partly as a result of limited potential for cost-efficient wind and solar power generation (McKinsey 2018, Fasihi/Breyer 2020). Secondly, in Germany at present a relatively high share of industrial production is in the basic materials industry and direct electrification is generally more difficult to achieve in this sector than in other sectors.

Table 2. Role of climate-neutral energy carriers in the industry sector's final energy demand in 2050.

Scenario	Share of electricity		Share of hydrogen and synthetic fuels		Share of biomass	
	Base year	2050	Base year	2050	Base year	2050
GERMANY						
GreenEe1	31 %	39 %	0 %	58 %	4 %	4 %
GreenSupreme	31 %	39 %	0 %	58 %	4 %	3 %
TM95	35 %	36 %	0 %	49 %	3 %	4 %
EL95	35 %	69 %	0 %	20 %	3 %	3 %
95 % path	32 %	34 %	0 %	0 %	4 %	34 %
EUROPE						
1.5TECH	31 %	55 %	0 %	19 %	9 %	16 %
1.5LIFE	31 %	51 %	0 %	20 %	9 %	18 %
Shared-efforts	31 %	54 %	0 %	11 %	12 %	22 %
WORLD						
B2DS	23 %	29 %	0 %	n.s. (small)	6 %	11 %
Supply Side	23 %	57 %	0 %	23 %	6 %	6 %

The EL95 scenario is a notable exception in the German scenarios when it comes to direct electrification and is also the scenario with by far the highest share of electricity in final energy demand by 2050 (69 %). This scenario explicitly explores how much the direct electrification strategy could contribute to substituting fossil fuel energy carriers in all sectors of the economy.³ In this scenario, industrial heat demand is assumed to be met increasingly through power-to-heat applications. The production of ethylene is gradually converted to the electricity-intensive methanol-to-olefins (MTO) production route, with the hydrogen produced in an interim step not counted as a final energy source but as a feedstock. Another reason for the strong growth in electricity demand is the assumed switch in primary steel production towards hydrogen-based direct reduction plants. While the considerable indirect electricity demand for hydrogen production is not included in industry's final energy demand, the direct reduction route also requires the use of electric arc furnaces, increasing the need for electricity in primary steel production compared to today's dominant blast furnace route. Finally, the assumed application of CCS by 2050 in several industrial plants also leads to additional electricity demand.

Hydrogen and/or synthetic fuels

Carbon-neutral hydrogen and synthetic fuels are used to a considerable extent by 2050 in most of the analysed scenarios. Their combined share in industry's final energy demand typically increases from 0 % in the respective base years to between 11 % and 58 % in 2050. Only the 95 % path and the 2BDS scenario do not rely to any significant extent on hydrogen and/or synthetic fuels to meet final energy demand in the industry sector by 2050.

The scenarios assume that by 2050 most of – or all – the hydrogen and synthetic fuels are derived from renewable-based electricity. In the German scenarios EL95 and TM95, most of the hydrogen and synthetic fuels will be imported by 2050, while the low overall energy demand in the GreenSupreme sce-

nario allows the hydrogen and synthetic fuel demand to be met from domestic renewable electricity generation. The breakdown between hydrogen and synthetic fuels also differs considerably between the scenarios. While the Supply Side scenario relies exclusively on hydrogen, in the scenarios GreenEe1, GreenSupreme, TM95, EL95, 1.5TECH and 1.5LIFE, synthetic methane is a more important energy source than hydrogen. These differences suggest that there is not yet a consensus among energy scenario developers about the relative merits of hydrogen and synthetic fuels, and the future role that each could play.

Biomass

Increasing the use of biomass is also a prominent strategy in the industry sector in many of the analysed scenarios. The share of biomass in industry's final energy demand increases in most European and global scenarios, roughly doubling between the respective base years and 2050. The ETC's "Supply Side" scenario is the only exception, exhibiting the same share in 2050 as in 2014. The German scenarios differ from most European and global scenarios when it comes to the future role of biomass. In all but one of the German scenarios, the biomass share remains roughly constant. However, the share increases considerably in the "95 % path", from 4 % in 2015 to 34 % in 2050, significantly higher than in any of the European and global scenarios.

There are at least two reasons for the different views on the future role of biomass in the industry sector. Firstly, views generally differ about the amount of sustainably sourced biomass that can be made available for energetic use, both currently and in the future. The BDI (2018) study assumes that an increase (albeit a moderate one) in biomass use compared to the base year is feasible in Germany until 2050, while the UBA (2019) study argues that the cultivation of biomass for energetic purposes should be phased out due to high land requirements and negative ecological consequences. Consequently, in the scenarios analysed in this study, considerably less biomass is available for energetic purposes in 2050 compared to today.

