Modelling the integrated impacts of decarbonisation in selected sectors at the EU in a global context

Deliverable 5.3

Andries Hof (PBL Netherlands Environmental Assessment Agency), Mariësse van Sluisveld (Lund University), Harmen-Sytze de Boer, Detlef van Vuuren (PBL Netherlands Environmental Assessment Agency)

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1 Motivation and aims

In the previous deliverables D4.3 (Schneider et al., 2020) and D4.10 (van Sluisveld et al., 2020) several different decarbonisations scenarios developed by respectively WISEE and IMAGE were assessed on their implications for technology and industrial GHG emissions. This report applies the integrated modelling framework IMAGE and synthesizes work in previous deliverables to examine economic, environmental and social equity impacts for the EU and for the world as a whole. We apply the Sustainable Development Goals (SDGs) as a framework to examine the economic, environmental and societal impacts. This provides a more comprehensive approach between decarbonisation innovations and their impacts, thus complementing the previous tasks.

To examine interaction with SDGs, we use the following three methods:

- *Literature review* to assess general overview of synergies and trade-offs between industry decarbonisation and SDGs (Section 4.1);
- *Synthesis*, combining results of D5.2 (impact specific innovations on SDGs) with D4.3 (innovations used in the pathways developed by the technology-rich WISEE model);
- *IMAGE modelling* for impacts on total power demand (related to energy security), SO_2 emissions (relevant for health via air pollution), land use (related to life on land), and total carbon captured.

Section 2 shortly introduces the narratives used and maps out how the scenarios of D4.3 (Schneider et al., 2020) and D4.10 (van Sluisveld et al., 2020) compare. Section 3 puts the scenarios of D4.10 in a wider context by showing global results for the industry decarbonisation scenarios. Section 4 focuses on interaction with SDGs using the three methods mentioned above and Section 5 concludes.

2 Scenarios narratives

Deliverable D3.7 (Lane, 2019) described four archetypal narratives to a zero-carbon emission industry sector: Technological replacement, process efficiency, demand management, and circular economy. For each of these narratives, the IMAGE model was used to developed quantitative scenarios in deliverable D4.10 (van Sluisveld et al., 2020). In deliverable D4.3 (Schneider et al., 2020), the WISEE model was used to developed two scenarios. For steel and plastics, a producer-driven and circular-driven scenario were developed, and for paper & pulp, a CCS and a carbon looping scenario were developed. The circular-driven scenario combines the Demand management and Circular economy narratives. The producer-driven scenario of WISEE is very similar to the Technological replacement and Process efficiency scenario of IMAGE (both pathways rely more strongly on electrification than on CCS).

For the IMAGE runs, it is important to mention that the same carbon price is applied throughout the whole economy, but no specific interventions related to narratives are applied beyond industry.

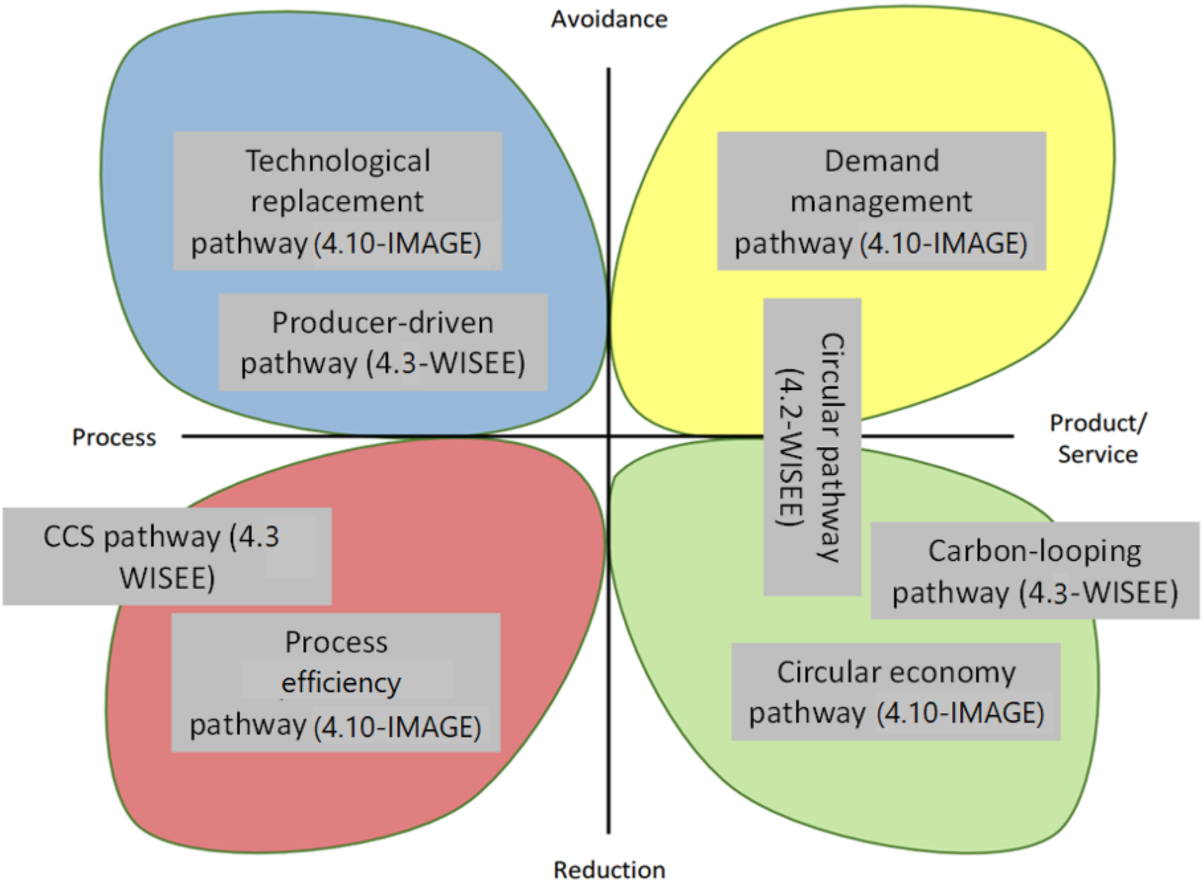

Figure 1. Mapping of the scenarios from IMAGE and WISEE on the pathway narratives
Adapted and reprinted from Lane (2019)

3 Scenarios in a wider context

Deliverable D4.10 (van Sluisveld et al., 2020) showed detailed pathways for industry in Europe towards 2050. In this section, we shortly discuss the wider context of the different industry decarbonisation scenarios as presented in deliverable D4.10 (van Sluisveld et al., 2020). We focus particularly on the implications of decarbonisation pathways towards net-zero emissions on a systemic and sectoral level for Europe and the other world regions represented in the IMAGE integrated assessment model (see Stehfest et al. (2014) for a complete breakdown of regions). Scenario results that are more specifically relating to certain SDGs, including power generation, land use, and air pollutant emissions, are discussed in section 4.3.

3.1 Decarbonisation in the broader context

3.1.1 Economy-wide decarbonisation

Net-zero emissions are achieved on various timings and across different systemic levels (see Figure 2). Overall, on the highest aggregate level, most of the global regions in IMAGE are able to reach a net-zero goal on the full economy level. We distinguish between net-zero emissions on a CO_2 emissions level and on a full greenhouse gas emissions level for the full economy. No single scenario developed in REINVENT is able to reach carbon neutrality for Europe by 2050 on its own. Only a combined scenario (indicated as *Total* in Figure 2), utilizing all the optimistic assumptions of all four scenarios together[1], is able to present CO_2 neutrality by 2050. Europe is also considered the most difficult continent to decarbonise, given how most other continents are generally projected to reach net-zero greenhouse gas emissions sooner in the rational-economic context of the IMAGE integrated assessment model.

On an energy supply level, we find that CO_2 emissions neutrality is achieved for near all IMAGE scenarios, with the bulk of regions (including Europe) decarbonising this sector prior to 2050. Only a marginal difference across the scenarios is presented for each sector, implying that different industrial decarbonisation routes do not affect the decarbonisation trajectory for the energy supply sector. The electricity sector is shown to be among the first to reach net-zero CO_2 emissions.

For the energy demand sector as a whole less than half of the IMAGE regions can depict a net-zero CO_2 emissions pathway. This is mainly due to the complexity of mitigating the transport sector and the built environment as the IMAGE model is unable to present a net-zero CO_2 emissions pathway for these sectors. For industry, net-zero CO_2 emission pathways are projected for the majority of the regions in the IMAGE model, reaching this inflection point between 2040 to 2095 (or not at all). For Europe only two out of four scenarios show to reach net-zero CO_2 emissions in industry during the second half of the century.

