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COMMISSION STAFF WORKING DOCUMENT

IMPACT ASSESSMENT REPORT

Part 3

Accompanying the document

COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS

Securing our future

Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society

{COM(2024) 63 final} - {SEC(2024) 64 final} - {SWD(2024) 64 final}

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Annex 8: Detailed quantitative analysis of GHG pathways

1 KEY TRANSFORMATIONS TO CLIMATE NEUTRALITY BY 2050

The impact assessment explores different GHG emission pathways in the 2030-2050 period, building on the Fit-for-55 and REPowerEU policy package for 2030 and beyond, and achieving climate neutrality by 2050. The first section below describes the evolution of GHG emissions in the various pathways explored, looking at their reduction and the contribution of carbon removals. The following sections provide details on the associated transformation in various sectors: the energy system, with dedicated analysis on the energy supply, buildings, industry, transport, as well as non-CO_2 emissions, agriculture and LULUCF emissions.

The model-based analysis is a technical exercise based on a number of assumptions that are shared across scenarios. Its results do not prejudge the future design of the post-2030 policy framework.

1.1. GHG emissions

1.1.1. GHG budgets and net GHG emissions

1.1.1.1.GHG budgets

The target options provide different remaining GHG budgets for the period 2030-2050: 21 GtCO2-eq for the linear option, 18 GtCO2-eq for option 2 (at least 85% up to 90%) and 16 GtCO2-eq for option 3 (at least 90% up to 95%) (see section 5.2 in the main document).

The ESABCC analyses a (intra-EU) range of 11-16 GtCO2-eq for the EU to contribute to limiting global warming to 1.5°C with no or limited overshoot (1). The ESABCC report highlights that scaling-up of energy technologies beyond challenging levels is required to achieve the more ambitious end of this range: not overcoming such technological deployment challenge moves the range to 13-16 GtCO2-eq. ESABCC also recommends a range of 11-14 GtCO2-eq (9).

1.1.1.1.Net GHG emissions

The scenarios achieve net GHG reductions in line with the budgets associated to each target option.

Table 1 shows the 2040 and 2050 net GHG emissions in S1, S2, S3, and LIFE (see Annex 6 for their description), as well as the corresponding reductions compared to 1990. The values are provided for Union-wide GHG emissions and removals regulated in Union law, in accordance with the climate neutrality target scope (2). With the fit-for-55

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(1) The ESABCC provides ranges for intra-EU emissions which do not take into account international emissions under Union Law as in the European Climate Law and analysed in this impact assessment.

(2) Regulation (EU) 2021/1119, Article 2

package (3), this covers all domestic net emissions (in the sense of the UNFCCC inventories), international intra-EU aviation, international intra-EU maritime, and 50% of international extra-EU maritime from the Monitoring Reporting and Verification (MRV) scope (4). The table also provides a range to illustrate the uncertainties on the future evolution of LULUCF net removals, considering a lower level and an upper level depending on the effect of policies or other factors (See 1.8 of this Annex for more details).

Table 1: Net GHG emissions and reductions compared to 1990

	2040				**2050**	
	S1	**S2**	**S3**	***LIFE***	**S3**	***LIFE***
Total Net GHG - MtCO2-eq	**1051 [1051 to 893]**	**578 [681 to 520]**	**356 [458 to 298]**	**353 [469 to 302]**	**-38 [90 to -100]**	**-70 [85 to -117]**
Reduction vs 1990 - %	-78% [-78% to -81%]	-88% [-86% to -89%]	-92% [-90% to -94%]	*-93% [-90% to -94%]*	-101% [-98% to -102%]	*-101% [-98% to -102%]*

Note: Main values reported correspond to the LULUCF net removals considered in the scenarios, with net GHG emissions with lower and upper level of LULUCF net removals are in brackets. S1 and S2 values for 2050 are similar to S3.

Source: PRIMES, GLOBIOM, GAINS.

While all scenarios achieve climate neutrality in 2050, in 2040, the net GHG emissions are clearly different across scenarios.

S1 leads to total net GHG emissions reaching about 1050 MtCO2-eq (ranging down to 890 MtCO2-eq depending on the behaviour of the LULUCF net removals), representing a reduction of 78% compared to 1990. This scenario focuses on strengthening the existing trends with limited contribution of more advanced mitigation options supported by novel technologies (5) by 2040 and fits a linear trajectory of net GHG emissions between 2030 and climate neutrality in 2050.

The S2 scenario deploys the full potential of existing decarbonisation solution, such as electrification and renewable and relies upon novel technologies such as carbon capture and a higher uptake of e-fuels using fossil free carbon (see sections 1.1.3 and 1.2 in this Annex), as well as further abatement in the agriculture sector (see 1.1.4 and 1.7). It reaches about 580 MtCO2-eq in 2040, or 88% reduction compared to 1990 (ranging between 86% and 89%).

The S3 scenario foresees early implementation of novel technologies to attain net GHG emissions levels of around 360 MtCO2-eq in 2040, and a reduction level of -92%, with a range between -90% and -94%.

LIFE implements additional circular economy and sufficiency actions in industry, transport and agriculture, achieving similar reduction as per S3, but with a different sectoral distribution of emission (see 1.1.2 in this Annex). This setting illustrates the

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(3)COM/2021/550 final

(4) Regulation (EU) 2015/757 (amended by Regulation (EU) 2023/957)

(5) Not yet commercially available at large scale, such as carbon capture and renewable hydrogen

important role of demand-side policies and measures to reduce GHG emissions, and to enhance the environmental performance of mitigation actions by limiting the consumption of natural resources, including raw materials and land or further improving some direct environmental benefits of climate action (see sections 1.4, 1.7.5 and 1.9.1).

The levels of emission reductions achieved in the different scenarios are in line with ranges found in the literature, spanning from 84% to 89% (6), from 87% to 91% (7), around 89% (8) and from 88 to 95% by the ESABCC (9).

The distribution of emissions between CO2, non-CO2 gases and GHGs coming from LULUCF sector is reported in Table 2. A more detailed analysis of the sectoral reduction for S1, S2, S3 and LIFE is described in the following sections.

Table 2: CO2, non-CO2 and emissions from LULUCF sector.

	2040				2050	
	S1	**S2**	**S3**	**LIFE**	**S3**	**LIFE**
Total Net GHG - MtCO2-eq	**1051**	**578**	**356**	**353**	**-38**	**-70**
*CO2 (excl. LULUCF) * – MtCO2*	815	521	331	432	5	83
*Non-CO2 (excl. LULUCF) ** – MtCO2-eq*	454	373	342	281	291	236
*LULUCF*** – MtCO2-eq*	-218	-316	-317	-360	-333	-389

*Note: *includes CO2 from fossil fuel combustion (category 1 in inventories), industrial processes and product use (category 2) and agriculture under category 3. **Includes non-CO2 emissions under categories 1, 2, 3 and 5 of the inventories. ***Only main values are reported.*

1.1.2. GHG emissions and role of removals

According to the IPCC, reductions in gross GHG emissions, nature-based and industrial carbon removals are all needed to reach net zero (10). While gross GHG emissions need to decrease significantly, the deployment of carbon removals is unavoidable to counterbalance hard-to-abate residual emissions and replace residual fossil fuels. However, relying primarily on carbon removals without intervening in gross GHG emissions may be unrealistic since the potential for removals is limited by land constraints, feasibility, cost-efficiency, public acceptance and technological consideration (11).

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(6) ECEMF (2023), ECEMF Policy Brief: Insights on EU2040 targets based on a model intercomparison exercise of EU Climate Neutrality Pathways. DOI 10.5281/zenodo.8337667. https://zenodo.org/record/8337668 Full model range, including international bunkers.

(7) Rodrigues et al., (2023). 2040 greenhouse gas reduction targets and energy transitions in line with the EU Green Deal, *Nature Communication,* Under Review. Intra-EU scope.

(8) Graf, A., et al. (2023). Breaking free from fossil gas. A new path to a climate-neutral Europe. Agora Energiewende.

(9) ESABCC (2023). Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050. DOI: 10.2800/609405. Table 9, Table 12. The range spans from 88-92% and up to 95% if technological challenges can be overcome.

(10) IPCC (2022): *Climate Change 2022: Mitigation of Climate Change.* Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

(11) CLG Europe (2023). Raising European Climate Ambition for 2040 A CLG Europe position paper.

The increasing role of carbon removals is also highlighted in the public consultation questionnaire, where majority of respondents (around 65%, including all categories) calls for 2040 carbon removal targets separate from net emission, and experts from the academic, economic and public sectors are in favour of an important role of the carbon removals. 61% of the papers analysed also comment on carbon removals, with most of them indicating removals instrumental to reach climate neutrality, if complementary to GHG emission reduction at source. There is no clear preferred pathway indicating the contribution of nature-based vs industrial removals. In position papers, the emphasis of forests as carbon sink is underlined, while carbon capture for industrial removals plays an important role for energy-intensive industries to reduce hard-to-abate emissions within the sector. The public consultation indicates a general slight inclination for relying on nature-based removals (around 30% of respondents) or a balanced approach between nature-based and industrial removals (around 27% of respondents). This preference is confirmed also when looking individually at the different stakeholder groups, except for large businesses and SMEs, who expressed by majority a preference for either a balance between nature-based and industrial removals or a stronger reliance on industrial removals.

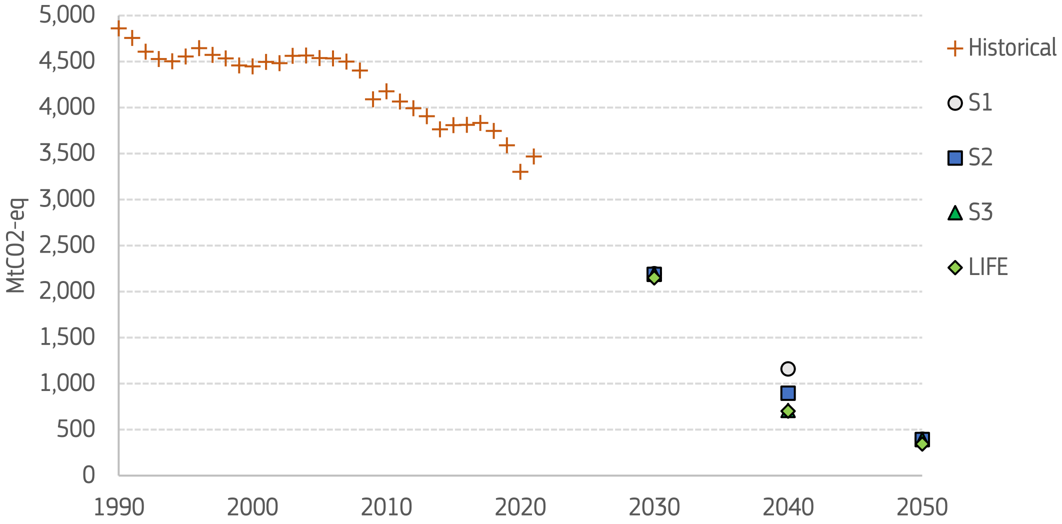
1.1.2.1.Gross GHG Emissions

The “gross GHG” emissions are defined as the actual GHG emissions excluding the contribution of industrial removals and net LULUCF removals that are part of the computation of “net GHG” emissions meeting EU’s climate objectives for 2030 and 2050.

Figure 1 shows the evolution of EU gross GHG emissions over 1990-2050. In 2021, EU gross emissions achieved around 3570 MtCO2-eq, with a reduction of around 28% compared to 1990 ([12]). The trajectory until 2030 is consistent with the Fit-for-55 policy package, where emissions reach around 2300 MtCO2-eq. Post-2030, these emissions keep decreasing in all scenarios, albeit at difference pace by 2040 and beyond. They reach about 400 MtCO2-eq in 2050, when they are compensated by industrial and LULUCF net carbon removals to converge to climate neutrality.

([12]) EEA Greenhouse Gases Data Viewer. DAS-270-en Published on 18 Apr 2023

Figure 1: Domestic Gross GHG emissions



Note: Gross GHG emissions represented here include only domestic emissions and excludes industrial carbon removals and the LULUCF net removals.

Source: PRIMES, GAINS.

Table 3 summarises the gross GHG emission by sector. In S1 gross GHG emissions decrease following a linear profile over 2031-2050, reaching around 1270 MtCO2-eq in 2040, which correspond to a decrease of around 75% compared to 1990 levels. Most sectors undergo significant emissions reductions already over 2031-2040, with emissions ranging from around -70% in the domestic transport sectors to about -10% in agriculture. The S2 scenario achieves further reductions of gross GHG emissions by 2040, reaching around 940 MtCO2-eq or 80% reduction compared to 1990. Significant additional reductions with respect to S1 take place notably in power and heat, industry and agriculture. The S3 scenario achieves a reduction of around 85% in 2040, driven by extra reductions to S2 in all sectors, including the industry sector, where they are triggered by higher recourse to carbon capture and storage of fossil fuels (see section 1.1.3.2), the power system, buildings and transport. LIFE, which aims at the same overall reduction as S3, redistributes gross emissions across the different sectors. While energy and industry sectors reduce to a level intermediate between S2 and S3, mostly due to a lower use of e-fuels and DACC, agriculture emissions reduce more than in S3.

Table 3: Gross GHG emissions

MtCO2-eq		2005	2015	2030	2040				2050			
					S1	S2	S3	*LIFE*	S1	S2	S3	*LIFE*
Total Gross GHG Emissions		**4641**	**3914**	**2301**	**1273**	**943**	**748**	***740***	**416**	**413**	**411**	***360***
Power and district heating		1300	1012	339	123	42	23	*34*	21	22	19	*15*
*Other Energy sectors**		277	237	133	71	59	53	*57*	39	39	38	*36*
Industry (Energy)		469	360	232	126	94	75	*86*	6	6	9	*11*
Domestic Transport		822	772	583	190	143	120	*134*	10	8	7	*9*
*Residential and Services***		648	514	221	119	92	75	*92*	20	19	19	*29*
Industry (Non-Energy)		343	233	157	139	88	14	*13*	7	7	7	*7*
*Other Non-Energy sectors****		101	130	56	33	26	25	*25*	23	22	22	*22*
International transport (target scope)	*Intra-EU aviation*	35	38	43	31	29	28	*14*	14	12	11	*10*
	Intra-EU navigation	31	27	25	7	6	4	*0*	0	0	0	*0*
	50% extra-EU maritime MRV	50	42	44	14	11	9	*0*	0	0	0	*0*
*Agriculture*****		390	385	361	351	302	271	*209*	*249*	*249*	*249*	*194*
Waste		155	118	87	68	55	55	*55*	*32*	*32*	*32*	*.32*
CO2 calibration		15	43	24	3	-1	-1	*-1*	0	0	0	*0*
Non-CO2 calibration		5	2	-3	-3	-3	-3	*-3*	*-3*	*-3*	*-3*	*-3*
Memo Items												
International aviation (Intra-EU and Extra-EU)		96	103	117	83	80	78	73	38	34	31	27
International maritime (Intra-EU and Extra EU)		152	129	134	41	33	25	33	0	0	0	0

*Note: Calibration of total to inventory 2023. *Includes emissions from energy branch and other non-CO2 emissions from the energy sector; **Includes fossil fuel combustion in the agriculture/fishery/forestry sector; ***Includes CO2 fugitive emissions and non-CO2 emissions from direct use or specific products (e.g., aerosols, foams, etc). **** Excludes fossil fuel combustion in the sector, but includes "category 3" CO2 emissions, assumed constant at 10 MtCO2.*

Source: PRIMES, GAINS.