Secondly, there is no broad consensus on where the limited bioenergy potential should be used in the future. In the 95 % path scenario from the BDI (2018) study, almost 60 % of the assumed 2050 bioenergy potential is used in the industry sec-

3. It should be noted that the authors of the scenario study conclude that adopting such a strong direct electrification strategy is not cost-optimal compared to a more balanced choice of mitigation strategies.

Table 3. Role of carbon capture and storage and carbon capture and use in the industry sector in 2050.

Scenario	CO ₂ captured and stored in 2050 relative to base year emissions of industry	CO ₂ captured and used in 2050 relative to base year emissions of industry
GERMANY		
GreenEe1	0 %	0 %
GreenSupreme	0 %	0 %
TM95	9 %	3 %
EL95	9 %	3 %
95 % path	49 %	0 %
EUROPE		
1.5TECH	35 %	11 %
1.5LIFE	9 %	9 %
Shared-efforts	8 %	0 %
WORLD		
B2DS	41 %	0 %
Supply Side	52 %	12 %

tor, based on the argument that solid biomass can be used with low energy losses for low and medium-temperature heat production. Furthermore, in the same scenario, burning biomass in large-scale industrial plants enables the CO₂ to be used as a renewable carbon source to produce power-to-gas. Other scenarios, such as the EL95 scenario, see the need for an increased use of bioenergy in the transport and buildings sectors, with more limited amounts of bioenergy used in the industry sector.

CARBON CAPTURE

CCS

Carbon capture and storage (CCS) is used as a mitigation strategy in the industry sector in all but two of the analysed scenarios (see Table 3). However, the extent to which CCS is relied upon to reduce industry sector CO₂ emissions (energy-related as well as process-related) differs considerably between the scenarios. In some of the scenarios, an amount equalling 8 % or 9 % of base year industry sector CO₂ emissions are captured and sequestered in 2050. However, four of the scenarios foresee much higher shares: the German 95 % path (49 %), the European 1.5TECH (35 %) and both global scenarios, B2DS and Supply Side (41 % and 52 % respectively). In these scenarios, the use of CCS represents a particularly important strategy. Industrial plants typically assumed to be equipped with CCS technology in these scenarios are blast furnaces, cement kilns and steam reforming plants.

Of all the scenarios, only two German scenarios by the German Environmental Protection Agency (UBA 2019) do not assume that CCS will be used in the future, citing associated environmental risks and a lack of social acceptance for the use of this technology. These two scenarios put a much stronger emphasis than other scenarios on strategies that aim to reduce the need for primary materials. They also assume the significant use of hydrogen and hydrogen-derived synthetic fuels by 2050.

CCU

Many of the analysed scenarios do not provide information about carbon capture and use (CCU). It is, therefore, assumed that CCU is not incorporated into these scenarios, at least not

to a significant extent. The scenarios with no use, or only a negligible use, of CCU are the German scenarios GreenEe1, GreenSupreme and 95 % path, the European scenario Shared-efforts and the global scenario B2DS. In the German scenarios TM95 and EL95 it is assumed that 5 Mt of captured CO₂ (equal to 3 % of the industry sector's CO₂ emissions in the base year) will be used by 2050. However, the study does not provide details on the exact CCU applications. The European scenarios 1.5TECH and 1.5LIFE rely more heavily on the CCU strategy, using 11 % and 9 % of industry sector baseline CO₂ emissions by 2050 respectively. The CO₂ captured from industrial sources is used mostly for the production of synthetic materials in these two scenarios; mainly plastics but also building materials.⁴ The Supply Side scenario does not provide an exact figure for the use of CCU in 2050, but suggests that about 1.5 Gt CO₂ could be used annually by 2050, arguing that opportunities are greatest in concrete production where absorbing CO₂ can improve product quality. None of the scenarios provide details on the exact nature of the CCU technologies they anticipate using or on the long-term net CO₂ reduction potential of their CCU applications.

REDUCTION IN DEMAND FOR PRIMARY MATERIALS

Table 4 illustrates that strategies to reduce the demand for primary materials are pursued to quite different extents in the analysed scenarios. Two German scenarios (GreenEe1 and GreenSupreme) and two European scenarios (1.5LIFE and Shared-efforts) rely on all of the four sub-strategies to reduce demand for primary materials. The respective storylines of these four scenarios specifically focus on, or include, societal and lifestyle changes towards greater sustainability. Consequently, it is assumed in these scenarios that people will not only accept changes in product design but will also agree to end-use demand reductions in the form of lower consumption

4. In both scenarios, more CO₂ is used to produce synthetic fuels than to produce synthetic materials. However, CO₂ for the production of synthetic fuels is assumed to be obtained largely through direct air capture.