[1] A combined scenario leads to some narrative inconsistencies between TechReplace and ProcEff, and CircEco and DemandMan due to several conflicting configurations of measures. This scenario is only shown here as an illustrative example of an combined effect and should not be considered as an internally consistent output of the REINVENT project.

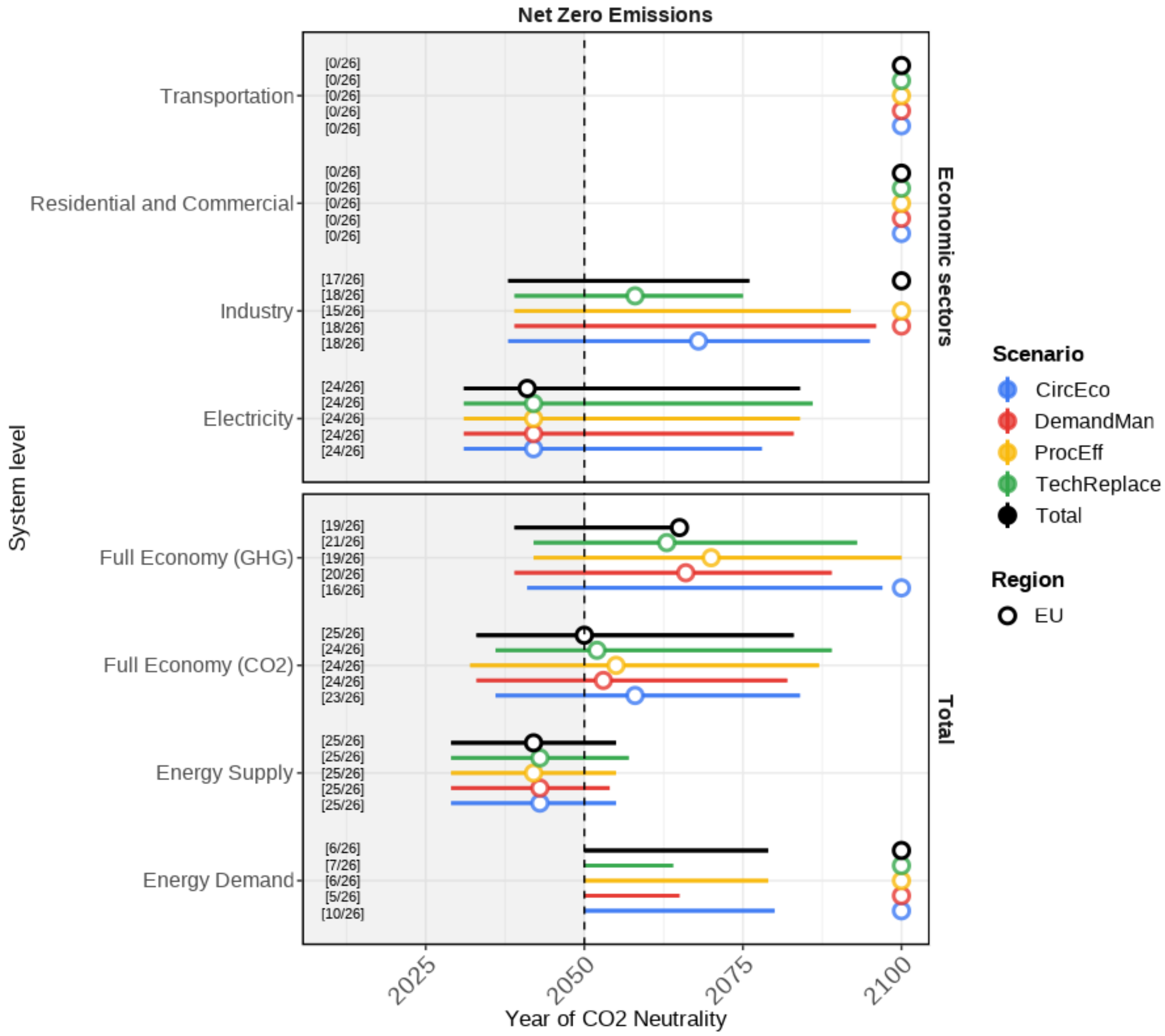

Figure 2. Overview of when net-zero CO_2 emissions are achieved per economic sector for the 26 IMAGE regions (CO_2 unless otherwise stated)

The numbers indicate the number of regions that are able to reach net-zero emissions from a total of 26 world regions in the IMAGE model. For the "Total" scenario, see also footnote 1 on page 7.

The variety in timings and decarbonisation potentials across the economic sectors lead to differences in total impact on the cumulative emission budget. By 2050, Europe is projected to have emitted 3 times more CO_2 emissions than it has captured or stored since 2020. Major challenges become more apparent when the timeline is extended towards 2100, as Europe is projected to have sunk the largest volume of (residual) emissions compared to other major regions around the world.

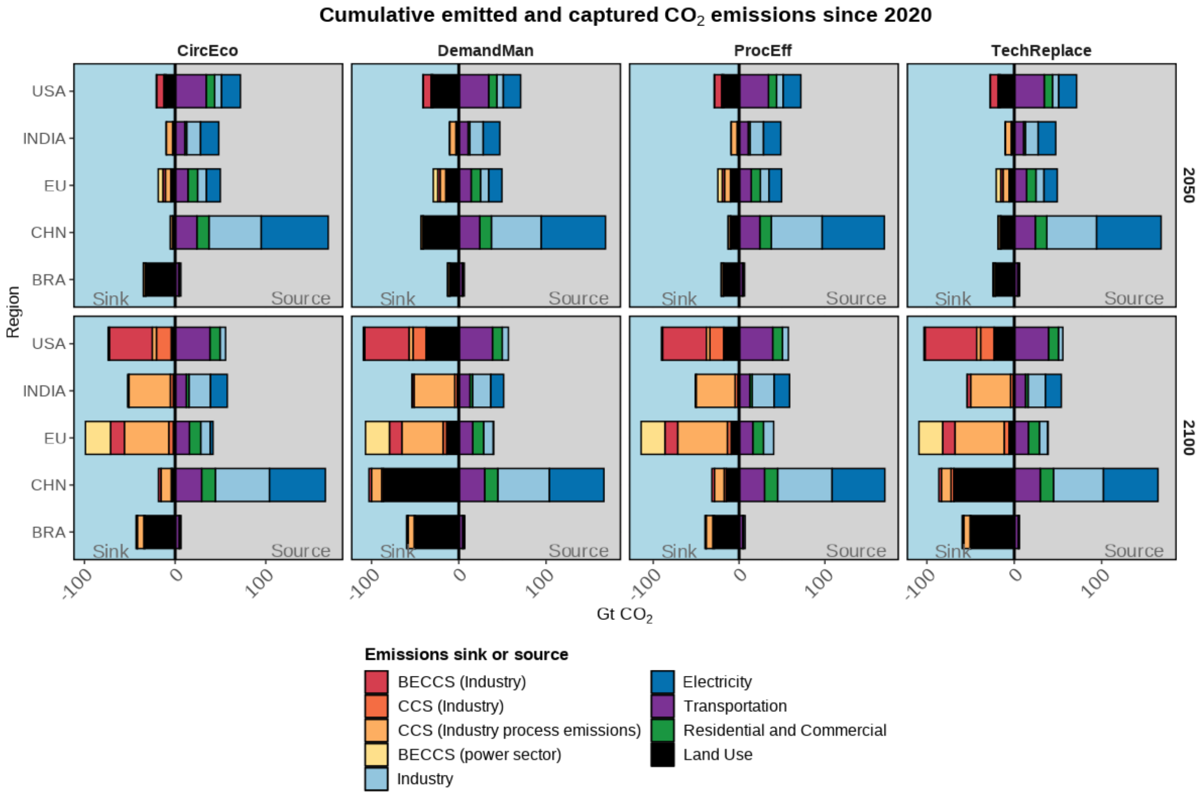

Figure 3 - Overview of decarbonisation strategies for major and emerging economies per archetypical narrative

Legend: EU: Europe, CHN: China, USA: United States, INDIA: India and BRA: Brazil

3.1.2 Industry decarbonisation

By zooming in to the specific material processing industries, we observe that IMAGE is able to present net-zero emission pathways for the pulp and paper industry for nearly all countries by 2050. The cement sector shows decarbonisation potential, reaching full decarbonisation before 2050 for nearly half of the regions in the IMAGE model. Europe is projected to reach a decarbonised cement sector only in *TechReplace* in 2060. The decarbonisation of the iron and steel and the chemical industry is shown to be more sensitive to the narrative assumed and exclusive to only a limited number of regions in the IMAGE model. For example, IMAGE is unable to present a full decarbonisation pathway for the chemical sector under the *DemandMan* scenario for any represented region, while other narratives do. In the iron and steel sector, the decarbonisation narratives show some potential to reaching net-zero emissions, but none of them include a European decarbonisation pathway. The only exception that systematically leads to decarbonisation in the iron and steel sector is *TechReplace*. For no IMAGE region or decarbonisation narrative a full decarbonisation pathway could be found for the food processing sector. Carbon offsets need to come from elsewhere in the value chain for this sector.