Sectors that reduce little in 2031-2040 accelerate their decarbonisation in the 2041-2050 decade, while sectors that have already reached low emissions levels by 2040, maintain or slow down the reduction rate by 2050, leading to a balanced contribution to climate neutrality for all sectors across 2030-2050. Overall, gross GHG emissions in 2050 reduce to -92% vs 1990 across all scenarios.

1.1.2.2.Nature-based carbon removals

Table 4 shows the LULUCF net removals in the different scenarios. The central level for 2040 is close to -320 MtCO2-eq in all scenarios by 2040, slightly above the target for 2030 (-310 $MtCO_2$-eq). The differences between S1, S2 and S3 are driven by the different bioenergy needs in the energy systems underpinning the scenarios (see section 1.8 in this Annex). LIFE is characterised by a different food system that frees up land for carbon farming activities such as afforestation.

The table also provides a range (from lower level to upper level) to illustrate the uncertainties on the future evolution of LULUCF net removals, depending on the effect of policies or other factors (see section 1.8 in this Annex).

Table 4: LULUCF net removals by scenarios in 2040 and 2050

MtCO2-eq	2040				2050			
	S1	S2	S3	*LIFE*	S1	S2	S3	*LIFE*
Lower level	***-218***	*-213*	*-215*	*-243*	*-213*	*-202*	*-206*	*-234*
Central level	*-319*	***-316***	***-317***	***-360***	***-341***	***-332***	***-333***	***-389***
Upper level	*-376*	*-374*	*-376*	*-410*	*-403*	*-394*	*-396*	*-436*

Note: The 'Central level' is derived from applying in the modelling the same policy intensity as the one necessary to meet the 2030 target, except for S1 in 2040. The 'Lower level' is derived from assuming no additional cost as the lower boundary of the LULUCF net removals level. The 'Upper level' is derived from the maximum mitigation potential as the upper boundary of the LULUCF net removals level. The ***numbers in bold*** *are used to compute the overall net GHGs for the different scenarios.*

Source: GLOBIOM

The expected contribution of LULUCF to the 2040 climate target stays within the boundaries of the ESABCC, which discusses an upper bound of 400 MtCO2-eq in 2040 (13) and describes three iconic scenarios that display a larger range from 323 MtCO2-eq to 601 MtCO2-eq in 2040 and from 312 MtCO2-eq to 669 MtCO2-eq in 2050 (14).

Section 1.8 in this Annex provides more details on the LULUCF sector and the related GHG emissions and removals.

1.1.2.3.Industrial carbon removals

Industrial carbon removals, together with nature-based removals, are projected to play an increasing role in the EU economy in the next decades (15), in the view of balancing EU GHG emissions by 2050, and achieving negative emissions thereafter (16).

Industrial removals can contribute to compensate residual GHG emissions from hard-to-abate sectors. They can also progressively replace fossil carbon feedstock in processes like the production of plastics or e-fuels (17), (18) and become the main source of (fossil-free) carbon in sectors where carbon will still be needed in the long-term.

Figure 2 shows the industrial removals projected by PRIMES and differentiated by their source. The total amount of carbon removed until 2040, whether captured from the atmosphere, from biomass combustion or from biogas upgrading, varies across scenarios. Removals are projected to remain marginal in the S1 scenario by 2040, to reach

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(13)ESABCC (2023). Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050. DOI: 10.2800/609405. Section 7.7.1. This risk level was based on research by Pilli et al. (2022) who provide as a probable range of -100 to -400 MtCO$_2$-eq for the LULUCF sink in 2050 taking future climate change impacts based on RCP 2.6 into account. Scenarios exceeding the upper bound of -400 MtCO$_2$-eq may rely on implausibly high LULUCF sink levels.

(14) Ibid. Table 15

(15) COM(2021) 800 final

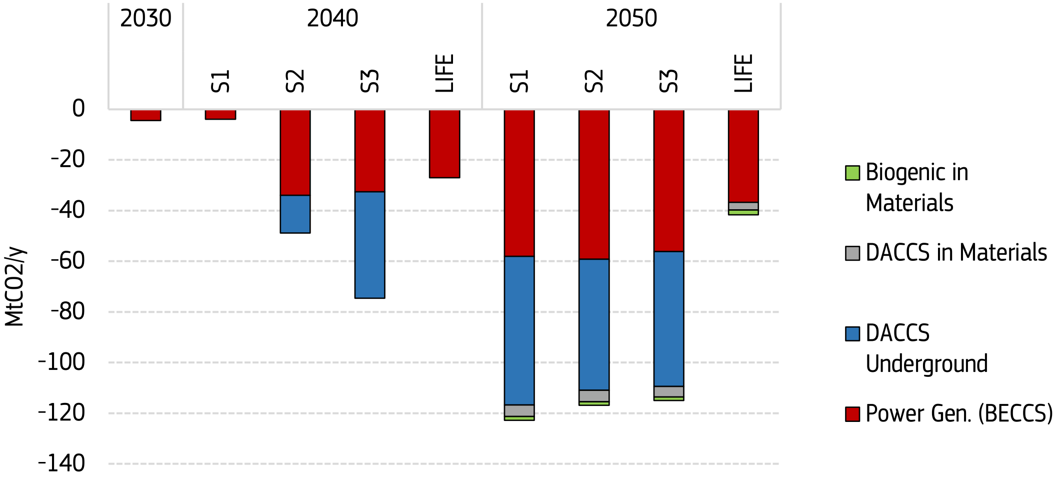
(16) European Climate Law (Regulation (EU) 2021/1119), Article 2.

(17) The Global CO2 Initiative (2016). Global Roadmap for Implementing CO2 Utilization.

(18) CEFIC (2021). Shining a light on the EU27 chemical sector's journey toward climate neutrality.

50 MtCO2 in S2 and up to 75 MtCO2 in S3. Removals deploy progressively from S1 to S3 and allow for higher reductions of net GHG emissions (see also Figure 7). LIFE models lower carbon removals: demand-side actions and enhanced LULUCF net removals can reduce the need for industrial removals, and, in this projection, eliminate the recourse to DACC in 2040.

Figure 2: Carbon removals by source and use



Source: PRIMES.

The amount of carbon removed by industrial means in 2050 is similar across scenarios and reaches around 120 MtCO2/y, suggesting the need for significant carbon removals to achieve climate neutrality. While most of the storage takes place in underground sites, limited storage in permanent materials also appears in the last decade. The slightly higher values for S1 are required to compensate for delayed climate action in 2031-2040.

While the modelling shows a similar share of BECCS and DACCS by 2040 in S3 and beyond by 2050, their actual relative deployment will depend on a number of factors, e.g.: high costs and technological uncertainty (DACCS ([19]) ([20])), cost and competition on biomass resource and possible negative impact on LULUCF (BECCS ([21])([22])([23]), see

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([19]) Motlaghzadeh, K., Schweizer, V., Craik, N., & Moreno-Cruz, J. (2023). Key uncertainties behind global projections of direct air capture deployment. *Applied Energy*, 348, 121485. https://doi.org/10.1016/j.apenergy.2023.121485.

([20]) Lehtveer, Mariliis & Emanuelsson, Anna. (2021). BECCS and DACCS as Negative Emission Providers in an Intermittent Electricity System: Why Levelized Cost of Carbon May Be a Misleading Measure for Policy Decisions. *Frontiers in Climate*. 647276. 10.3389/fclim.2021.647276.

([21]) Slade, R., Bauen, A., and Gross, R. (2014). Global bioenergy resources. Nat. Clim. Change 4:99. doi: 10.1038/nclimate2097

([22]) Creutzig, F., et al. (2015). Bioenergy and climate change mitigation: an assessment. GCB Bioenergy 7, 916–944. doi: 10.1111/gcbb.12205

([23]) Directive (EU) 2018/2001 (amendment to be published) section 1.8 in this Annex), creation of the transport and storage infrastructure, public acceptance and equitable and sustainable technology scale up (24).

Both technologies add requirements on the ambitious and challenging industrial sectors' decarbonisation plans, and these needs to be coupled effectively with feasibility analysis and supporting measures as appropriate. While the scenarios filtered by the ESABCC attribute a minor role to carbon captured from the atmosphere (25), the IEA indicates that more efforts are needed to fully develop DACCS (26). The demand side, with the amount of e-fuels required by other sectors and the need to compensate residual emissions, will also influence the deployment of each technology.

Given the lack of predictability for the uptake of one removal technology over another by 2040, a comparison between different deployment pathways is performed.

Figure 3 compares the industrial carbon removals obtained in 2040 with the PRIMES model, with deployment pathways projected by the POTEnCIA model. In PRIMES (Figure 3, left) BECCS tends to come first, and considerations of sustainable biomass availability limits its expansion. The remaining needs for removals are fulfilled by DACCS, which appears as complementary to BECCS. The POTEnCIA model (Figure 3, right), where the cap on the amount of sustainable biomass supply for bioenergy is relaxed (see also Annex 6), illustrates a stronger deployment of BECCS, reaching up to around 80 MtCO2 in 2040 in S3, complemented by storage of biogenic carbon from biogas upgrade and very limited development of DACCS. Higher recourse to BECCS leads to an increase of bioenergy demand, with a possible negative impact on the LULUCF net removals (see 1.8.2).

Both pathways modelled provide an amount of total industrial removals in 2040 lower than the estimated maximum in the scenarios considered by the ESABCC, corresponding to 214 MtCO2 (27), and consistent with ranges of 10-220 MtCO2 that can be found in the literature (28), (29), (30), (31).

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(24) Liebling K., et al. (2023). International Governance of Technological Carbon Removal: Surfacing Questions, Exploring Solutions.

(25) ESABCC (2023). Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050. DOI: 10.2800/609405. Table 16.

(26) IEA (2023), Tracking Direct Air Capture. Accessed on 14-08-23

(27) ESABCC (2023). Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050. DOI: 10.2800/609405. Table 16 summing DACCS and BECCS.

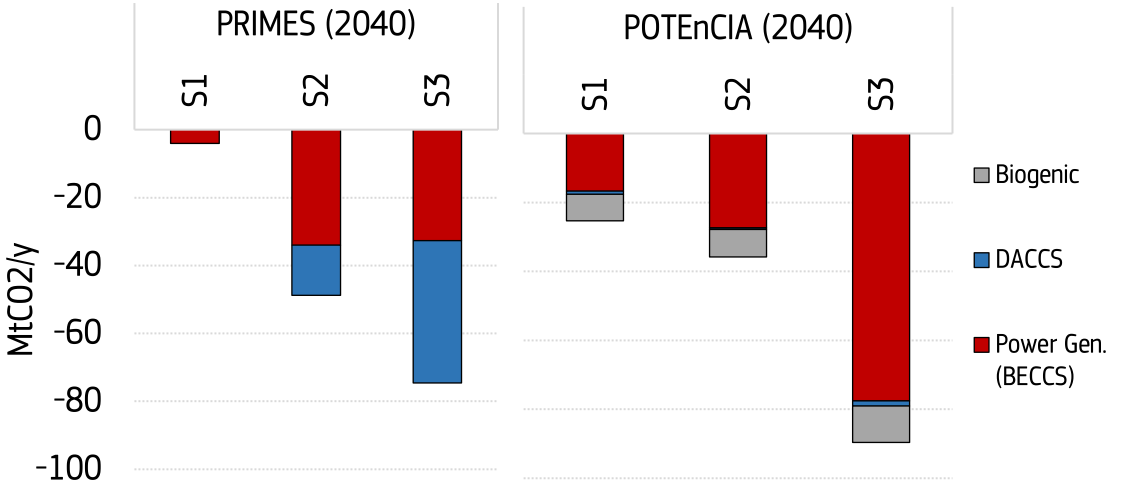
(28) Rodrigues et al., (2023). 2040 greenhouse gas reduction targets and energy transitions in line with the EU Green Deal, *Nature Communication*, Under Review.

(29) Kalcher, L. et al., (2023). The post-2030 climate target debate starts now, *Strategic Perspectives and Climact*. https://strategicperspectives.eu/the-post-2030-climate-target-debate-starts-now/

(30) Graf, A., et al. (2023). Breaking free from fossil gas. A new path to a climate-neutral Europe. *Agora Energiewende.*

(31) Climate Analytics (2022). 1.5°C National Pathways Explorer. *Climate Analytics*.

Figure 3: Industrial carbon removals in PRIMES and POTEnCIA in 2040



Source: PRIMES, POTEnCIA.

1.1.2.4.Balancing emissions and removals

In Figure 4, gross GHG emissions (excluding all removals) only reduce between 75% and 85% in 2040 and around 92% in 2050 (vs 1990 (32)). In comparison, net GHG emissions (including all removals) reduce more and achieve net-zero in 2050. This suggests that removals complete other mitigation options and are needed to achieve climate neutrality. In 2040, the PRIMES modelling analysis shows that total (industrial and LULUCF net) removals range from around 220 MtCO2-eq in S1 to around 390 MtCO2-eq in S3 (with upper level of LULUCF net removals). Around 360 MtCO2-eq are needed to achieve net reductions of 90% and beyond in 2040 (considering the lowest level of gross emissions projected in S3), with this value increasing in the range of 430-460 MtCO2-eq in 2050 to attain net-zero.