Table 4. Overview of measures enacted in the scenarios to reduce demand for primary materials.

Scenario	
GERMANY	
GreenEe1	<ul style="list-style-type: none"> • <i>Material efficiency</i>: Greater increase in material efficiency than in the past (up to 1.1 %/a), by actions such as reducing losses in manufacturing. • <i>Circular economy</i>: Significant increase in recycling rates (e.g. by 2050, 67 % of steel production is sourced from recycled material compared to 40 % today). • <i>Material substitution</i>: Increased use of timber in building construction. • <i>End-use demand reductions</i>: More sustainable lifestyles, especially in terms of mobility (e.g. car sharing, smaller cars, fewer flights).
GreenSupreme	<ul style="list-style-type: none"> • <i>Material efficiency</i>: Greater increase in material efficiency than in the past (up to 1.2 %/a), by actions such as reducing losses in manufacturing. Consumers buy high-quality and durable or repairable goods. • <i>Circular economy</i>: Significant increase in recycling rates (e.g. by 2050, 67 % of steel production is sourced from recycled material compared to 40 % today). • <i>Material substitution</i>: Greatly increased use of timber in building construction and use of textile concrete, substituting 20 % of reinforced concrete by 2050. • <i>End-use demand reductions</i>: More sustainable lifestyles, especially in terms of mobility (e.g. significant levels of car sharing and ride sharing (by 2050 car density in cities is only 1/3 of today's level), smaller cars, fewer flights).
TM95	<ul style="list-style-type: none"> • <i>Circular economy</i>: Increase in the steel recycling rate relative to the reference scenario (48 % instead of 40 % of 2050 steel production is from recycled material).
EL95	<ul style="list-style-type: none"> • <i>Circular economy</i>: Increase in the steel recycling rate relative to the reference scenario (48 % instead of 40 % of 2050 steel production is from recycled material).
95 % path	<ul style="list-style-type: none"> • <i>Circular economy</i>: Increase in recycling rates (e.g. of steel and paper) relative to the baseline.
EUROPE	
1.5TECH	<ul style="list-style-type: none"> • No information provided.
1.5LIFE	<ul style="list-style-type: none"> • <i>Material efficiency</i>: Reductions in material losses in manufacturing (not quantified). • <i>Circular economy</i>: Higher recycling rates reduce primary production of various materials, including iron & steel (by 6 %) and chemicals (by 9 %) relative to the baseline projection. • <i>Material substitution</i>: Material substitution is mentioned, but not quantified. • <i>End-use demand reduction</i>: Changes in lifestyles and consumer choices are assumed, including a trend towards lower meat consumption, a sharing economy in transport and limits to growth in air transport demand.
Shared-efforts	<ul style="list-style-type: none"> • <i>Material efficiency</i>: Products consumed by 2050 are of higher added-value with a better design, lasting on average 13 % longer than today. These lifetime improvements reduce demand for steel, chemicals and cement by more than 20 % relative to the baseline. • <i>Circular economy</i>: The share of recycled materials in new products increases, e.g. to 60 % for steel and 16 % for high-value chemicals. • <i>Material substitution</i>: 10 % of steel is replaced by carbon fibre in land vehicles and 25 % in airplanes. In buildings, 10 % of cement is replaced by plastics and, in appliances, 5 % of steel is replaced by plastics. • <i>End-use demand reductions</i>: Relative to the baseline, by 2050 steel demand is 28 % lower, chemicals demand 8 % lower and cement demand 33 % lower through changes in consumption patterns, e.g. increases in vehicle occupancy rates.
WORLD	
B2DS	<ul style="list-style-type: none"> • <i>Material efficiency</i>: Manufacturing yields increase by 8 % on average in crude steel and 16 % in aluminium production by 2060. • <i>Circular economy</i>: Recycling rates increase, e.g. global collection of waste plastics for recycling improves from 10 % in 2014 to 41 % by 2060 and steel recycling is 14 % higher by 2060 than in the reference scenario.
Supply Side	<ul style="list-style-type: none"> • No information provided.

levels and increased sharing of products. In the other scenarios, fewer or no sub-strategies for reducing material demand are pursued; in TM95, EL95, 95 % path and B2DS, it is assumed that circular economy efforts will increase the recycling rates of steel and other materials. In addition, the B2DS scenario also explicitly assumes material efficiency improvements; specifically increases in manufacturing yields. In the two remaining scenarios (1.5TECH and Supply Side) none of the sub-strategies for reducing demand for primary materials are pursued, or at least no information on any such measures could be found in the studies.