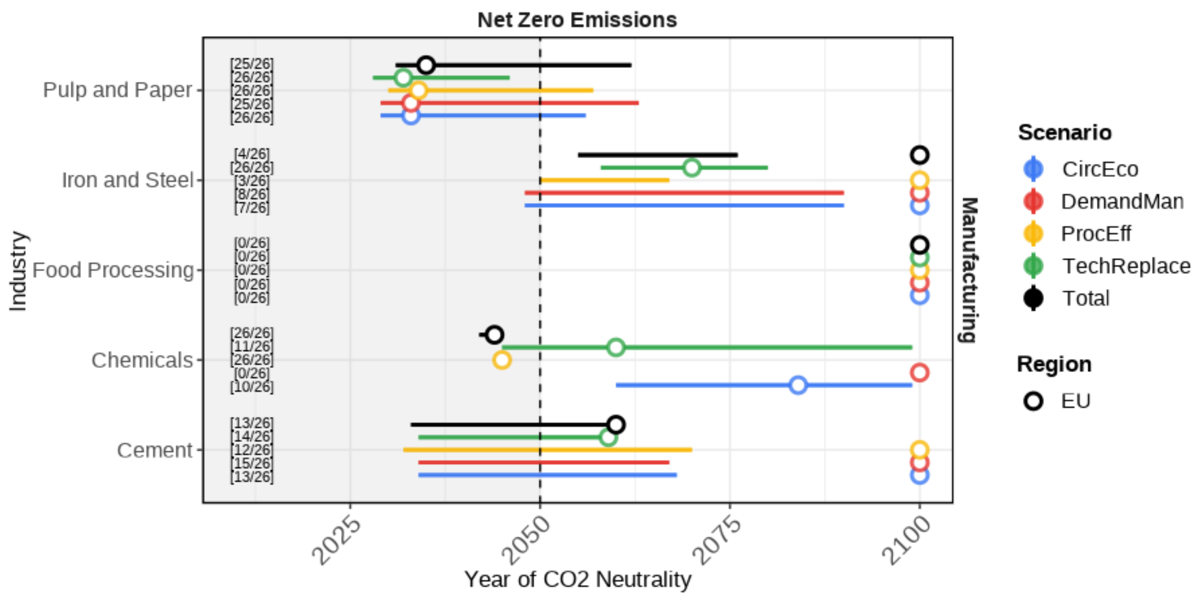

Figure 4. Overview of when net-zero CO_2 emissions are achieved in the heavy industry sector sector for the 26 IMAGE regions

The numbers indicate the number of regions that are able to reach net-zero emissions from a total of 26 world regions in the IMAGE model. For the "Total" scenario, see also footnote 1 on page 7.

3.1.3 Material production

Todays' production volumes of basic materials show to be lower per capita in Europe than for the global average (Figure 5). For food products, Europe shows to be the biggest producer per capita of all the global regions represented in IMAGE. Over time this balance shifts, showing and increasing cement and olefin production per capita in Europe than on a global scale by 2050. Due to differences in population growth the dynamics per region in total volume differs, leading to higher total production in e.g. China and India than in Europe.

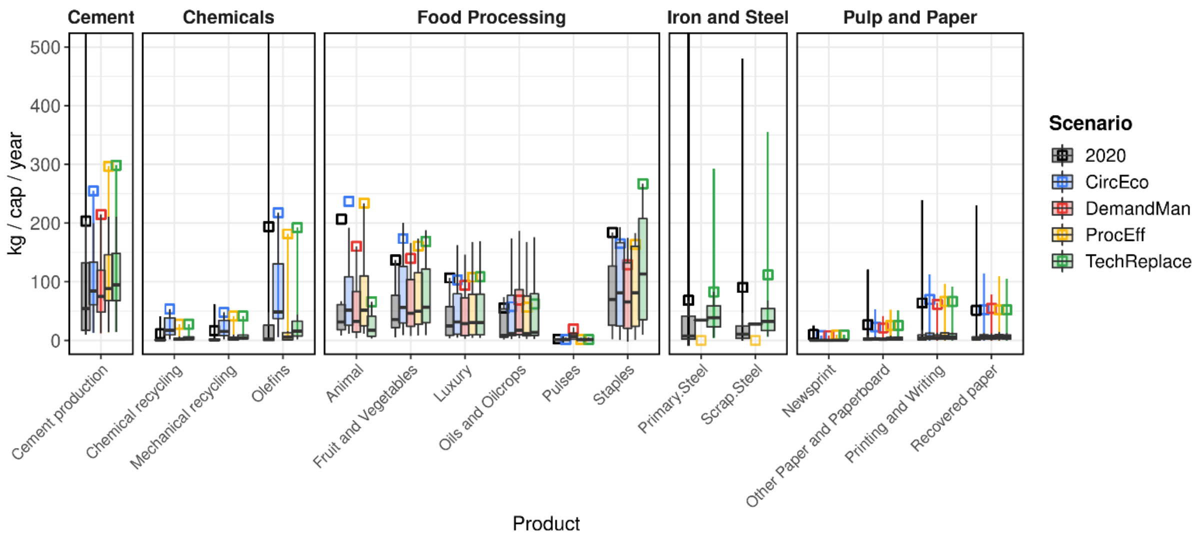

Figure 5. Overview of primary and secondary material consumption per capita for the regions reaching net-zero emissions.

The range of the bars represent up to 26 world regions in the IMAGE model. The number of included regions are corresponding to the numbers as presented in Figure 4. The food processing sector represents the consumption in 2050. Chemicals are in 10^2 J / cap/ year. The square shape indicates Europe.

3.1.4 Industrial final energy consumption

The share of energy carriers in total final energy consumption in Europe and the other regions in IMAGE are shown in Figure 6. Todays' global secondary energy consumption shows an overall larger dependency on coal than is considered for Europe. Gaseous fuel becomes more important in the cement sector for Europe under a decarbonisation pathway, while the other IMAGE regions show a larger dependency on biofuels. In the chemical sector Europe shifts the most to biofuel use, while the rest of the world maintains a larger dependency on liquid fuels. The only European decarbonisation pathway for the iron and steel sector that could be presented by the IMAGE model is achieved via increased electrification in the *TechReplace* scenario. The other IMAGE regions display decarbonisation routes via diversification, utilizing a blend of various energy carriers (fossil fuels, electricity, biofuel and hydrogen). The European pulp and paper sector, characterised as a sector utilizing a high share of biofuels in the present, shows to reduce its dependency on fossil fuels through diversification. The other IMAGE regions show to follow suit, albeit under varying sets of configurations.