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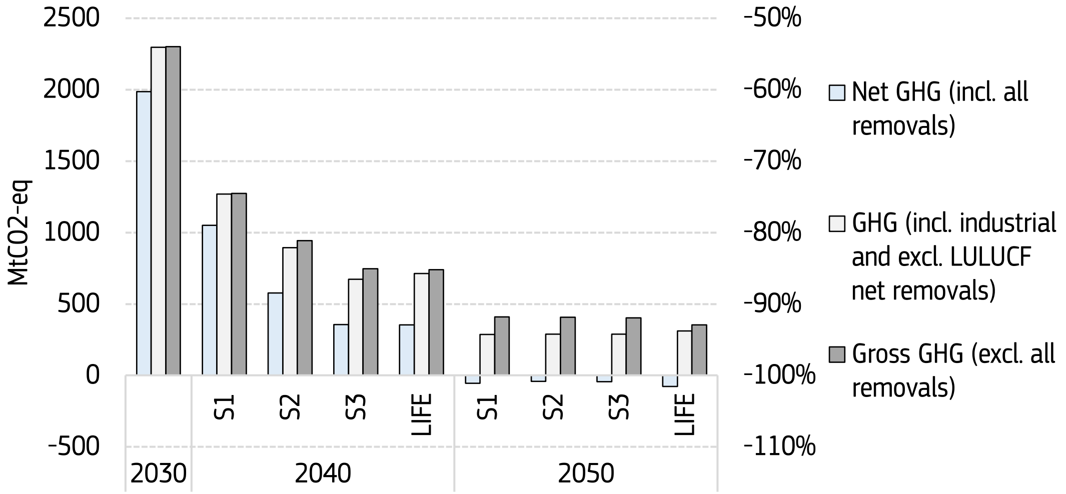
(32) In line with the remaining gross emissions without counting compensation from removals analysed by the ESABCC and corresponding to around 390 MtCO2.

Figure 4: Net and Gross GHG Emissions and % reductions vs 1990



Note: "Net GHG" includes domestic emissions, international intra-EU aviation and maritime transport and 50% of extra-EU maritime transport (as per MRV). "Excl. LULUCF" subtracts the LULUCF net removals from net GHG. "Excl. all removals" subtracts industrial removals and LULUCF net removals from net GHG, resulting in gross GHG emissions.

Source: PRIMES, GAINS.

Table 5 summarises the model projections on different type of removals and show that nature-based and industrial removals play different roles. While LULUCF net removals contribute significantly in 2030 and along until 2050, the role of industrial removals becomes more relevant from 2040 in pathways with the lowest carbon budget (S3) and by 2050 in all cases. LIFE always shows a relative higher contribution of LULUCF net removals compared to industrial removals, and a slightly more moderate recourse to overall removals in 2050. This means that all pathways need a strong LULUCF net removals, which needs to be complemented by industrial solutions.

Table 5: LULUCF net removals and industrial carbon removals

	2030	**2040**				**2050**			
		S1	**S2**	**S3**	**LIFE**	**S1**	**S2**	**S3**	**LIFE**
Total Removals (MtCO2-eq)	-314	**-222 [-222 to -380]**	**-365 [-262 to -423]**	**-391 [-290 to -450]**	**-387 [-270 to-437]**	**-462 [-334 to -525]**	**-447 [-318 to -510]**	**-447 [-319 to -509]**	**-428 [-274 to -476]**
Net LULUCF sink (MtCO2-eq)	-310	-218 [-218 to -376]	-316 [-213 to -374]	-317 [-215 to -376]	-360 [-243 to -410]	-341 [-213 to -403]	-332 [-202 to --394]	-333 [-206 to -396]	-389 [-234 to -436]
Industrial Removals (MtCO2)	-4	-4	-49	-75	-27	-121	-115	-114	-40
BECCS	*-4*	*-4*	*-34*	*-33*	*-27*	*-58*	*-59*	*-56*	*-37*
DACCS	*0*	*0*	*-15*	*-42*	*0*	*-63*	*-56*	*-57*	*-3*

Source: PRIMES, GLOBIOM.

The 36 scenarios selected by the ESABCC (33) offer an overview of the possible balances between removals and emission reductions: for 2040, the level of gross emission lies

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(33) The range refers to the 36 filtered scenarios, including also scenarios not complying with environmental risk that led to an emission reduction for 2040 between 83% and 96%.

between 1596 and 697 MtCO2-eq (34) and the contribution of removals is split into land-based removals (range between -100 and -400 MtCO2-eq, with majority between -300 and -400 MtCO2-eq) and industrial removals (BECCS and DACCS ranging between -46 and -214 MtCO2, with majority around -200 MtCO2) (35).

In the modelling analysis, the amount of projected gross GHG emissions in 2040 and the contribution of nature-based removals lies within the range of the 36 ESABCC scenarios studied by the ESABCC. Instead, while the industrial removals in the main scenarios lie in the lower end of the range of the 36 scenarios analysed, achieving reductions up to 90% and beyond in 2040 cannot rely only on LULUCF net removals and needs to be complemented by development of industrial removals.

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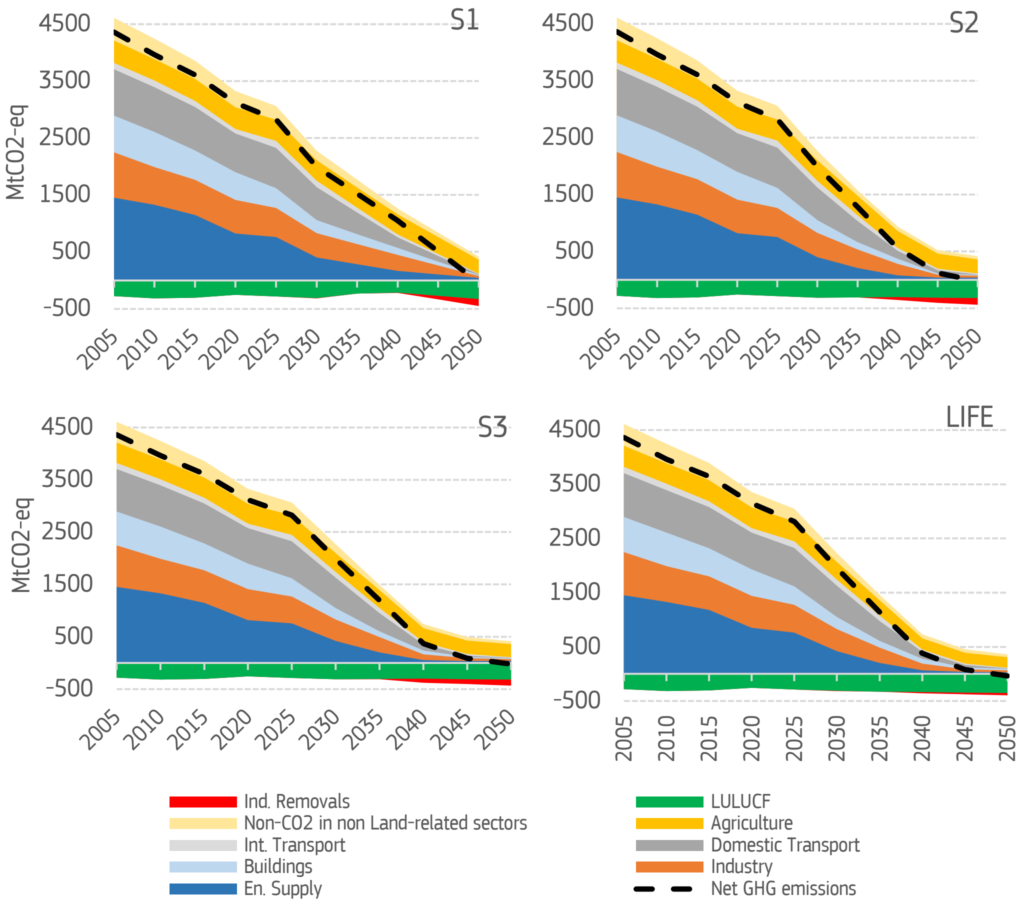
(34) ESABCC (2023). Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050. DOI: 10.2800/609405. Figure 37

(35) Ibid., Figure 35, Figure 36 and Table 16

1.1.2.5.GHG pathways

Figure 5 summarises the analysis of the previous sections and shows the net economy-wide GHG emission pathways. While all scenarios follow the same pathway until 2030, they diverge after that year, leading to distinct trajectories for the 2030-2050 decade before converging to net-zero by 2050.

Figure 5: Economy-wide GHG emission pathways



Source: PRIMES, GAINS, GLOBIOM.

1.1.3. Energy and Industry CO2 emissions

1.1.3.1.Net CO2 emissions

Figure 6 shows the trajectories for the energy and industry net CO2 emissions (36) in the different scenarios.

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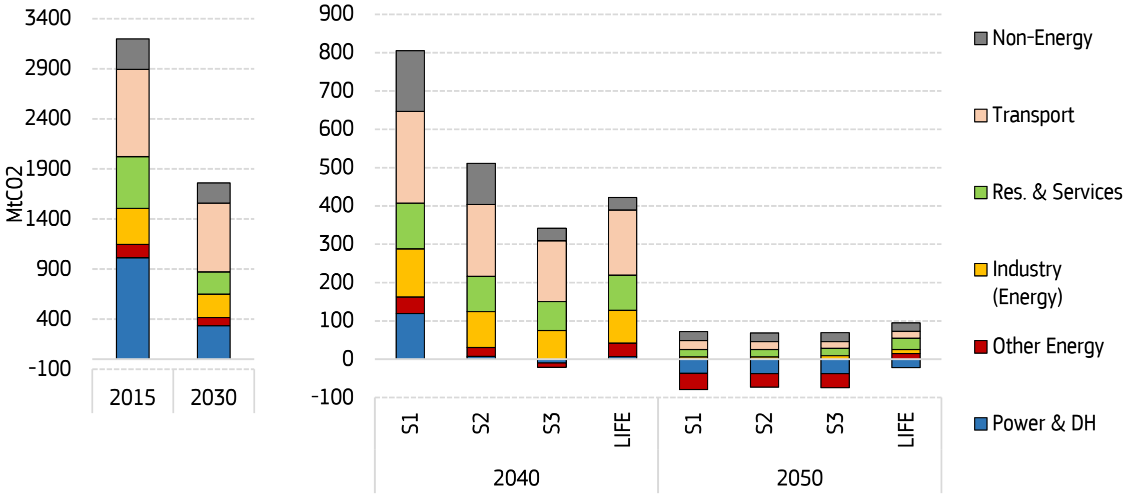
(36) The emissions scope includes the net domestic energy-related CO2, the net domestic non-energy related CO2, the intra-EU transport and 50% of the international extra-EU maritime as per MRV.

Figure 6: Energy and Industry net CO2 emissions



Note: Power and District Heating (DH) include BECCS. Other energy includes energy branch and DACCS. Residual and services includes fossil fuel combustion in the agriculture/fishery/forestry sector. Non-Energy includes industrial processes and fugitive emissions.

Source: PRIMES.

In line with current policies, CO2 emissions from the energy sector are projected to more than halve already in 2030 with respect to 2015. Achieving net-zero in 2050 projects net CO2 emissions in 2040 to be in the range of 330-800 MtCO2 across scenarios, meaning a reduction between 80% and 92% compared to 1990. S3 reduces emissions by an additional 500 MtCO2 with respect to S1: this amount corresponds to around 20% of 2030 total net GHG emissions, indicating the important contribution of the energy and industry sectors to decarbonise the EU economy already by 2040. In 2050, the sum of emissions coming from all sectors analysed achieves slightly negative levels in all scenarios, with industrial carbon removals compensating for the residual hard-to-abate emissions. LIFE shows a level of energy and industry CO2 emissions intermediate between S2 and S3 in 2040, and slightly higher emissions of around 70 MtCO2 in 2050. These additional emissions are compensated by lower emissions in agriculture (see 1.7) and enhanced land-based removals (see 1.8), highlighting a redistribution of emission reductions across sectors: total net GHG emissions levels comparable to S3 are achieved in LIFE mostly with a reduced need for industrial carbon capture.

The domestic CO2 emissions (Table 6) decrease significantly already in the decade 2031-2040 and reach slight negative levels in the main scenarios in 2050. Energy related emissions (37) in 2040 are between 40% and 20% the level of 2030, with the power generation, district heating and transport sectors reducing the most, driven by the decarbonisation of the power system, the energy efficiency measures and the implementation of renewables in final energy sectors. Residual energy emissions are then reduced gradually in the decade 2041-2050 and reach cumulative negative values of around -40 MtCO2 in 2050, as result of the contribution of industrial removals. Non-energy related CO2 emissions decrease only by around 35% in 2030 vs 2015, and

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(37) Essentially, the emissions from fuel combustion.

additional reductions between 20% and 80% (compared to 2030) are achieved in 2031-2040, driven by the decrease of industrial processes emissions: the large variation across scenarios is justified by the late (in S1) and early (in S3) entry into market of low-carbon innovative manufacturing technologies, including carbon capture, utilisation and storage. In 2050, emissions from industrial processes reduce to negligible values and the non-energy emissions stagnate. International emissions within the scope decrease by around half in the period 2031-2040 and range around 10-15 MtCO2 in 2050. Further details on sectoral CO2 emissions, including transport, are discussed in sections 1.2-1.5.