Discussion and conclusions

Table 5 provides an overview of the extent to which the ten analysed scenarios rely on nine⁵ key strategies to achieve deep emission reductions in the industry sector by 2050. One finding is that the scenarios pursue many different combinations of mitigation strategies. This suggests that different pathways towards deep decarbonisation of the industry sector could be feasible and there is currently no widespread consensus on the most likely or preferred combination of strategies. Interestingly, none

5. The tenth key strategy mentioned earlier (energy efficiency) could not be analysed due to insufficient information provided in the scenario studies.

Table 5. Overview of the role of nine key industry sector mitigation strategies in the analysed scenarios.

Scenario	Use of climate-neutral energy carriers			Carbon capture		Reduction in demand for primary materials			
	Direct electrification	Hydrogen and/or synthetic fuels	Biomass	CCS	CCU	Material efficiency	Circular economy	Material substitution	End-use demand reductions
GERMANY									
GreenEe1	++	+++	o	o	o	++	+++	++	++
GreenSupreme	++	+++	o	o	o	+++	+++	+++	+++
TM95	o	+++	o	+	+	o	+	o	o
EL95	+++	++	o	+	+	o	+	o	o
95 % path	o	o	+++	+++	o	o	+	o	o
EUROPE									
1.5TECH	++	++	++	+++	+++	o	o	o	o
1.5LIFE	++	++	++	+	++	+	+	+	++
Shared-efforts	++	+	++	+	o	++	++	++	++
WORLD									
B2DS	+	o	++	+++	o	+	+	o	o
Supply Side	+++	++	o	+++	++	o	o	o	o

o = strategy is not pursued or only pursued very lightly

+ / ++ / +++ = strategy is pursued to a moderate / strong / very strong extent

of the nine differentiated strategies is pursued as a key mitigation strategy in *all* the scenarios. This suggests that while deep emission reductions in the industry sector will require a combination of different strategies, there may be room for societies to choose which specific strategies to pursue or reject. Another interpretation of this finding could be that if all the strategies were pursued, this might constitute a more robust approach to achieving near-zero emissions by the middle of the century.

Differences in the combination of strategies between the analysed scenarios may, to some extent, be due to the different regional coverage of the studies. For example, in Germany the potential for increasing domestic biomass use is widely considered to be limited, which may explain why many German scenarios do not rely heavily on this strategy.

Not surprisingly, the main priorities pursued by the scenario studies also seem to be reflected in the scenarios' choice of strategies. For example, the German Federal Environmental Agency generally emphasises the need for environmental improvements in areas such as climate change, biodiversity protection and sustainable resource extraction. Consequently, the scenarios in their study (UBA 2019) focus more strongly than other scenarios on strategies that reduce the need for primary materials, stressing the ecological benefits of such an approach. The study commissioned by the Federation of German Industries (BDI 2018), on the other hand, focuses on biomass use and CCS, stressing that these strategies are expected to be the most cost-effective and, therefore, have the potential to retain the international competitiveness of German industry. It could be added that these two strategies are also among the least transformational. By substituting one energy carrier with another (biomass) and adding an end-of-the-pipe solution to existing technologies and processes, the risk of losing existing assets can be minimised.

Future research could analyse available scenarios in respect to the differences in their choice of mitigation strategies in key subsectors, focusing for example on the steel, chemicals or cement sectors. Such an approach could reveal a fuller understanding of the reasons for the differences between scenarios than the industry-wide perspective of this article. As many scenario studies covering the entire energy system lack a detailed description of individual subsectors, such an analysis could include roadmaps for specific industry sectors (such as IEA 2018 and IES-VUB 2019).^{6,7}

While the paper at hand focuses on the year 2050, future work could put greater emphasis on the strategy-specific challenges and opportunities related to the transformational *process* of the industry sector.

Another future research avenue arising from this paper is the need for a better understanding of the advantages and disadvantages of the different industry sector mitigation strategies. One area of focus could be to what extent direct electrification should be pursued relative to the increased use of hydrogen, synthetic fuels or biomass. Likewise, the advantages and disadvantages of hydrogen compared to synthetic fuels could be more closely examined. Due to the close interaction of the industry sector with other energy demand and supply sectors (both now and in the future) any such analysis should apply a system-wide perspective.

6. These meta-analyses would benefit greatly from efforts of scenarios developers to describe their scenarios in sufficient detail and to provide helpful quantitative tables or annexes.

7. In the next phase (June 2020 to July 2021) of the ongoing SCI4climate.NRW project, such a subsector-specific meta-analysis of available studies will be conducted.

Finally, recent studies (e.g. Material Economics 2019, Grubler et al. 2018, UBA 2019) have highlighted the potential contribution that strategies to reduce primary material demand could make in reducing industry sector CO₂ emissions. Future research could focus more strongly on the achievable potential of these strategies, as well as on the necessary conditions for their successful implementation.

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