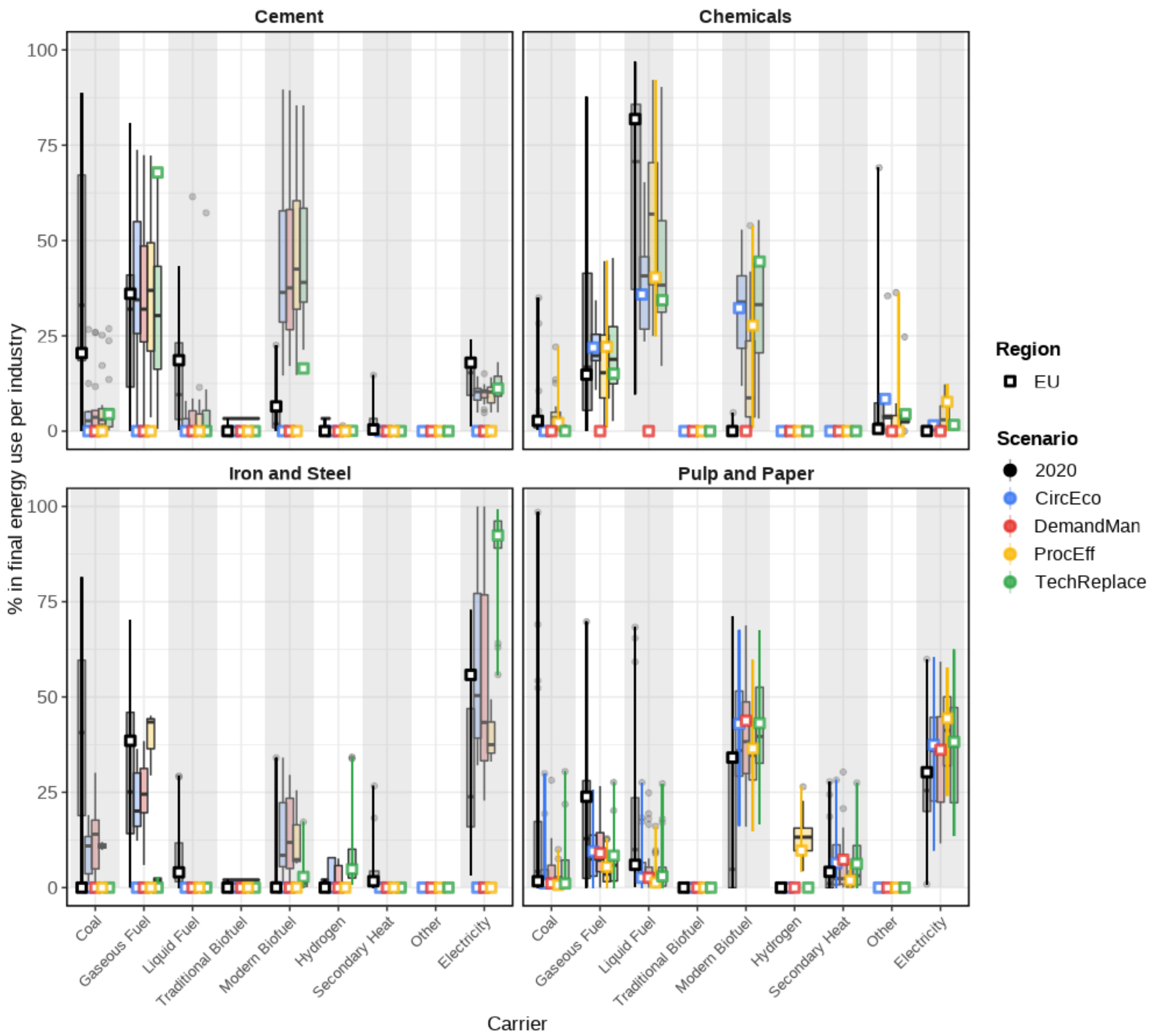

Figure 6 - Overview of final energy use per industry at the year when net-zero emissions are achieved.

The range of the bars represent up to 26 world regions in the IMAGE model. The number of included regions are corresponding to the numbers as presented in Figure 4. Food processing industry is not included in this graph due to lack of net-zero emission pathways.

3.1.5 Industrial production capacity

To present the decarbonisation strategies we have grouped the specific production capacities per sector as presented in van Sluisveld et al. (2020) to five standardized categories:

1. **Fossil-based production capacity**: all production capacity that exists today that predominately utilizes fossil fuels without abating energy or process emissions;
2. **CC(U)S**: All production capacity that retrofits carbon capture and storage technologies to existing or innovative new technologies. Also represents process innovations where carbon from process emissions is used as a new feedstock for chemical production;
3. **Energy innovations**: all production capacity that has adopted innovations related to the more efficient use of fuels, or using fuels with a lower carbon content than hydrocarbons, for driving the production processes (e.g. fuel switching, energy and thermal efficiency improvements);

4. **Process innovations**: all production capacity that has adopted innovations relating to the efficiency or carbon removal capacity of the represented capital stock or feedstock uses in the production process (e.g. technology innovations, feedstock substitution);
5. **Material innovations**: all production capacity that has adopted innovations relating to the use of materials (e.g. consumption, material efficiency, end-of-life measures).

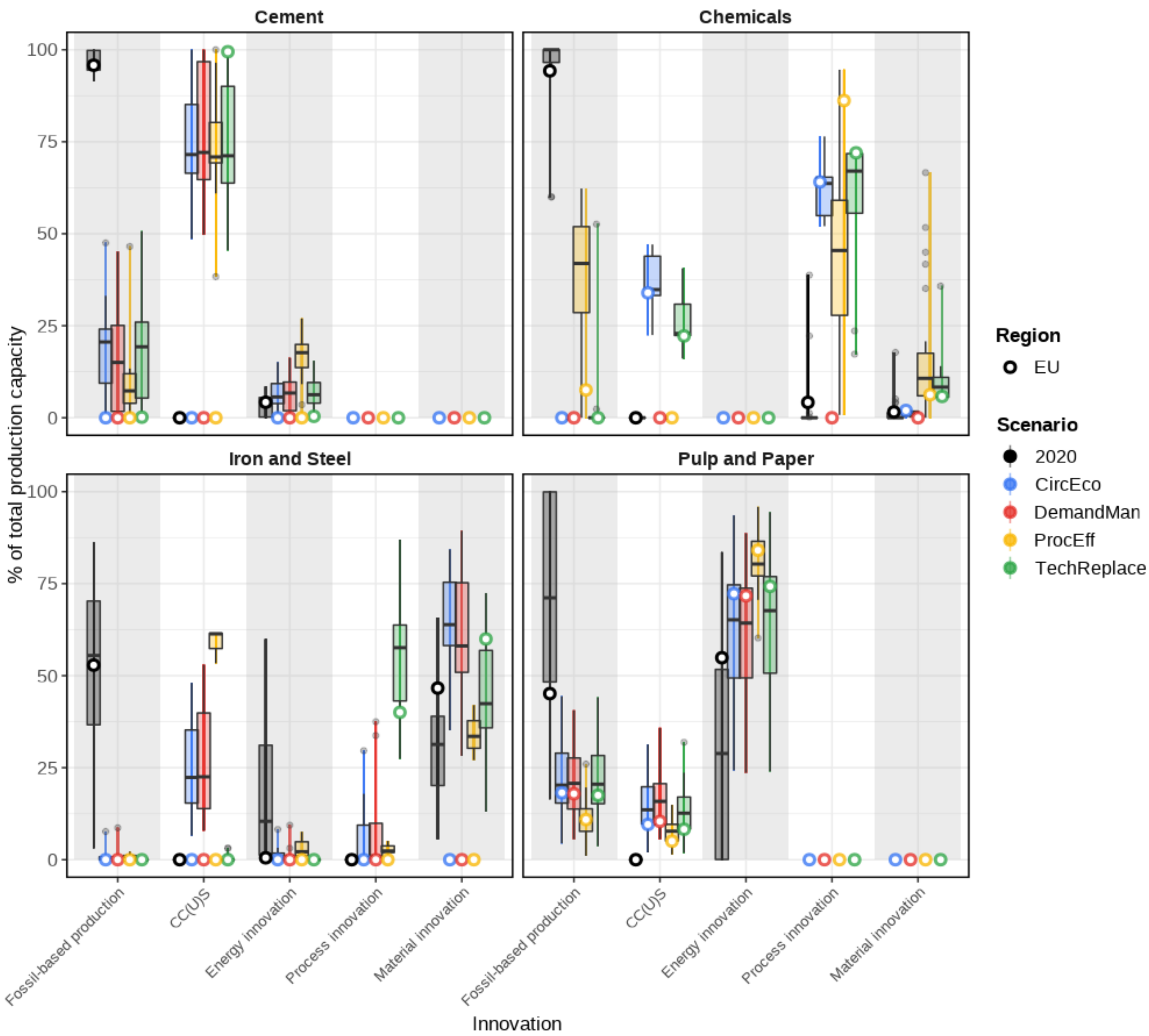

Figure 7 - Overview of decarbonisation strategies per industry applied at the year when net-zero emissions are achieved.

The range of the bars represent up to 26 world regions in the IMAGE model. The number of included regions are corresponding to the numbers as presented in Figure 4. Food processing industry is not included in this graph due to lack of net-zero emission pathways.

As shown in Figure 7, the IMAGE projections show how the cement sector shifts away from an unabated fossil-fuel based production capacity stock to a capital stock that is fully dependent on carbon capture and storage. If combined with a high share of biomass-fired lime kilns (creating negative emissions), some unabated production capacity can remain in operation without compromising the net-zero status. The chemical sector makes a similar shift as the cement sector, showing to be fully driven on fossil based feedstocks in 2020. The archetypical pathways show that the European chemical sector can reach net-zero emissions via process innovations (which are either the electric cracker in *ProcEff* or new feedstocks in *TechReplace*). The other IMAGE regions also show that material innovation (recycling) could lead to a large contribution to the decarbonisation of the chemical sector. The only European iron and steel sector decarbonisation pathway in IMAGE (*TechReplace*) shows a large contribution from process (via hydrogen or electrochemical steelmaking) and material innovations (such as recycling and lifetime extension) to reaching net-zero CO_2 emissions. The European steel sector has a greater focus on material innovations than the other IMAGE regions, due to a high recycling rate present today. Other IMAGE regions also show decarbonisation pathways in the iron and steel sector via CC(U)S in combination with material innovations to reach net-zero emissions. For the pulp and paper sector, a large share of the capital stock in Europe is already utilizing renewable energy carriers in 2020 (considered under energy innovation). The decarbonisation pathways imply a strengthening of the use of renewable energy carriers in combination with CC(U)S. The more use of biofueled heating capacity, the lower the dependency on CC(U)S. Other IMAGE regions show more or less similar behaviour, albeit with a higher dependency on unabated fossil-fuelled capacity, CC(US) or renewable energy carriers.