Table 6: Energy and Industry net CO2 emissions

	2005	2015	2030	2040				2050	
	-	-	-	**S1**	**S2**	**S3**	**LIFE**	**S3**	**LIFE**
Total Energy and Industry CO2 emissions	**3837**	**3197**	**1759**	**805**	**511**	**321**	**422**	**-5**	**73**
Net Domestic CO2 Emissions: Energy Related	**3381**	**2787**	**1448**	**594**	**357**	**247**	**351**	**-40**	**41**
*Power and district heating**	1300	1012	334	119	8	-10	7	-38	-22
*Other Energy sectors***	152	136	84	43	23	-11	35	-37	15
Industry (Energy)	469	360	232	126	94	75	86	9	11
Transport	812	764	577	187	141	117	132	6	8
*Residential and Services****	648	514	221	119	92	75	92	19	29
Net Domestic CO2 Emissions: Non-Energy Related	**325**	**260**	**176**	**156**	**109**	**34**	**33**	**23**	**22**
Industry (Non-Energy)	288	226	150	133	86	12	11	4	2
*Other non-energy******	37	35	26	23	23	22	22	20	19
International intra-EU and 50% extra-EU	**116**	**107**	**112**	**52**	**46**	**41**	**39**	**11**	**10**
international intra-EU aviation	35	38	43	31	29	28	26	11	10
international intra-EU navigation	31	27	25	7	6	4	4	0	0
50% extra-EU MRV maritime MRV	50	42	44	14	11	9	8	0	0
Residual CO2 for calibration	15	43	24	3	-1	-1	-1	0	0

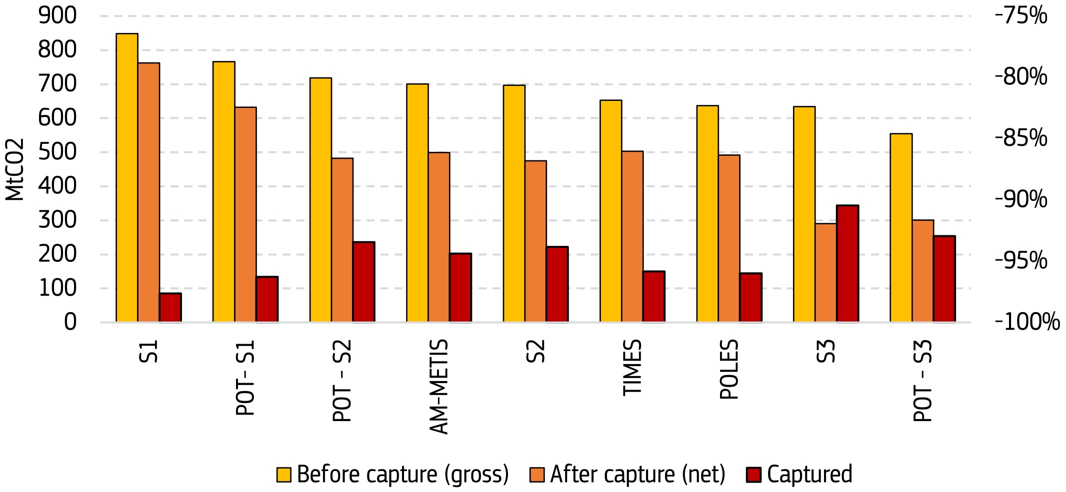
*Note: *Includes BECCS. **Includes emissions from energy branch and DACCS; ***Includes fossil fuel combustion in the agriculture/fishery/forestry sector; ****Includes fugitive emissions. S1 and S2 values in 2050 are similar to S3 and described in more details in sectoral sections 1.2, 1.3, 1.4 and 1.5 of this Annex.*

Source: PRIMES.

1.1.3.2.Role of carbon capture

To investigate the role of carbon capture and understand better the uncertainties associated to the deployment of this technology, a cross-model analysis comparing PRIMES projections with the ones provided by POTEnCIA, AMADEUS-METIS, POLES and EU-TIMES (see Annex 6) is performed (Figure 7). Results show how the level of climate ambition achievable in 2040 in the energy and industry sectors strongly depends on the amount of carbon captured and, as discussed in section 1.1.2.3, of carbon removals. The level of domestic energy and industry CO2 emissions before capture (i.e., gross emissions) spans from 580 to 850 MtCO2, with most of the models projecting in the 650-750 MtCO2 range. Limited differences exist across modelling runs (reductions between -78% and -85% compared to 1990) and even in scenarios with the highest uptake of novel technologies (excluding carbon capture) the energy and industry CO2 can reduce at most by around 85%, meaning that the 2040 potential for the implementation of mitigation solutions other than carbon capture modelled in the scenarios is mostly attained. The picture of emissions after capture (i.e., net emissions) is different. Limited carbon capture allows for a marginal further decrease in emissions (see S1 and POTEnCIA-S1 (POT-S1) on the left of Figure 7), while a more substantial deployment of the technology achieves emission levels of around 470-520 MtCO2 in S2, POTEnCIA-S2 (POT-S2), AMADEUS-METIS (AM-METIS), POLES and EU-TIMES, and down to around 250-350 MtCO2 in S3 and POTEnCIA-S3 (POT-S3). Carbon capture allows to reach additional reductions of between 2-3% (corresponding to around 80-130 MtCO2 captured in S1) and 4-6% (corresponding to around 150-240 MtCO2 captured in S3) of 1990 levels and represents a key mitigation solution to reach deeper net GHG emission reductions. The models show that above 150 MtCO2 (including removals) need to be captured in 2040 to achieve a total reduction of energy and industry CO2 emissions of at least 88% and above 250 MtCO2 to reach above 90%.

Figure 7: Energy and Industry CO2 emissions in 2040



Note: Emissions (left) and relative reductions vs 1990 (right).

Sources: AMADEUS-METIS, EU-TIMES, POLES, POTEnCIA, PRIMES.

Figure 8 shows the evolution of the carbon captured yearly (left), and corresponding additional carbon captured at the end of each decade until 2050 (right) projected by PRIMES. A yearly capture level of around 50 MtCO2 is projected in 2030 across all scenarios, in line with the Net Zero Industry Act (38), which then increases in 2040 to around 90 MtCO2 in S1, above 200 MtCO2 in S2 and to 350 MtCO2 in S3 and converges in 2050 to around 450 MtCO2 in S1, S2 and S3. LIFE projects a level of carbon capture intermediate between S2 and S3 in 2040, and more moderate in 2050., showing that sustainable lifestyle and circular economy actions leads to a more extensive use of nature-based removals and lower the need for carbon capture in industry (see 1.4 and 1.8).

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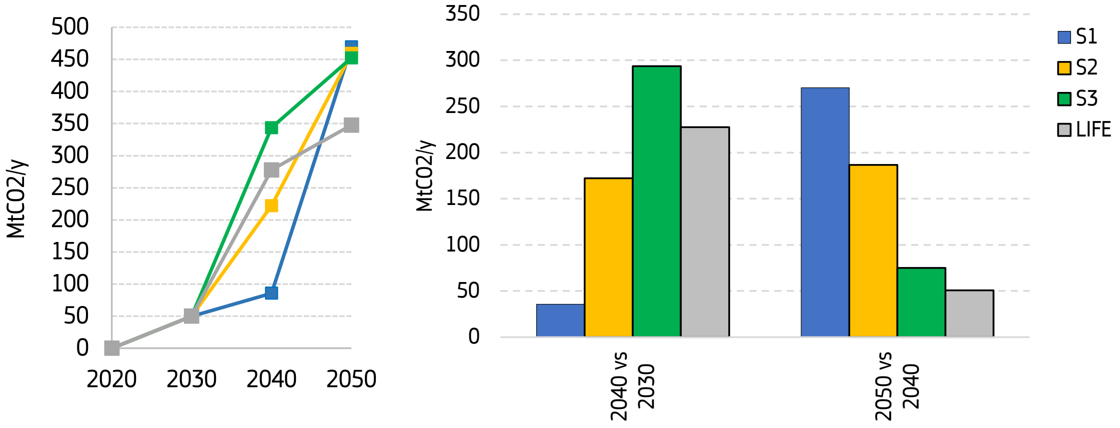
(38) COM(2023) 161

Figure 8: Total (left) and additional (right) carbon captured yearly in selected years



Source: PRIMES.

The projections for carbon capture are in line with ranges found in the literature: in 2040, the ENGAGE project depicts a yearly amount of carbon captured around 300 MtCO2 ([39]), the ECEMF ([40]) provides a range of 215-376 MtCO2, Rodrigues at al. ([41]) describe a range of 120-330 MtCO2 and Ecologic indicates a range between 46 and 160 MtCO2 (with a stronger reliance on land-based removals) ([42]). For 2050, ESABCC ([43]) and other literature ([44]) show the maximum threshold for feasibility of this technology at around 500 MtCO2.

As a result of different amount of carbon captured in 2031-2040 and 2041-2050 in the main scenarios, the additional minimum capacity ([45]) per decade necessary to capture carbon varies significantly: in S1, delayed climate action results in additional installations capable of capturing up to 35 million tonnes of CO2 extra in 2040, but this number multiplies by around 7.5 times by 2050. S2 shows a minimum additional capacity able to capture around 180-190 MtCO2/y extra at the end of each decade. S3 suggests a large deployment of extra 300 MtCO2/y captured by 2040, and only additional 75 MtCO2/y by 2050. LIFE shows an intermediate level of additional capacity needed in

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([39]) ENGAGE Scenario Explorer, *Engage: Feasibility of Climate Pathways Project*, https://www.engage-climate.org/ Accessed 15-09-23

([40]) ECEMF (2023), ECEMF Policy Brief: Insights on EU2040 targets based on a model intercomparison exercise of EU Climate Neutrality Pathways. DOI 10.5281/zenodo.8337667. https://zenodo.org/record/8337668 Full model range, including international bunkers.

([41]) Rodrigues et al., (2023). 2040 greenhouse gas reduction targets and energy transitions in line with the EU Green Deal, *Nature Communication*, Under Review.

([42])Ecologic and Oeko-Institut, *Designing the EU 2040 climate target*, 2023.

([43]) ESABCC (2023). Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050. DOI: 10.2800/609405.Table 5.

([44]) ENGAGE Scenario Explorer, *Engage: Feasibility of Climate Pathways Project*, Accessed 15-09-23

([45]) These values only represent indicative capacities and will have to take account of normal operational downtimes and be supported by a total geological storage capacity of several giga-tonnes of CO2.

2040 between S2 and S3 and a minimal increase in the 2041-2050 related to the overall lower need of industrial capture in these settings.

Achievement of the required level of carbon capture capacity by 2040 is not trivial, especially in the S3 scenario. Several barriers to a large deployment of the technology exist today: the transition from R&I stage to the full-scale, replicable, commercial deployment for certain steps of the technology, the need to establish a new (cross-border) carbon value chain, including storage sites (46) (47), and a lack of market coordination for fast deployment of the technology. A large development of carbon capture means foreseeing the build up of commercially ready carbon capture infrastructure on existing or new-build industrial capacity, often in sectors characterized by long investment cycles. Hence, sound regulatory predisposition and long-term financial planning taking into account the impact on industrial competitivess become necessary to provide certainty to industrial investors. Downstream of the carbon capture value chain, storage operators face high upfront costs to identify, develop and appraise storage sites before they can apply for a regulatory permit that is necessary to operate, while their future customers are willing to invest in carbon capture only if access to operating storage site is secured. Subsequently, market players have little templates for commercial contracting or risk sharing and depend on each other's plans and project progress to de-risk their own investment decisions. Regulatory uncertainty and inexperience also represent a challenge, for instance in terms of supplementing the CCS directive (48) and clarifying future link between industrial removals and ETS or cross-border transport of captured CO2. To overcome these challenges, several Member States have CO2 value chain strategies in place or are developing them (NL, DK, FR, DE) (49) and consolidated effort is needed to stimulate and guide a market development that can deliver the scale needed, as described in the Communication on Industrial Carbon Management (50).

When looking at the different sources of carbon captured in 2040, and only considering this specific pathway modelled by PRIMES, a veritable "merit order" emerges (Figure 9). S1 shows that carbon is first captured in industrial processes and power generation (emitting from fossil fuels) in order to reduce emissions in those sectors, with very little coming from BECCS, the upgrade of biogas to biomethane (biogenic carbon) and DACC. A larger uptake of the technology in S2 leads first to the increase of the level of fossil carbon coming from industrial processes and power generation, and then taps into industrial removals, mostly BECCS. Being the potential for BECCS limited by sustainability constraints on biomass availability, and possible negative impact on the LULUCF net removals, an increase in demand for the production of e-fuels opens the doors to deployment of DACC in 2040: this happens already in S2 and becomes even

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(46) Lane, J., Greig, C., & Garnett, A. (2021). Uncertain storage prospects create a conundrum for carbon capture and storage ambitions. *Nature Climate Change, 11*(11), 925-936. https://doi.org/10.1038/s41558-021-01175-7

(47) Koelbl, B. S., et al. (2014). Uncertainty in the deployment of Carbon Capture and Storage (CCS): A sensitivity analysis to techno-economic parameter uncertainty. *International Journal of Greenhouse Gas Control*, *27*, 81-102.

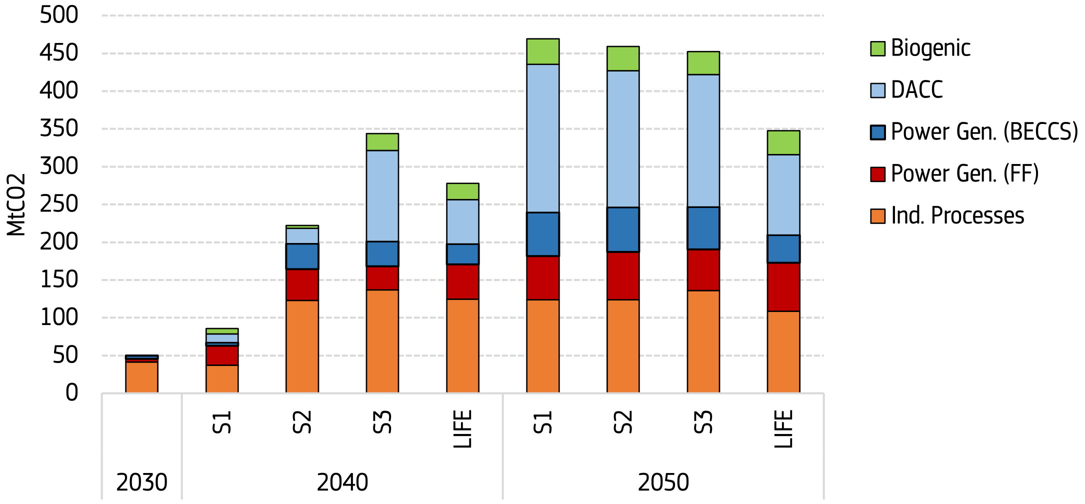
(48) Directive 2009/31/EC

(49) This list is to be published by JRC mid-october 2023.

(50) Industrial Carbon management Communication (upcoming).

more evident when moving from S2 to S3, where the additional carbon is captured almost exclusively through DACC. In 2050, the share of the different technologies is similar across S1-S2-S3. Proportionally, LIFE also shows a similar distribution, with less DACC than S3 in 2040 and an overall capture level in 2050 lower than the other scenarios.

Figure 9: Carbon captured by source



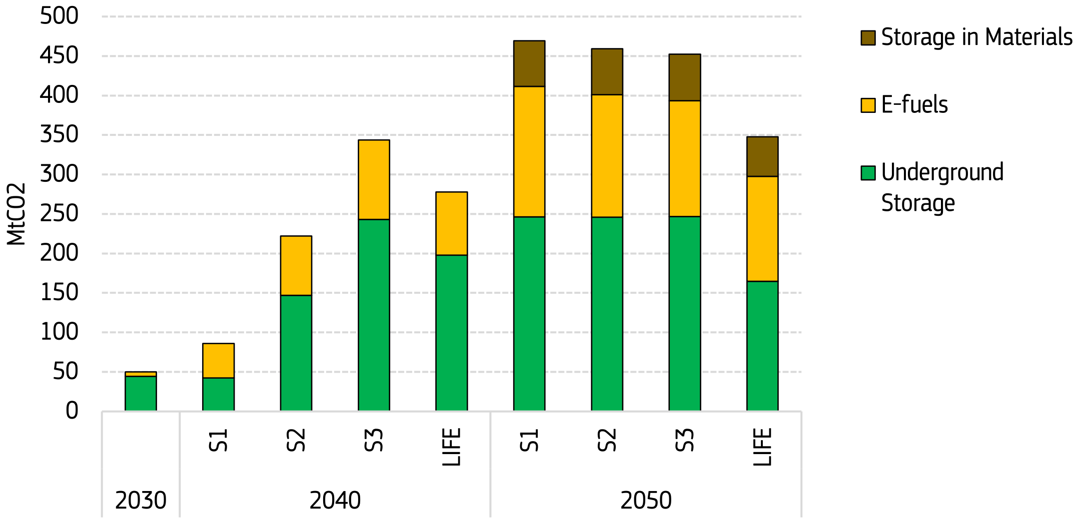
Note: Biogenic carbon indicates the carbon resulting from the upgrade of biogas to biomethane.

Source: PRIMES

The order in which carbon capture technologies are deployed to satisfy increasing demand reflects the results of the public consultation questionnaire for the 2040 target, where respondents would prioritise deployment of carbon capture from industrials process (highest priority given by 36% of respondents), followed by combustion of biomass (23%) and fossil fuel (20%). The strong preference for carbon capture from industrial process is also confirmed when looking at different stakeholders' group, indicating a general agreement on the development of this technology. The picture is less technology-specific when analysing positions papers collected during the consultation: about half of them, published by business associations, public authorities and academia, encourages the uptake of carbon capture and storage technologies, without assigning priority to one specific technology type.

The modelling shows that capture of carbon in 2040 is mainly driven by the demand for e-fuels required in other sectors and by the need to reduce net emissions within the sector through underground storage (Figure 10). In the 2041-2050 decade, where e-fuels are to be produced using fossil-free carbon and all residual emissions needs to be compensated, the action of these drivers continue, increasing the amount of carbon captured for these two applications. The increasing demand for industrial feedstock also creates a new market for storage in materials, where CO2 is chemically bound in products, balancing industrial CO2 needs, making local CO2 networks an attractive option.

Figure 10: Carbon Captured by end application



Source: PRIMES.

In the 2030-2050 period, the model shows that carbon capture does not only reduce emissions in hard-to-abate sectors, but above all generates carbon feedstock for e-fuels or fossil-free products as well as industrial removals (in terms of BECCS and DACCS). A real carbon management industry is to be created, connecting different carbon technologies and sources to final end-user applications through industrial feedstocks, balancing carbon flows in the EU economy. Figure 11 shows the carbon flows between sources and uses in 2040 in the different scenarios. These carbon flows can be also affected by the projected levels of emission reduction. For instance, while e-fuels can be produced by carbon captured from fossil fuels in power generation and industrial processes in scenarios with higher 2040 emissions (S1 and S2), the higher ambition of S3 makes necessary the permanent storage of these fossil fuel emissions. In S3, the production of e-fuels in 2040 relies mostly on fossil-free sources of carbon derived from biomass (either captured from bioenergy combusting application or of biogenic origin from the upgrade of biogas to biomethane) and, given the limited sustainable biomass resources, from DACC. Beyond 2040, when fossil fuels are excluded (51) from possible source of carbon for production of RFNBOs across all scenarios, and e-fuels demand increases even further, they are produced mostly using carbon derived from DACC and in part from biomass. All remaining fossil carbon is then permanently stored (either underground or in products).

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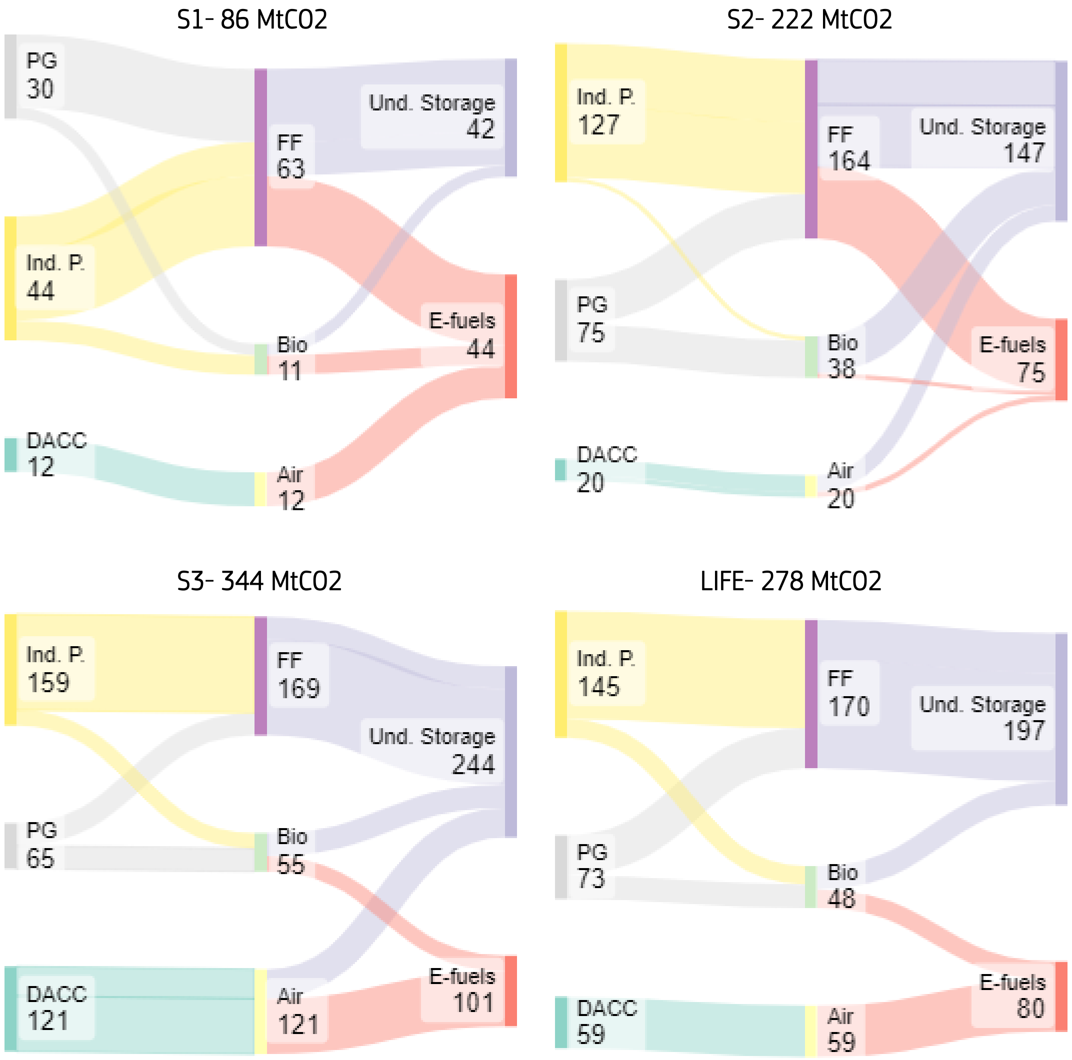
(51) Commission Delegated Regulation (EU) 2023/1184

Figure 11: Flow of captured carbon in 2040



Note: "Ind. P." stands for Industrial processes and include fossil carbon from industrial processes as well as carbon of biogenic origin coming from the upgrade of biogas to biomethane. "FF" stands for "fossil fuels". "PG" stands for "power generation". "Bio" refers to CO2 produced by the combustion of biomass in power generation and produced during the upgrade of biogas into biomethane. "DACC" stands for "Direct Air Capture of CO2", for underground storage (DACCS) or use in efuels.

Source: PRIMES.

1.1.4. Non-CO2 GHG emissions

Non-CO2 GHG emissions declined considerably over the past decades in the EU. Currently, however, significant amounts of non-CO2 greenhouse gases are still being emitted every year, representing around 20% of total GHG emissions. In 2015, the EU's total non-CO2 GHG emissions added up to more than 700 MtCO2-eq. As shown in Figure 13, most of these were CH4 emissions (61%), whereas the rest were N2O and F-gas emissions (25% and 14%, respectively). Agriculture was the largest emitting sector, representing roughly 53% of the EU's total non-CO2 GHG emissions (mostly CH4 and N2O emissions associated to enteric fermentation, manure management and fertiliser application), followed by waste treatment (17%, mostly CH4 emissions stemming from uncaptured emissions caused by anaerobic digestion of solid waste and wastewater streams), energy and transport (16%, mostly methane leakage and emissions related to fuel combustion), and heating/cooling installations (11%, mostly F-gas emissions), as shown in Figure 12.

In the S1 scenario, which considers mitigation due to current policies (but no more), non-CO2 GHG emissions drop to around 457 MtCO2-eq in 2040 (i.e., 35% less than in 2015). Note that the degree of reduction by 2040 varies considerably across sectors (see Figure 12). Agriculture is the sector showing the smallest decrease in relative terms (9% reduction between 2015 and 2040). Non-CO2 GHG emissions from the waste management sector decline by 42% over the same period (driven by the implementation of existing legislation on landfilling and additional legislative proposals, such as the proposal on a revised Urban Wastewater Treatment Directive, see Section 1.6.1 and Annex 6), while the energy and transport sector shows a deep reduction (-71%) driven by the phase down of fossil fuel use in the energy system. The heating and cooling sector shows the largest decrease in relative terms (97% relative to 2015), driven mostly by the assumed implementation of the F-gas regulation proposal (see Annex 6). Looking at the disaggregation per gas, total N2O emissions across all sectors decrease by 14% between 2015 and 2040, CH4 emissions decline by 32% over the same period, and F-gas emissions decrease by more than 90%, as shown in Figure 13.

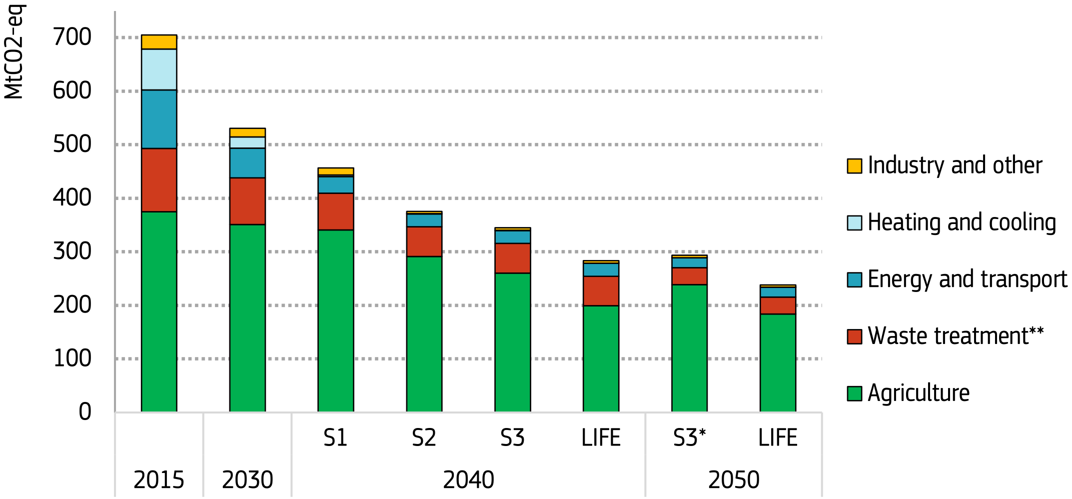
The S2 and S3 scenarios show a more ambitious reduction of net GHG emissions by 2040 than the S1 scenario, and this requires stronger non-CO2 emission reductions than those delivered by current policies. In the S2 scenario, total non-CO2 GHG emissions go down to 376 MtCO2-eq in 2040 (i.e., 81 MtCO2-eq less than in the S1 scenario), that is to say, they decrease by 47% compared to 2015. In the S3 scenario, total non-CO2 GHG emissions drop to 345 MtCO2-eq in 2040 (i.e., 112 MtCO2-eq less than in the S1 scenario), which translates into a 51% reduction compared to 2015 (i.e., more than three-quarters of the emissions reduction trajectory between 2030 and 2050). As shown in Figure 12, the main difference compared to the S1 scenario are additional reductions in emissions in the agriculture sector (22% reduction between 2015 and 2040 in S2, 13 percentage points more than in S1, and 30% reduction between 2015 and 2040 in S3, 21 pp more than in S1). Most of this additional reduction corresponds to N2O emissions from agricultural soils and CH4 emissions from enteric fermentation and manure management (see Figure 13 and Section 1.7.5). In the S3 scenario, all sectors (including agriculture) are close to reaching their maximum mitigation potential both in 2040 and in 2050.

In LIFE, total non-CO2 GHG emissions go down to 284 MtCO2-eq in 2040 (which means a 60% reduction relative to 2015, and 61 MtCO2-eq less than in S3) and 238 MtCO2-eq in 2050 (i.e., 55 MtCO2-eq less than in S3). As shown in Figure 12, the only significant difference compared to the S3 scenario is an additional decrease in emissions in the agriculture sector (47% reduction between 2015 and 2040, 17 percentage points more than in the S3 scenario), which is mainly due to the smaller amount of livestock and lower use of mineral fertilisers assumed in LIFE. All sectors (including agriculture) are close to reaching their maximum mitigation potential both in 2040 and in 2050.

A more detailed analysis of the non-CO2 GHG emission trajectories in all scenarios can be found in Sections 1.6 and 1.7.

Table 7 shows the emission residuals related to the calibration of the GAINS and PRIMES models to the UNFCCC inventory, which have not been considered in the discussion above. These residuals are small and not assigned to any particular sector. The table also shows the CO2 emissions produced by the agriculture sector (including only "category 3" emissions).