4 Impact on SDGs

4.1 General interactions industry and SDGs

Based on available literature, the IPCC (2018) has identified the most important interlinkages between climate mitigation measures and SDGs. Three broad types of mitigation measures in industry are distinguished: accelerating energy efficiency improvement, low-carbon fuel switch (predominantly to hydrogen or biomass), and decarbonisation/CCS/CCU (with decarbonisation mainly referring to electrification). For each interaction, the following information is provided:

- Interaction, indicated by a score from -3 (cancelling/strong trade-off) to +3 (indivisible/strong synergy)
- Evidence, indicated by a score from 1 (limited evidence) to 4 (robust evidence)
- Agreement, indicated by a score from 1 (low) to 4 (high)
- Confidence, synthesizing the author teams' judgments about the validity of findings as determined through evaluation of evidence and agreement, indicated by a score from 1 (very low) to 5 (very high)

Table 1 synthesizes the most important linkages as identified by the IPCC (2018) for industry. A green cell indicates a synergy and an orange cell a trade-off – with a darker colour indicating stronger interactions. The number in the cell indicates the level of confidence. A white cell indicates that there is no direct interaction.

Table 1. Interactions between the mitigation options in industry and SDGs

	Mitigation option		
	Electrification /CCS/CCU	Low-carbon fuel switch	Energy efficiency improvement
SDG1 – No poverty			1
SDG3 – Good health	3	2	2
SDG4 – Quality education		2	2
SDG6 – Clean water and sanitation	2 2	3 3	2 2
SDG7 – Affordable & clean energy	2 2	1	4
SDG8 – Decent work & economic growth	3	4	3
SDG9 – Industry, innovation & infra	4	4	2
SDG10 – Reduced inequalities			3
SDG11 – Sustainable cities		1	1
SDG12 – Responsible cons. & production	4	4	3
SDG14 – Life below water	1		
SDG15 – Life on land		1	
SDG17 – Partnerships for the goals	3	2	3

Weak synergy/trade-off
Medium strong synergy/trade-off
Strong synergy/trade-off

1 Very low confidence
2 Low confidence
3 Medium confidence
4 High confidence
5 Very high confidence

Source: Based on IPCC (2018)

The table clearly shows that mitigation options in industry have more synergies than trade-offs with SDGs. However, there are no strong synergies identified, and only a few medium strong synergies with high confidence.

The strongest synergies between electrification/CCS/CCU and SDGs are with SDG9 (industry, innovation, and infrastructure) and SDG12 (responsible consumption and production). Synergies with both SDGs are quite straightforward: CCS and other decarbonisation options like electrification require refurbishing existing large-scale plants, inhibiting radical innovations and responsible production processes. Collaboration among partners and policy change is essential for these investments to take place, as they entail large risky investments to be made by energy-intensive processing industries like steel, chemical, and paper industries, mostly operated by multinationals with long investment cycles (Wesseling et al., 2017). Switching to low-carbon fuels has similar synergies as decarbonisation through electrification or CCS/CCU.

Improving energy efficiency in industry has the strongest synergy with SDG7 (affordable and clean energy). Also here, the synergy is quite straightforward: energy efficiency leads to reduced energy demand and hence energy supply and energy security. Interactions with other SDGs are mainly positive, but either weak and/or with low confidence.

Of the three broad main mitigation options, CCS/CCU has the most trade-offs with other SDGs – although these are all weak or with low confidence. CCS/CCU can have synergies and trade-offs with SDG6 (clean water and sanitation), as CCU/S requires access to water for cooling and processing which could contribute to localized water stress, but CCS/U processes can potentially be configured for increased water efficiency compared to a system without carbon capture via process integration.

The above identified synergies and trade-offs are very general. In the end, the synergies and trade-offs are strongly dependent on specific mitigation measures and can be different for each industry sector. In section 4.2, we therefore dive into more detailed synergies and trade-offs based on the results of the scenario modelling (deliverable D4.3 and D4.10 (Schneider et al., 2020; van Sluisveld et al., 2020)) and the analysis of coherence between sector based innovations and the SDGs as done in deliverable D5.2 (O'Gara et al., 2020).

4.2 SDG interactions for specific industry sectors and pathways

4.2.1 Steel sector

For the steel sector, deliverable D4.3 (Schneider et al., 2020) has analysed two decarbonisation pathways: one strongly producer-driven and one focussing more on circularity. In both pathways, the current BF/BOF route to produce primary steel is in 2050 completely replaced by a carbon neutral production route by introducing hydrogen as a reducing agent to produce direct reduced iron (DRI), which is afterwards smelted and converted to crude steel in an electric arc furnace (EAF). The major difference between the two pathways is that in the circular pathway, steel demand is lower due to increased material efficiency and addressing consumer demand for products containing steel. This results in a much higher share of scrap-based steel (about 70% in 2050 compared to just over 50% in the producer-driven pathway). The reliance on hydrogen-based DRI is therefore lower in the circular pathway.

Deliverable D5.2 (O'Gara et al., 2020) identified synergies for hydrogen-based DRI with production and consumption and the natural resource base, but the contribution to related SDGs depends on where the hydrogen is sourced from (natural gas or carbon-free electricity). Positive impacts of hydrogen-based DRI on the natural resource base are related to reduced mining and fossil resource extraction (as coal is replaced by hydrogen and natural gas by renewable electricity). It may impact global peace, considering where coal and natural gas are purchased from. From a poverty & well-being perspective, novel technologies create new roles for younger people to learn. A potential trade-off with poverty & well-being, however, is that steel may become more expensive.

Deliverable D5.2 (O'Gara et al., 2020) also analysed the impact of voluntary low-carbon building standards and improved process technology and co-design with end users (specifically the automotive industry). Such measures are especially important in the circular pathway. Voluntary low-carbon building standards could result in reduced resource consumption while creating the conditions necessary for achieving sustainable cities and infrastructure. Industry professionals expect a minor enabling effect on the natural resource base goals due to small material savings from this innovation.

Table 2. Interactions between the decarbonisation pathways for steel and SDGs

	Producer driven pathway	Circular pathway
Production and consumption	1	3
Natural resource base	1	3
Poverty & well-being	1	2

(light green)	Strong synergy
(medium green)	Medium synergy
(dark green)	Low synergy

The numbers in the cell indicate the number of innovations with synergies in the respective pathways. Source: Synthesis from deliverable *D4.3, D4.10 and D5.2*

4.2.2 Plastics sector

For plastics, the same type of pathways were considered in deliverable D4.3 (Schneider et al., 2020) as for steel. Current routes for the production of high-value chemicals mainly consist of naphtha crackers, flexible crackers, and fluid catalytic cracking (FCC). In the producer-driven pathway, naphtha crackers are largely replaced by methanol to olefins (MtO) processes and the use of flexible crackers increases as well. In the circular pathway, a transition to the same processes take place, but production levels are almost half of those in the production-driven pathway in 2050, driven by less plastic use and higher recycling rates.

Two demand-side innovations and two production-based innovations were analysed for plastics in deliverable D5.2 (O'Gara et al., 2020). The production-based innovations were chemical recycling of carbon and carbon capture and usage (CCU). Recycling of carbon (plastic waste gasification to produce methanol) is an important technology in the circular pathway of deliverable D4.3 (Schneider et al., 2020), but the synergies with other SDGS were assessed to be low, although the technology could enable conditions for goals in the natural resource base cluster to progress. The demand-side innovations assessed in deliverable D5.2 (O'Gara et al., 2020) included bio-based jackets (based on wood residue) and zero-waste supermarkets. Zero-waste supermarkets have synergies especially with the natural resource base, as it reduces plastic waste, and with production and consumption.

Table 3. Interactions between the decarbonisation pathways for plastics and SDGs

	Producer driven pathway	Circular pathway
Production and consumption	0	1
Natural resource base	0	2
Poverty & well-being	0	1

(light green)	Strong synergy
(medium green)	Medium synergy
(dark green)	Low synergy

The numbers in the cell indicate the number of innovations with synergies in the respective pathways.
Source: Synthesis from deliverable *D4.3, D4.10 and D5.2*

4.2.3 Paper and pulp sector

In deliverable D4.3 (Schneider et al., 2020), two different pathways than for the other industry sectors were analysed: a carbon looping pathway and a CCS pathway. The core strategy in the carbon looping pathway is using biogenic carbon in the pulping industry for material use and electrifying steam supply using hydropower or wind power. The hydrocarbon by-product of the pulping process, black liquor, can be used in other sectors via black liquor gasification (deliverable D4.3 focuses on the use in the plastics industry). The CCS pathway focuses on storing the CO_2 emitted from biogenic fuel in depleted oil and gas fields in the North Sea, thereby creating negative emissions.