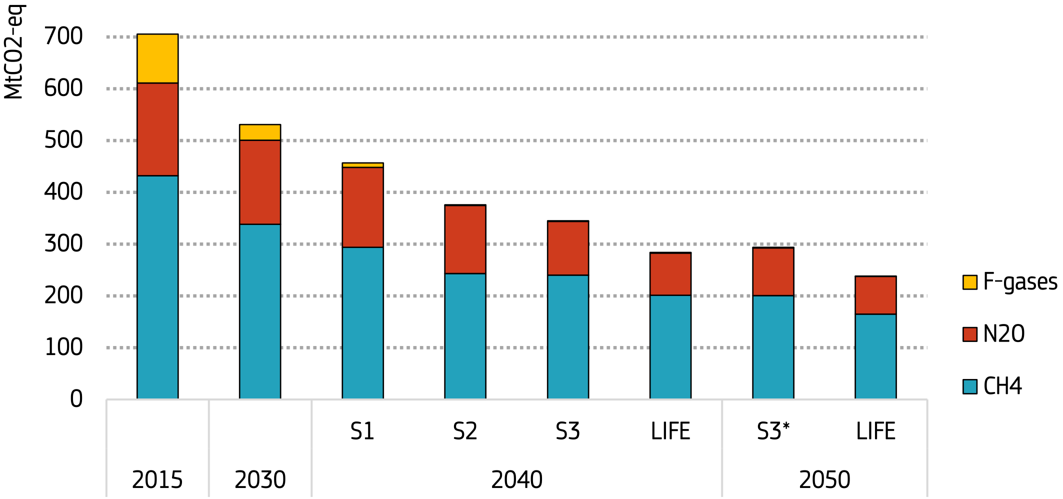
Figure 12: Evolution of non-CO2 greenhouse gas emissions by sector



Note: *In the S1 and S2 scenarios, emissions in 2050 are equal to those in the S3 scenario. **The waste treatment sector includes solid waste and wastewater treatment. ***Emission residuals related to the calibration of the GAINS and PRIMES models to the UNFCCC inventory (which are small and not assigned to any sector) are not included in this figure.

Source: GAINS.

Figure 13: Evolution of non-CO2 greenhouse gas emissions by gas



*Note: *In the S1 and S2 scenarios, emissions in 2050 are equal to those in the S3 scenario. **Emission residuals related to the calibration of the GAINS and PRIMES models to the UNFCCC inventory (which are small) are not included in this figure.*

Source: GAINS.

Table 7: Total non-CO2 GHG emissions in all sectors and CO2 emissions from agriculture

	Greenhouse gas emissions (MtCO2-eq)							
	2015	**2030**	**2040**				**2050**	
			S1	**S2**	**S3**	***LIFE***	**S3***	***LIFE***
Non-CO2 emissions	705	531	457	376	345	*284*	294	*238*
Non-CO2 calibration	2	-3	-3	-3	-3	*-3*	-3	*-3*
CO2 emissions from agriculture (category 3)	10	10	10	10	10	*10*	10	*10*

Source: GAINS.

1.2. Energy sector transformation

1.2.1. Energy supply

Gross Available Energy (52) **(53)** (GAE) reduces to between 1 018-1 022 Mtoe across the S1-S2-S3 scenarios in 2040, corresponding to approximately a 30% reduction compared to 2019 (see Figure 14). Thanks to the circular economy measures and consumption patterns, LIFE further reduces GAE. After 2040, GAE stabilises around 1020–1040 Mtoe, except for LIFE where, in 2050, it is further reduced by more than 50 Mtoe compared to other scenarios.

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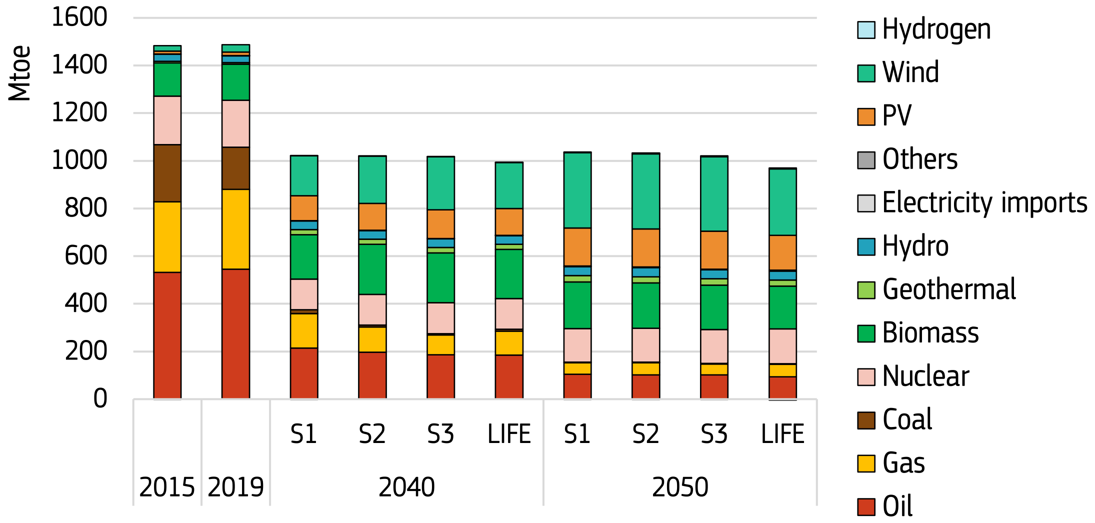
(52) The model-based analysis is a technical exercise based on a number of assumptions that are shared across scenarios. Its results do not prejudge the future design of the post-2030 policy framework.

(53) Gross Available Energy refers to the overall supply of energy for all activities of a country. It includes energy needs for energy transformation, for the energy sector itself, transmission and distribution losses, final energy consumption and the use of fuels for non-energy purposes. It also includes fuel purchased within the country that is used elsewhere (e.g., international aviation and shipping). These figures exclude ambient heat (from heat pumps).

Figure 14: Gross Available Energy by energy vector, 2015-2050



Note: Biomass and waste include non-renewable waste. Natural gas includes also manufactured gas.

Source: PRIMES.

Profound changes in the energy mix underpin the overall reduction of GAE over time. Fossil fuels are gradually reduced, from approximately 1060 Mtoe in 2019 to between 275 and 375 Mtoe in the S1-S2-S3 scenarios (a 65 to 74% reduction compared to 2019). In 2050, approximately 155 Mtoe of residual fossil fuels remain with little differences between the S1, S2 and S3 scenarios (-85% compared to 2019), largely consumed for non-energy uses and from long distance transport. In 2040, fossil fuels account for 27 to 37% of GAE in the S1-S2-S3 scenarios, down from more than 70% in 2019. Fossil fuels reach a share of total GAE of approximately 15% in 2050 across all scenarios.

Renewables undergo a pronounced growth in their share of total GAE as they gradually replace fossil fuels as the backbone of the EU energy system. The share of renewables in total GAE grows from just 17% in 2019 to 50-60% in the S1-S2-S3 scenarios (around 520-610 Mtoe) in 2040. Then, in 2050 the share of renewables reaches more than 70% in 2050 (around 690-735 under the S1-S2-S3 scenarios). LIFE decreases the overall use of renewables in GAE by more than 40 Mtoe in 2040 and more than 50 Mtoe in 2050.

Based on nuclear capacity assumptions in line with the Member State policies as described in the 2019 National Energy and Climate Plans ([54]), cf. sub-section 2.5.2.2, nuclear power is projected to experience a reduction in output over this decade from around 200 Mtoe in 2019 to 130 Mtoe in 2030 after which it broadly stabilizes, accounting for 13-14% of total GAE from 2040 onwards without major differences across scenarios.

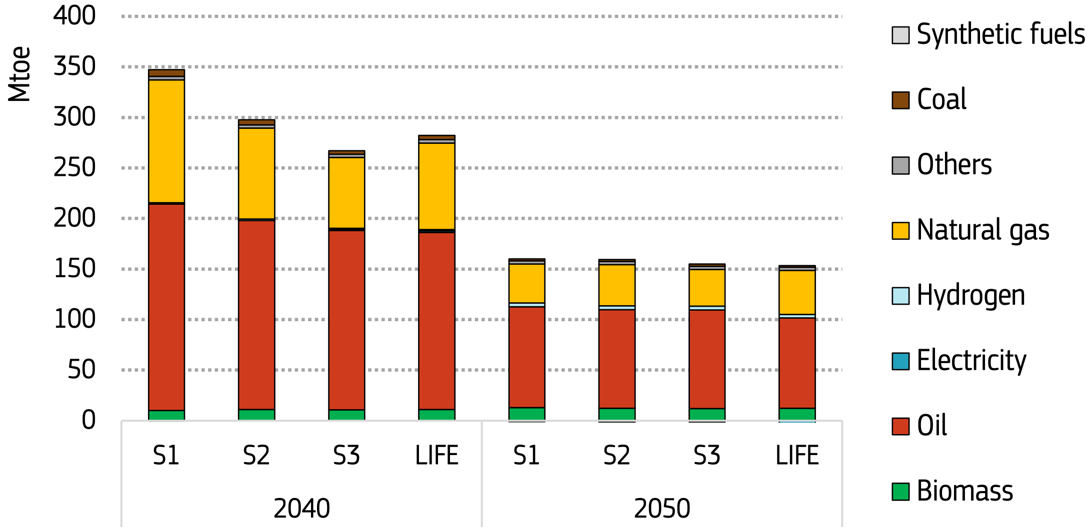
([54]) These assumptions reflect the situation until March 2023. In June 2023, France has adopted a law which removes the objective of reducing the share of nuclear power in the electricity mix. Additional 3.3 GWe nuclear capacity was officially announced for deployment by mid-2030s. See the box in 6.2.1 of the main Impact Assessment and the assumptions in Annex 6. Future EU policies and analysis will take the revised policies into account, as reflected in the updated National Energy and Climate Plans which are currently being drafted.

Overall, total GAE is quite stable across the S1, S2 and S3 scenarios, varying by less than 1% in 2040 and less than 2% in 2050, but measures in the LIFE scenario further decrease GAE. However, the trajectories (in terms of GAE) of the various energy vectors are characterised by considerable variations across scenarios: the S3 scenario shows a faster uptake of renewables at the expense of fossil fuels, while S1 scenario shows a slower uptake.

The gradual substitution of fossil fuels (largely imported from outside the EU) with renewables deployed domestically implies a steep reduction of net imports of energy commodities (Figure 15).

Total net imports of energy commodities are projected to reduce by 62%-71% in the S1-S2-S3 and LIFE scenarios (for a total of 270-350 Mtoe) compared to 2019. In 2050, net imports further decrease to 150 and 160 Mtoe in the S1-S2-S3 scenarios, 83% lower than in 2019. Net imports of coal virtually end by 2040 in all scenarios and those of natural gas and oil products drastically reduce with a very similar pace as the one of overall net imports. All scenarios meet the goal of the REPowerEU plan to phase out import of Russian gas (55). The amounts of imports of hydrogen and e-fuels remain relatively small in 2040, due to still relatively high costs.

Figure 15: Net imports by energy vector, 2015-2050



Note: Biomass and waste include non-renewable waste. Natural gas includes also manufactured gas. When the scenario name is not indicated for future years, the reasons is that trends are almost identical across scenarios.

Source: PRIMES.

As shown in Figure 15, the main difference in the fuel-specific pattern across scenarios is associated to natural gas: total net import in 2040 under the S3 achieves three-quarters of the level of the S2 scenario (around 70 Mtoe and 90 Mtoe respectively). Oil and natural gas are the last fossil fuels to be phased out and significant imports still occur in 2050. However, by mid-century almost half of oil consumed in the EU is used to make products in the non-energy sector. In 2050, more than half of the liquid fuels used for energy purposes in end-use sectors are RFNBOs.

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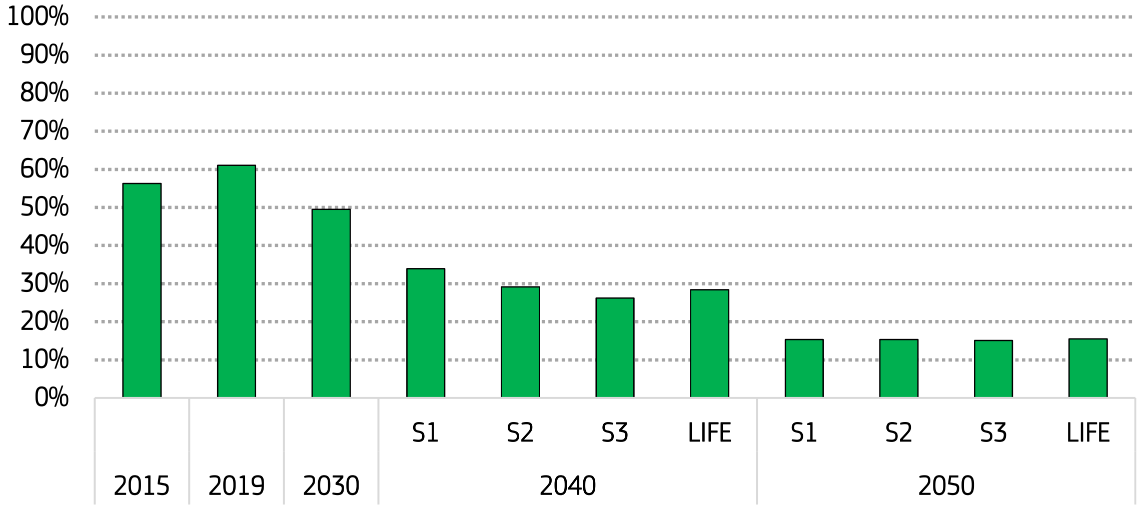
(55) COM/2022/230 final

The decline in imports has profound consequences for the EU's security of energy supplies. Import dependency (defined as the ratio of net imports to GAE excluding ambient heat) decreases from 61% in 2019 to 50% in 2030 and to 34% – 26% in 2040 (depending on the scenario). By 2050, only approximately 15% of the fuels used in Europe will be imported. The energy transition will greatly reduce the EU's dependency on energy imports. However – due to the decline of indigenous production and the fact that oil is the last fossil fuel to be abandoned – a large decrease in imports will occur only with deep decarbonisation (see Figure 16). As shown in Figure 15, import reduction is similar across scenarios depending mainly on the decarbonisation target.

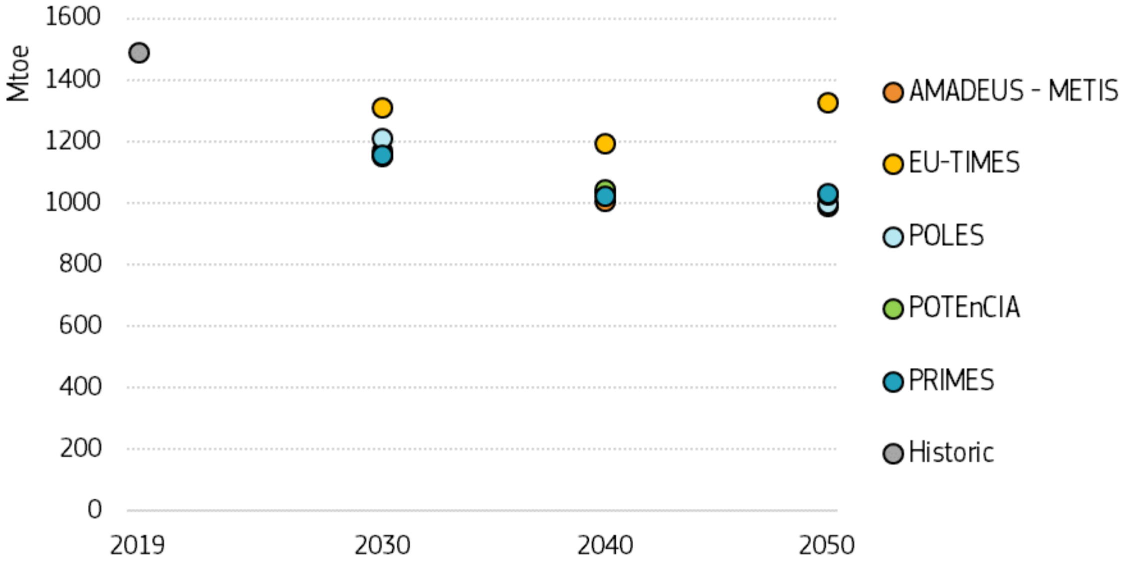
Figure 16: Import dependence



Source: PRIMES.

As introduced in Annex 6, complementary modelling tools have been used in addition to PRIMES to model the decarbonisation scenarios. Figure 17 compares the projections for total Gross Available Energy obtained from the POTEnCIA, AMADEUS-METIS, EU-TIMES and POLES models for the S2 scenario. Values and patterns are comparable across all models, with EU-TIMES showing the highest GAE throughout the time horizon and a trajectory that reduces up to 2040 and then increases again afterwards. The highest GAE in EU-TIMES is explained mainly by the lowest reduction in FEC (see Figure 17) linked to an extensive use of RFNBOs in comparison with electricity (see Figure 33 later in the text), and a high reliance on industrial carbon removals to compensate for emissions in hard-to-abate sectors, which has associated significant consumption of electricity and heat.

Figure 17: Total Gross Available Energy from different energy models, 2019-2050



Sources: AMADEUS-METIS, EU-TIMES, POLES, POTEnCIA, PRIMES.

1.2.2. Power generation sector

The coming decades require an increase in electricity supply due to the increasing electrification of the economy and the production of RFNBOs. Fossil fuel-fired electricity generation decreases substantially and is replaced by variable renewable electricity generation. To match variable supply and demand, more smart solutions are needed. The variability of wind and solar can be addressed through real time pricing signals and flexibility solutions on the demand side. Sector coupling technologies like storage, interconnection and carbon free dispatchable power generation are expected to play an increasingly important role (56).

In the context of reducing fossil fuels use in favour of direct electrification of end-use sectors, for instance via the deployment of heat pumps, electric vehicles and electrified low and mid-temperature industrial processes, demand for electricity increases by 31-34% between 2021 and 2040 in S1-S2-S3 (Figure 18).

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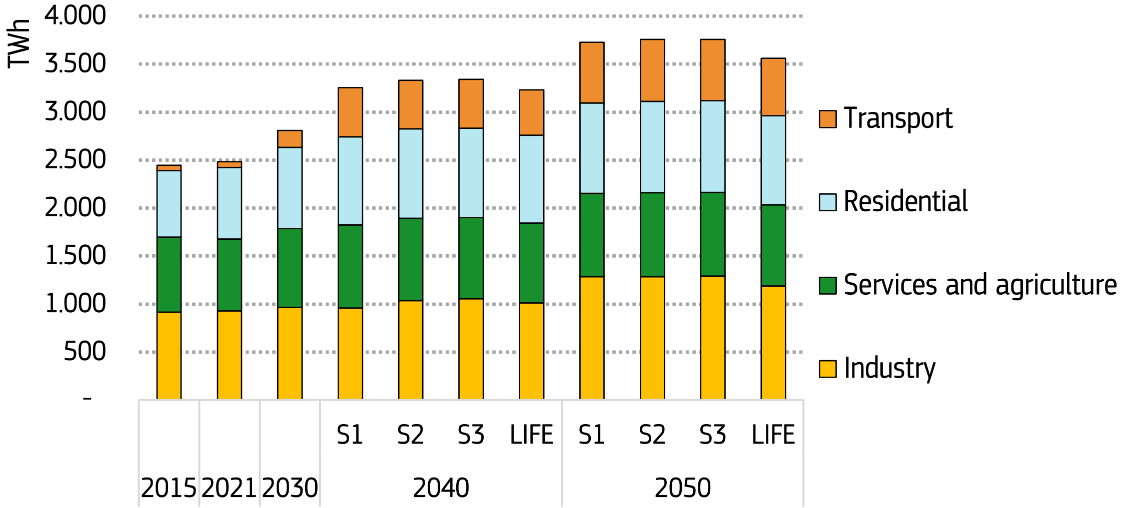
(56) Koolen, D. et al., Flexibility requirements and the role of storage in future European power systems, EUR 31239 EN, Publications Office of the European Union, Luxembourg, 2023, ISBN 978-92-76-57363-0, doi:10.2760/384443, JRC130519.

Figure 18: Final electricity consumption by end-use sector



Note: Total electricity consumption consists of final electricity consumption from end-use sectors (hereby shown), own consumption of the energy sector, RFNBOs production and transmission/distribution losses.

Source: PRIMES.

As shown in Figure 18, electrification of the economy drives final electricity demand in the transport, services & agriculture, industry and residential sectors. Total final demand increases from 2 485 TWh in 2021 to 2 810 TWh in 2030 and to 3 255-3 340 TWh in S1-S2-S3 in 2040. Measures following LIFE are projected to reduce electricity demand by 110 TWh.

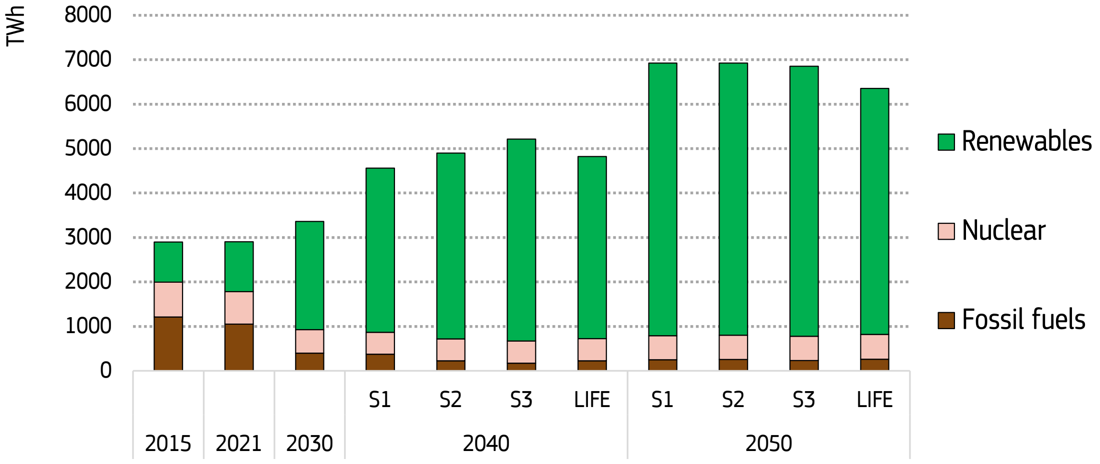
In the residential sector, overall electricity demand will increase by 23-25% between 2021 and 2040 due to an increased uptake of heat pumps replacing oil and gas-based heating systems (see Section 1.3.3). Due to the high efficiency of heat pumps, the overall increase of electricity demand is lower than the energy savings resulting from phasing out gas and oil boilers. There are only minor differences between the scenarios, with S1 reaching 920 TWh and S3 reaching 935 TWh.

Industry, agriculture and services show a similar picture. In those sectors, the share of electricity in the final energy demand is rising sharply due to the slight increase in electricity demand and the overall drop of final energy consumption. As a result of the interplay of electrification and energy efficiency, electricity demand in these sectors increases by 12% (industry) and 15% (services and agriculture) between 2021 and 2040 (S2). See sections 1.3.3 and 1.3.4 for more details.

The transport sector undergoes the strongest growth in final electricity consumption between 2021 and 2040, attributed to the large development of electric transport (see Section 1.5.3). Overall, final electricity demand in the transport sector will increase over the period 2021 to 2040 by a factor of 8 with no major differences between scenarios. In absolute terms, final electricity demand increases from 60 TWh in 2021 to 180 TWh in 2030 and 505-510 TWh in 2040, respectively. The LIFE measures would reduce final electricity consumption in the industry by 35 TWh.

Between 2040 and 2050, total final electricity demand increases again by 13% to 3 760 TWh. Transport (+26%) and industry (+22%) increase further sharply while the residential, services and agriculture sectors face a slowdown (both + 2%).

Figure 19: Electricity generation by energy carrier, 2015-2050



Source: PRIMES.

As a result of increased electricity demand, electricity generation increases from 2 905 TWh in 2021 to 3 360 TWh in 2030. The increase continues even more strongly until 2040 resulting in total electricity generation to reach 4 565-5 210 TWh in S1-S2-S3 in 2040 (+57 to 80% since 2021) (see Figure 19). The measures from LIFE are projected to reduce need for electricity generation by 390 TWh. The difference in electricity generation between scenarios is only to a small extent due to the final demand for electricity. Rather, it is driven by differences in the electricity required for the production of RFNBOs from 2030 onwards (which does not fall under final electricity demand). In 2040, electrolysers, RFNBO synthesis processes and DAC combined consumes approximately 490 TWh more electricity in the S3 scenario than in S1 (a 51% increase). The S2 scenarios consumes approximately 225 TWh more than S1 for the same purposes (23% increase).

The share of fossil-fired generation is projected to steadily decrease from 36% in 2021 to 12% in 2030 and further down to 3% – 8% in S1-S2-S3 in 2040. The residual fossil-fired generation in the last decade before 2050 is projected to consist almost solely of gas-fired power plants, with and without CCS. The plants equipped with CCS will generate the majority of the gas-fired electricity, while the ones without CCS equipment will only be used as peakers. Renewables in the electricity system generated around 40% of total electricity supply in 2021 and are expected to cover 81% – 87% by 2040. Nuclear power generation decreases over the decades from 730 TWh in 2021 to around 495 TWh in 2040 (-30%). Due to the high increase in overall electricity supply, the share of nuclear generation is projected to decrease from 25% in 2021 to 10 – 11% in 2040. The results in nuclear generation are based on nuclear capacity assumptions in line with the Member State policies as described in the 2019 National Energy and Climate Plans (57), cf. sub-section 2.5.2.2.

The three scenarios follow the same trend in the electricity mix with minor deviations. The higher production of RFNBOs in S3 requires more renewable electricity generation

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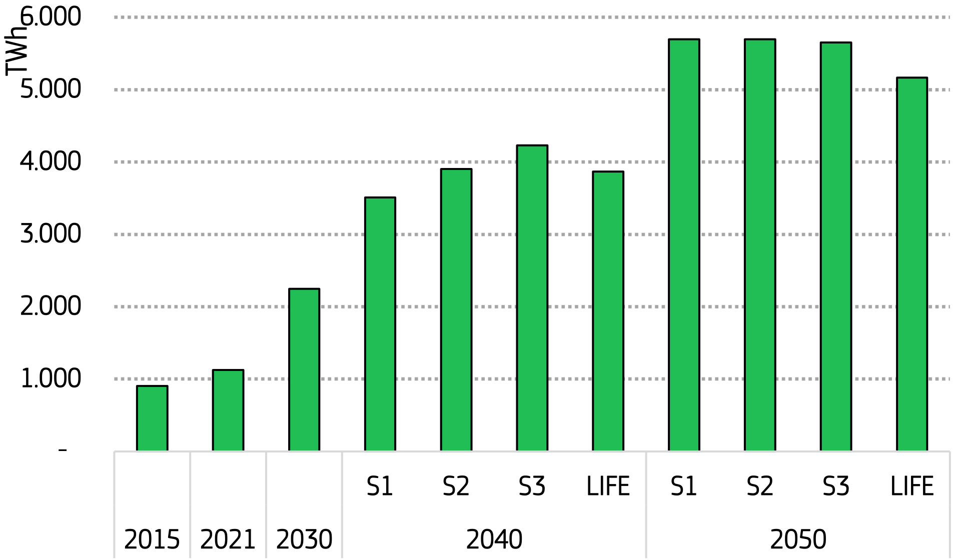
(57) Future EU policies and analysis will take the revised policies into account, as reflected in the updated National Energy and Climate Plans which are currently being drafted.

(around 850 TWh more in 2040 compared to S1). At the same time, S1 shows a higher use of fossil-fired generation by 2040 (around +200 TWh in comparison to S3) and result in overall lower emission reductions.

The electricity system will increasingly face the need to integrate variable wind and solar generation. Renewable generation will increase from 1 125 TWh in 2021 to 3 700 to 4 540 TWh in 2040 in the S1-S2-S3 (see Figure 20). As the total demand for electricity generation increases significantly but less than renewable generation, the share of renewables in the electricity mix increases continuously, from 39% in 2021 to 85% in 2040 and almost 90% in 2050.