The three innovations analysed for pulp and paper in deliverable D5.2 (O'Gara et al., 2020) include biorefineries, lime kilns, and biocomposite. The biorefinery innovation refers to replacing fossil-based chemicals with bio-based ones, in this case with the products of black liquor gasification as applied in the carbon looping pathway. The biorefinery has potentially strong synergies with SDGs, as the biorefinery model is based on a much more defused ownership of the raw material than fossil fuels. It therefore carries the benefits of having a much more distributed welfare system across society. Rural areas are often the places where the most poverty is seen, the biorefinery model may create an economic incentive in better managing land and include a wider community of stakeholders – contributing to a reduction in poverty and improving the quality of education though upscaling and learning new methods of resource optimization.

Lime kilns replace fossil fuels by wood powder, but this technique is not used in any of the pathways as fossil fuels are phased out in all pathways in the paper and pulp industry. Biocomposites are composite materials usually consisting of a biobased fibre mixed with a plastic, but are not considered in the pathways.

Table 4. Interactions between the decarbonisation pathways for paper and pulp and SDGs

	Carbon looping pathway	CCS pathway
Production and consumption	1	0
Natural resource base	1	0
Poverty & well-being	1	0

(light green)	Strong synergy
(medium green)	Medium synergy
(dark green)	Low synergy

The numbers in the cell indicate the number of innovations with synergies in the respective pathways.
Source: Synthesis from D4.3, D4.10 and D5.2

4.3 SDG interaction results from IMAGE

4.3.1 Power generation

The energy mix in Europe does not significantly change across the different industry decarbonisation narratives (all show an increased dependency on (BE)CCS and hydro and nuclear energy expansion) (see Figure 8). The decarbonisation strategy does affect the total demand for power generation. In all four scenarios, total power generation in Europe is larger than today, but the increase in the demand management (*DemandMan*) scenario is much lower than in the process efficiency (*ProcEff)* and technological replacement (*TechReplace*) scenarios. In fact, the demand management (*DemandMan*) scenario is the only decarbonisation scenario that shows a lower increase in power generation than in the baseline. The reason that power generation is higher in the technological replacement (*TechReplace*) scenario than in the baseline is strong electrification in steel and pulp & paper (see deliverable D4.10). In the process efficiency (*ProcEff*) scenario, electrification in the chemical industry largely explains the relatively strong increase in power generation.

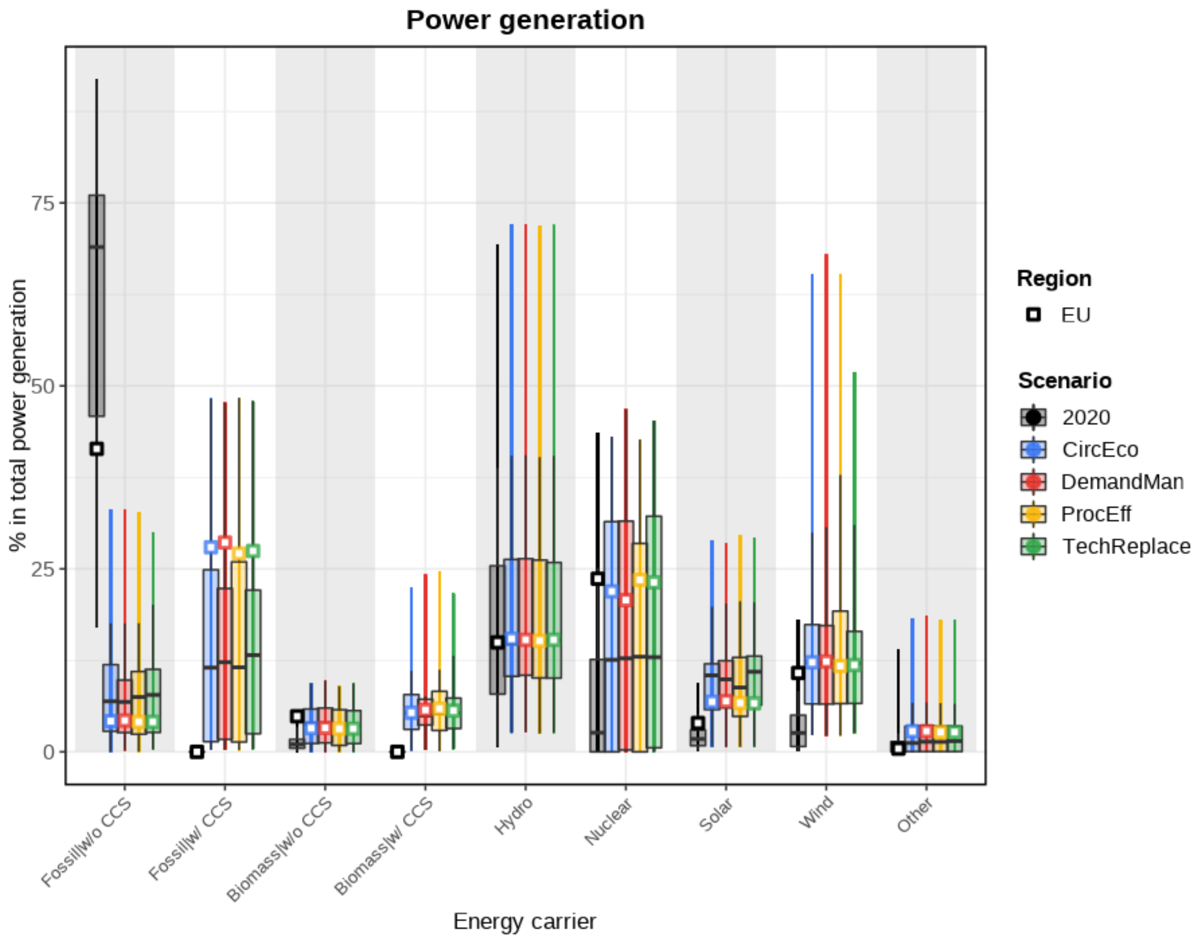

Figure 8. Power generation mix in the four scenarios for Europe and the IMAGE regions at the year in which net-zero emissions are achieved

The range of the bars represent up to 26 world regions in the IMAGE model. The number of included regions corresponds with the indicated number under "Electricity" in Figure 2.

While the total amount of power generation is not directly related to SDGs, there are important indirect relations. The most obvious one is with SDG7 (affordable & clean energy). Higher electricity demand will result in a higher risk of increased electricity prices. The demand management (*DemandMan*) scenario therefore has the strongest synergies with SDG7, as this scenario has the lowest electricity demand. This effect is stronger outside Europe than within Europe. As the pathways are only differentiated for industry, they do not show significant differences in the power generation mix.

4.3.2 Carbon capture and storage

As discussed in Section 4.1, carbon capture and storage has synergies and trade-offs with several SDGs. The total amount of carbon captured there gives an indication of the strength of these synergies and trade-offs. The differences in total carbon captured between the decarbonisation scenarios are relatively small (See Figure 9). The overall absolute annual volume of carbon emissions that needs to be captured and stored is higher for Europe than for the majority of IMAGE regions.

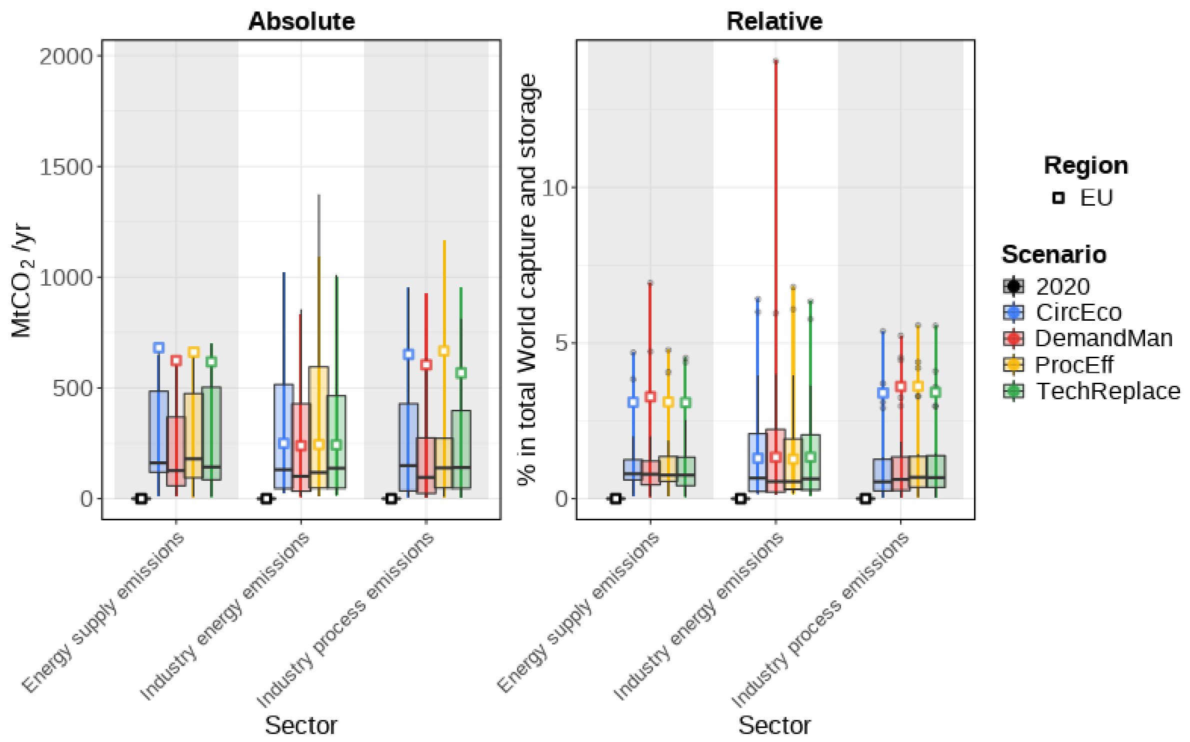

Figure 9. Total carbon capture and storage for Europe and the IMAGE regions at the year when net-zero emissions are achieved

The range of the bars represent up to 26 world regions in the IMAGE model. The number of included regions corresponds with the indicated number under "Full Economy" in Figure 2.

4.3.3 Land use

All decarbonisation scenarios show to use more cropland area than the 2020 levels. This is mainly due to the cultivation of bioenergy crops in all mitigation scenarios. Of all decarbonisation scenarios, the demand management (*DemandMan*) scenario shows the lowest use of cropland, which is due to less land needed for feed (as there is lower meat consumption and less food waste in this scenario). This is also the reason why pasture area is much smaller in this scenario, leaving more land available for forest. The technological replacement (*TechReplace*) scenario also has a relatively low pasture area, as meat is largely cultivated by 2050 in this scenario. In the process efficiency (*ProcEff*) scenario, higher livestock efficiency also leads to lower pasture area compared to baseline.

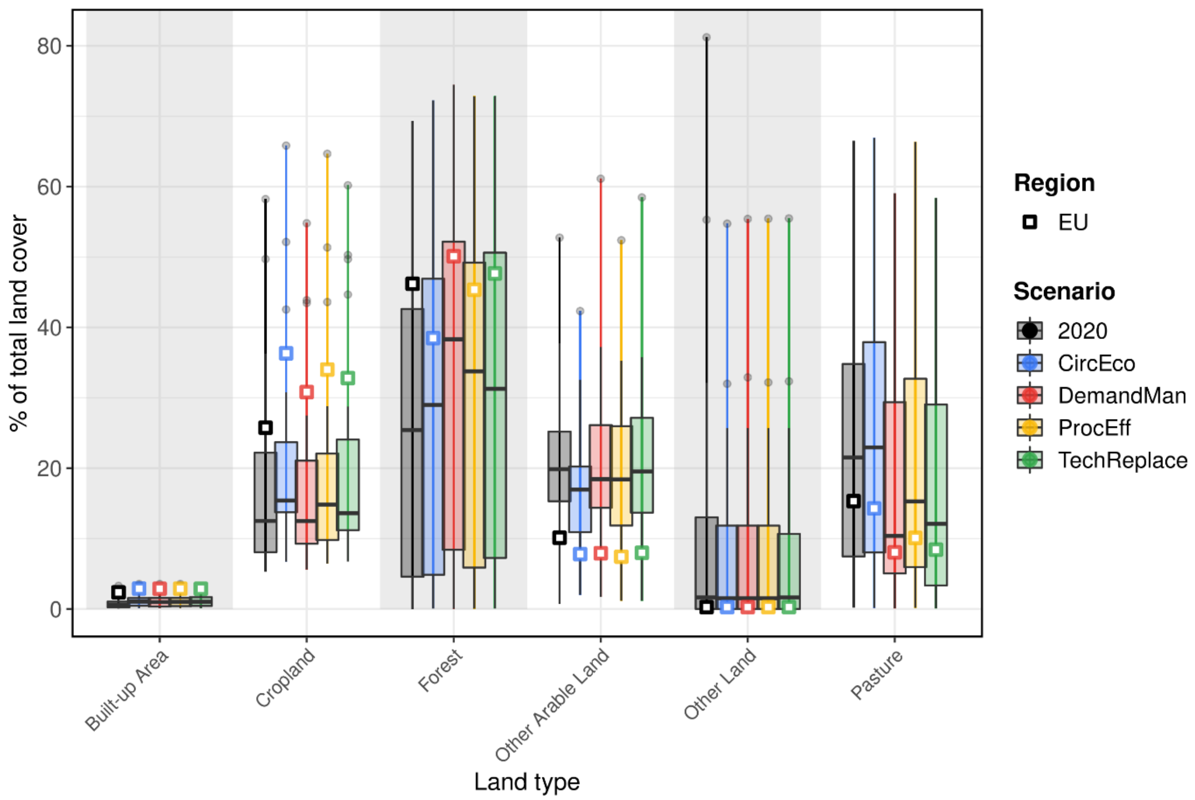

Figure 10. Land use coverage for Europe and the IMAGE regions at the year when net-zero emissions are achieved

The range of the bars represent up to 26 world regions in the IMAGE model. The number of included regions corresponds with the indicated number under "Full Economy" in Figure 2.

Changes in land use impact the non-CO_2 emissions. From all possible sources, the biggest contributor to methane emissions is the agriculture sector. Under stringent decarbonisation the methane emissions are projected to decline across all considered sources (see Figure 11). By assuming specific scenarios in which animal husbandry declines, this leads to lower agricultural methane emissions than in the other cases. Secondly, by invoking land-use change, or shifting to a greater use of cropland seems to be a promising option for mitigating N_2O emissions. N_2O mainly originates from the production and application of fertilizer and manure. As underscored in Figure 11 for the demand management (*DemandMan*) and technological replacement (*TechReplace*) scenario, more plant-based consumption and production leads to a greater fix of nitrogen from the atmosphere, and increases the nitrogen content in legumes (Prudhomme et al., 2020).

These results clearly show that the impact of changes in the food and dairy sector on SDGs are strong. In scenarios with more protein diversification, food waste reduction, improved efficiencies and yields, much less land for pasture is needed. This has a strong positive impact on achieving the targets set in SDG15 (life on land) and SDG3 (health and well being).

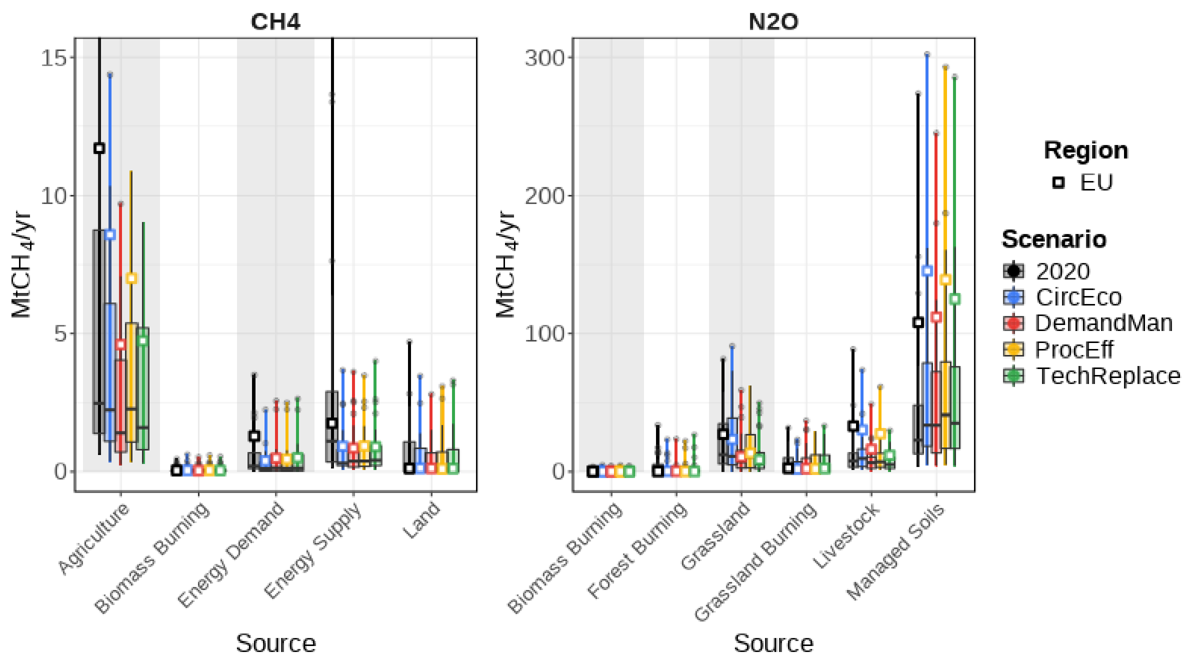

Figure 11 – Non-CO_2 emissions for Europe and the IMAGE regions at the year in which net-zero emissions are achieved.

The range of the bars represent up to 26 world regions in the IMAGE model. The number of included regions corresponds with the indicated number under “Full Economy” in Figure 2.

4.3.4 Air pollution

For the interaction with SDG3 (good health and well-being) we focus on emissions of sulfur dioxide (SO_2). Short-term exposures to SO_2 can harm the human respiratory system and make breathing difficult. People with asthma, particularly children, are sensitive to these effects of SO_2. Moreover, high concentrations of SO_2 in the air generally lead to the formation of other sulfur oxides (SO_x). SO_x can react with other compounds in the atmosphere to form small particles. These particles contribute to particulate matter (PM) pollution, which can penetrate deeply into the lungs and can contribute to health problems. At high concentrations, SO_x can also harm trees and plants by damaging foliage and decreasing growth.

The mitigation scenarios show to have quite some impact on total sulphur dioxide emissions, reducing it by about 80% under full decarbonisation. Over time, the industry sector becomes the main contributor of sulphur dioxide emissions. The decarbonisation scenarios differ in term of total industrial emissions of SO_2 (see Figure 12). The demand management (*DemandMan*) scenario has the lowest emissions of SO_2 and process efficiency (*ProcEff*) the highest. The latter can be explained by the fact that process efficiency (*ProcEff*) relies quite heavily on CCS, which has a marginal effect on reducing SO_2 emissions. Reducing activity levels, as assumed under demand management (*DemandMan*), results directly to lower SO_2 emissions. As a result both these pathways have stronger synergies with SDG3 (health and well being) than the other pathways.

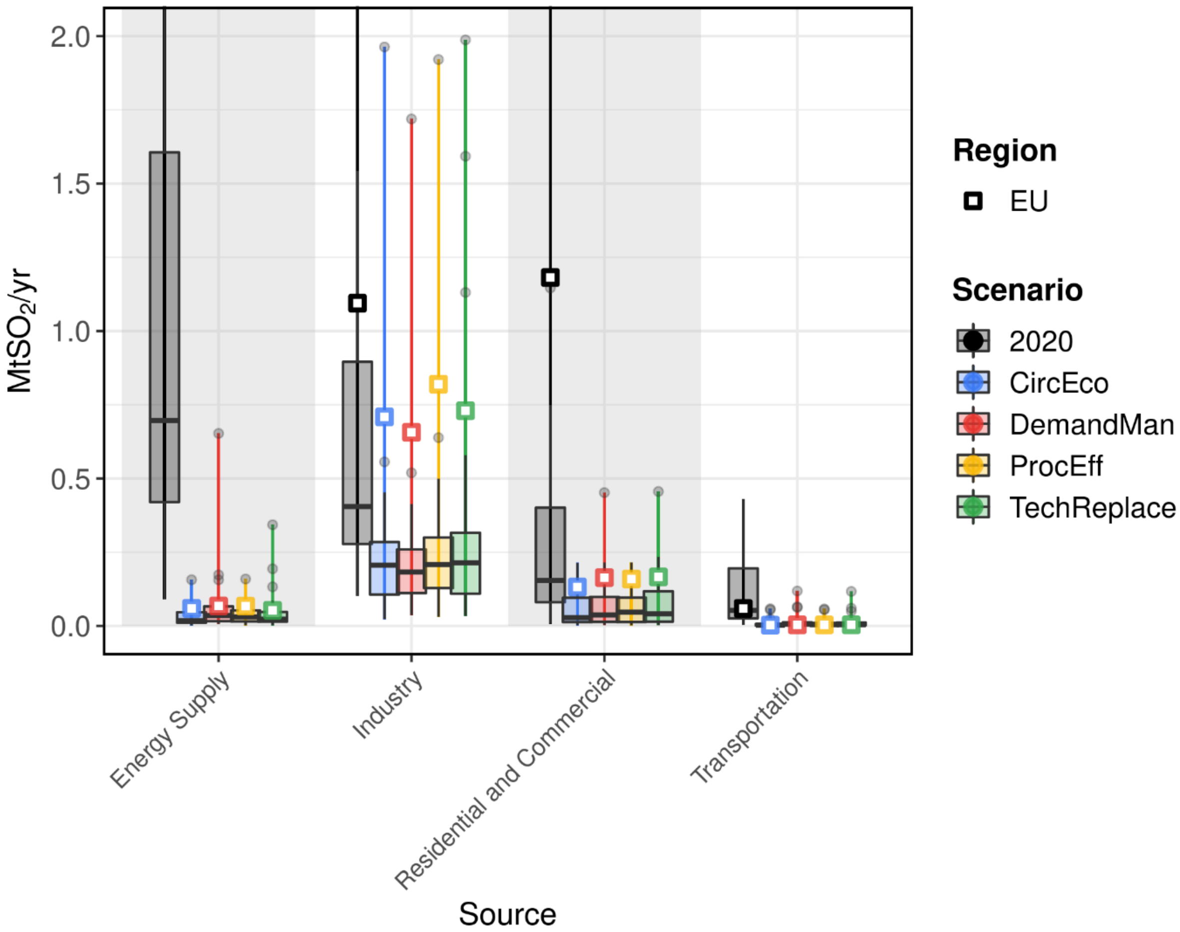

Figure 12. Sulfur dioxide emissions for Europe and the IMAGE regions at the year in which net-zero emissions are achieved.

The range of the bars represent up to 26 world regions in the IMAGE model. The number of included regions corresponds with the indicated number under "Full Economy" in Figure 2.

5 Discussion and conclusions

In this study we have analysed the results of the industry decarbonisation scenarios as developed in D3.7 (Lane, 2019), D4.3 (Schneider et al., 2020) and D4.10 (van Sluisveld et al., 2020) in a wider context. We synthesized the work to examine the economic, environmental and social equity impacts for the EU and other world regions in IMAGE.

Based on the analysis we draw the following conclusions from the integrated assessment:

- The industrial decarbonisation strategies presented in this work show that today's industrial systems can no longer exist in Europe. Current capital stock needs to be replaced or retrofitted with carbon capture and storage;
- The IMAGE model shows that the depicted European strategy can make the most of technical innovations of all the other regions; showing a high potential for biobased feedstocks and energy innovation.
- Net-zero emission ambitions need to be clearly defined and can imply different outcomes at different systemic levels. Carbon offsets are needed beyond sectoral boundaries to fully decarbonise various sectors across the modelled pathways.
- To achieve the EU's net-zero GHG ambitions, additional decarbonisation measures need to be pursued next to the ones currently presented in this research;

Synergies to SDGs:

- Industrial decarbonisation strategies have more synergies than trade-offs with the sustainable development goals (SDGs). The strongest synergies between electrification/CCS/CCU and SDGs are with SDG9 (industry, innovation, and infrastructure) and SDG12 (responsible consumption and production). Improving energy efficiency in industry has the strongest synergy with SDG7 (affordable and clean energy).
- The circular economy pathway has more synergies with the SDGs, as it targets both the sustainable development goal on industry, innovation and infrastructure (SDG9) and the goal on responsible consumption and production (SDG12);
- A carbon looping strategy has more synergies than a CCS strategy, but a CCS strategy can lead to much larger CO_2 reductions (even negative emissions under specific considerations);
- The demand management and Technological replacement pathways have strong synergies with i) health (SDG3) via reducing SO_2 emissions, and ii) land use (SDG11) by reducing pasture land use;

Unsurprisingly, the interactions identified in this work relate most to energy and earth system related SDGs. Much of the socio-cultural-institutional interactions are therefore unknown. As argued in van Soest et al. (2019), important areas of improvement for these kinds of studies lie in the human development and resource use areas. However, regardless of the many gaps in the representation of SDG targets, indicators, processes, and interactions in broader assessment studies, and recognizing the diversity of models available, they provide a good starting point for more comprehensive SDG assessments.

Furthermore, next to improving the research tools to better cover the interactions between the SDGs, it is also important to expand on the scope of research. As touched upon in this study, the synergies and trade-offs of certain decisions on the sustainable development goals can differ substantially on a regional level. Methodological development may be needed to account for these regional differences, as general assessments do not give justice to the complex interactions.

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