Figure 20: Electricity generation from renewables, 2015-2050

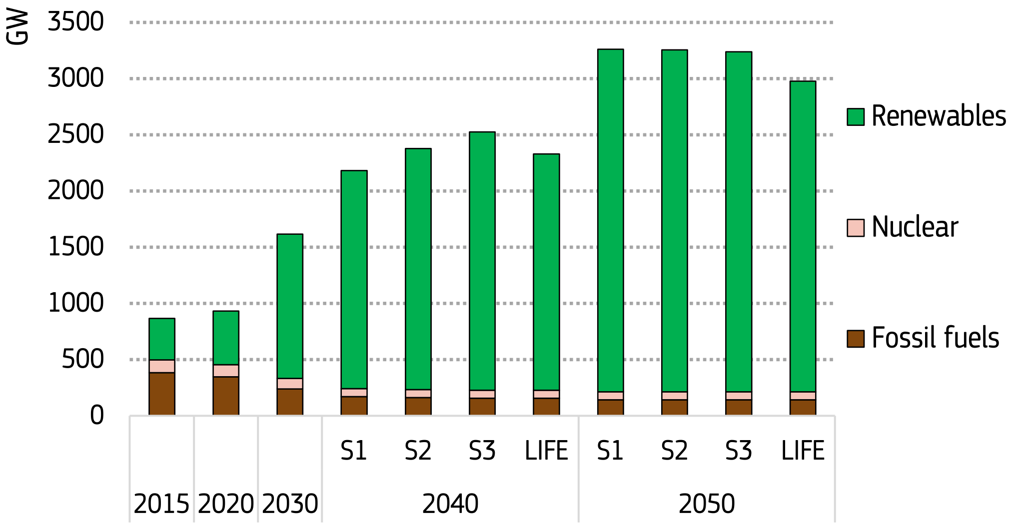


Source: PRIMES.

Due to the relatively low full load hours of wind and solar PV generation, total installed capacity is projected to grow more than two times faster than the amount of electricity generated between 2015 and 2040. The net capacity increases from 870 GW in 2015 to 2 180-2 525 GW in S1-S2-S3 in 2040, led by an increase of renewable capacity (see Figure 21). The implementation of LIFE measures reduces the need for installed power capacity by around 195 GW in 2040.

During the same time, the installed fossil-fuel capacity will decrease from 385 GW in 2015 to only 155-170 GW in 2040. While today the share of gas-fired power capacity is about half of total fossil-fired capacity, the share is projected to increase to around 90% in 2040 due to the overall decrease of fossil-based generation. A small amount of coal- and oil-fired capacity remains during this period.

Figure 21: Net installed capacity by energy carrier, 2015-2050



Source: PRIMES.

By 2030, the EU's nuclear power capacity is projected to decline from around 110 GW in 2015 to 95 GW in 2030 and 70 GW in 2040, under the current modelling assumptions, cf. sub-section 2.5.2.2. The decline in capacity can be attributed to the policy decisions of the respective EU Member States ([58]).

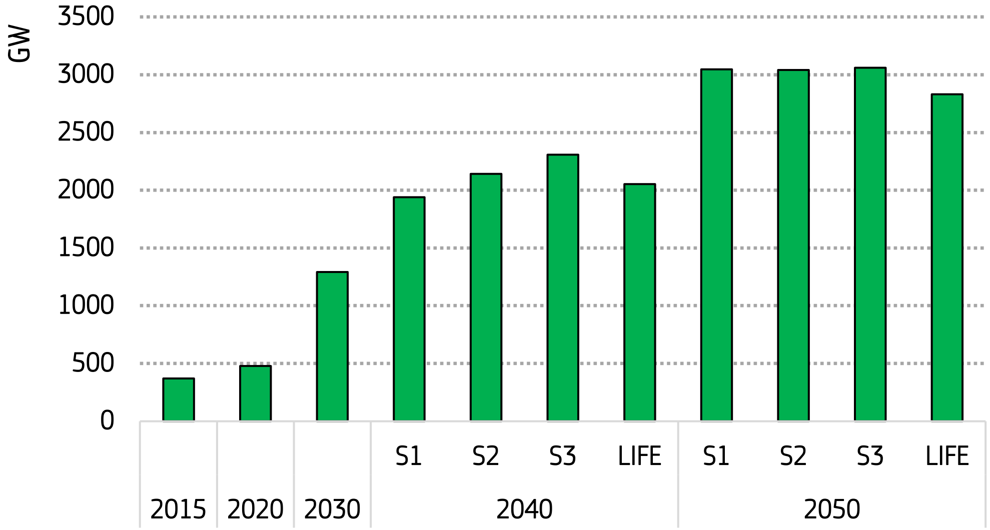
Only a limited use of CCS for power generation is projected in the considered scenarios. In 2030, there is only a small amount of CCS-equipped installed capacity which increases to 10-20 GW in 2040 in S1-S2-S3 and 30 GW in 2050 in the S2 scenario.

The difference in the scenarios for total installed capacity results from the higher electricity consumption in the S3 scenario. The difference to S1 in total installed capacity is 345 GW, which is covered by higher renewable capacity deployment.

Net installed renewable capacity increases dramatically by a factor of 4 to 5 between 2020 and 2040 (see Figure 22).

([58]) The installed nuclear capacity is mostly exogenous based on the NECPs submitted in 2019 and modifications based on discussions with Member States, which however reflect the status only until March 2023. In June 2023, France has adopted a law which removes the objective of reducing the share of nuclear power in the electricity mix. Additional 3.3 GWe capacity was officially announced for deployment by mid-2030s. . See the box in 6.2.1 of the main Impact Assessment and the assumptions in Annex 6. Forthcoming analysis will take the revised policies into account, as reflected in the updated National Energy and Climate Plans which are currently being drafted. See Annex 8 for more details.

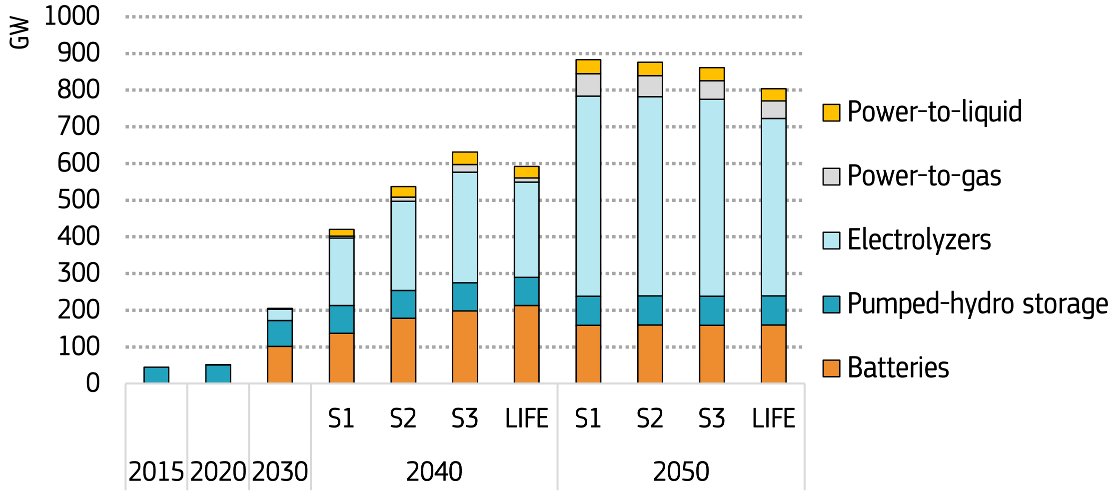
Figure 22: Net installed renewable capacity, 2015-2050



Source: PRIMES.

The increasingly high share of variable renewable electricity generation will increase flexibility requirements. These flexibility needs will increasingly be addressed by new flexibility technologies and storage solutions. Regarding the latter, pumped hydro storage and increasingly batteries will allow to store electricity when demand does not match supply. Albeit not the main driver, electrolysers may also provide some form of storage in the form of power-to-power. Total capacity from technologies that may provide such storage solutions is multiplied by 10 (from 50 to 350-530 GW) between 2020 and 2040 in the S1-S2-S3 (see Figure 23). Pumped-hydro storage capacity is projected to grow from 50 GW in 2020 to 75 GW in 2040. Deployment of battery storage is projected to accelerate after 2030, from 100 GW to 135-200 GW in S1-S2-S3 in 2040 enabling mostly the daily and weekly storage of electricity. Electrolyser capacity increases from 30 GW in 2030 to 185-300 GW in 2040. The measures accompanying LIFE reduce the need for flexibility, in particular of electrolyser capacity. Comparing the 2040 scenarios, the increased deployment of renewables in S3 results in an additional 180 GW of installed storage technologies in comparison to S1. Between 2040 and 2050, batteries and pumped storage are projected to remain relatively stable, while electrolysers show additional growth (from 300 to 535 GW).

Figure 23: Net installed storage and new fuels production capacity, 2015-2050

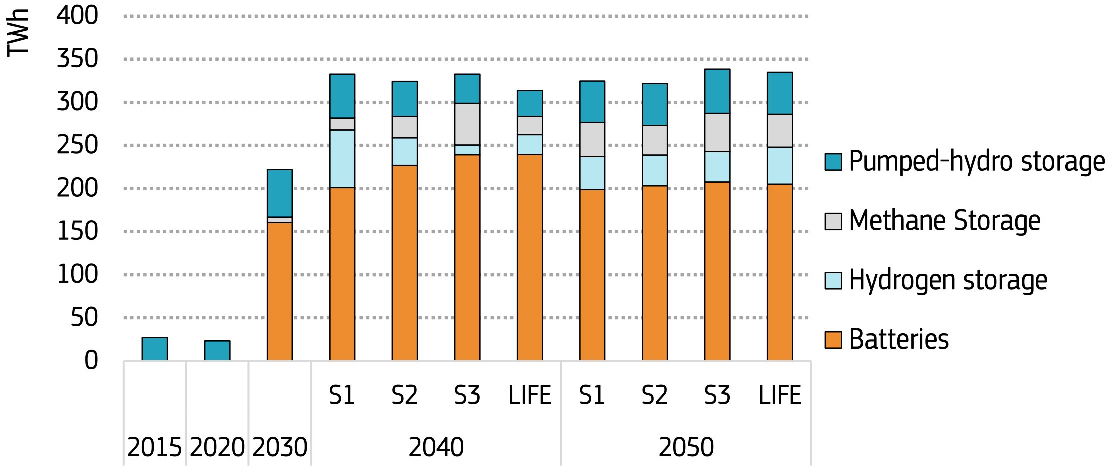


Source: PRIMES.

Power-to-X technologies provide additional flexibility in the future by adjusting production levels to match the pattern of intermittent electricity generation. Installed power-to-gas and power-to-liquid capacities remain relatively low amounting to 5-20 GW and 20-35 GW, respectively, by 2040. Power-to-X capacity further increases from 55 GW in 2040 to 85 GW in 2050.

Electricity is stored in the form of direct electricity storage (via pumped-hydro storage or batteries) and chemical storage (via hydrogen or clean gas). Figure 24 shows the stored energy across scenarios. Storage needs are currently met by pumped hydro storage and increasingly batteries. The electricity stored in pumped hydro is projected to grow from 25 TWh in 2020 to 35-50 TWh in 2040. Batteries are expected to surpass pumped hydro storage as the main source of providing storage between 2025 and 2030, reaching 160 TWh in 2030. By 2040, electricity stored in electrolysers (10-70 TWh) plays a minor role in providing storage to the electricity system than that stored in batteries (200-240 TWh), as the available electrolyser capacity to produce hydrogen (see Figure 23) will be used in sectors other than the power sector. In 2040, methane storage, i.e., clean gas, will play a minor role covering 4-15% of stored electricity in S1-S2-S3. The measures of LIFE are projected to result in a slight reduction in stored electricity in 2040. The four scenarios result in different compositions of stored electricity by technology. Methane storage displays a crucial uptake in S3 where it reaches 50 TWh or 15% of all stored electricity in 2040. The lower use of methane storage in S1 is compensated by hydrogen, which covers 20% of the total stored electricity, in contrast to S3, where it only accounts for 4%. Until 2050, batteries remain the dominant electricity storage covering 63% of all stored electricity. The amount of total stored electricity remains stable between 2040 and 2050 despite the uptake of renewables in the electricity mix.

Figure 24: Stored energy by technology, 2015-2050

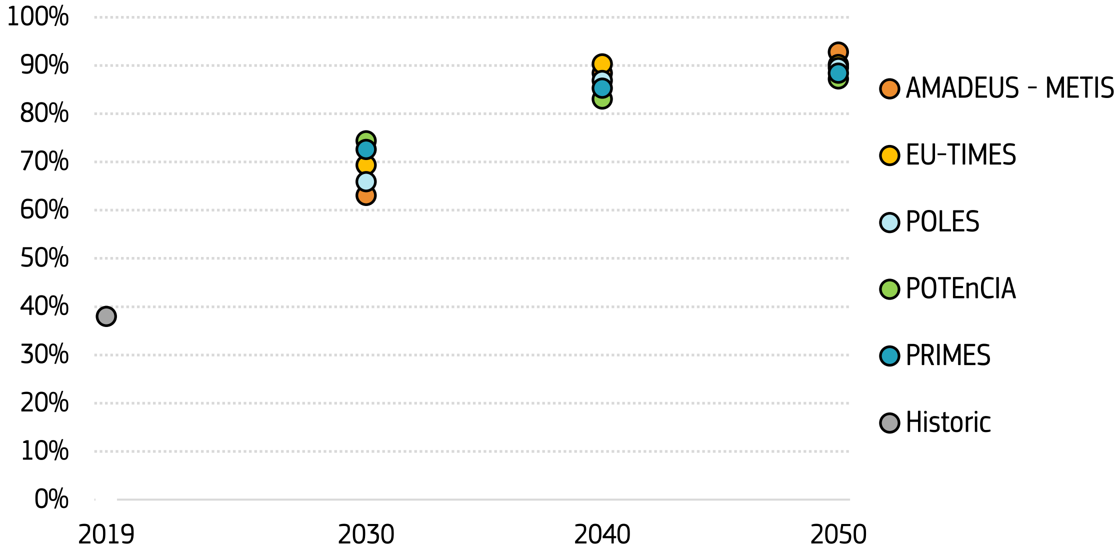


Source: PRIMES.

The five models used for this impact assessment show a high degree of similarity in the trajectory of the share of renewables in gross electricity generation, which increases quite steeply over the course of this decade to fulfil the Renewable Energy Directive and then at slower pace over the rest of the time horizon. Figure 25 shows the share of renewables in gross electricity generation across models. Four out of five models reach a renewable share in gross electricity generation around 85% in 2040, while one already achieves

90% by then. Then, in 2050 all five models identify that the share of renewables reaches around 90% (87-93%) to achieve the 2050 climate neutrality objective.

Figure 25: Share of renewables in gross electricity generation, 2019-2050



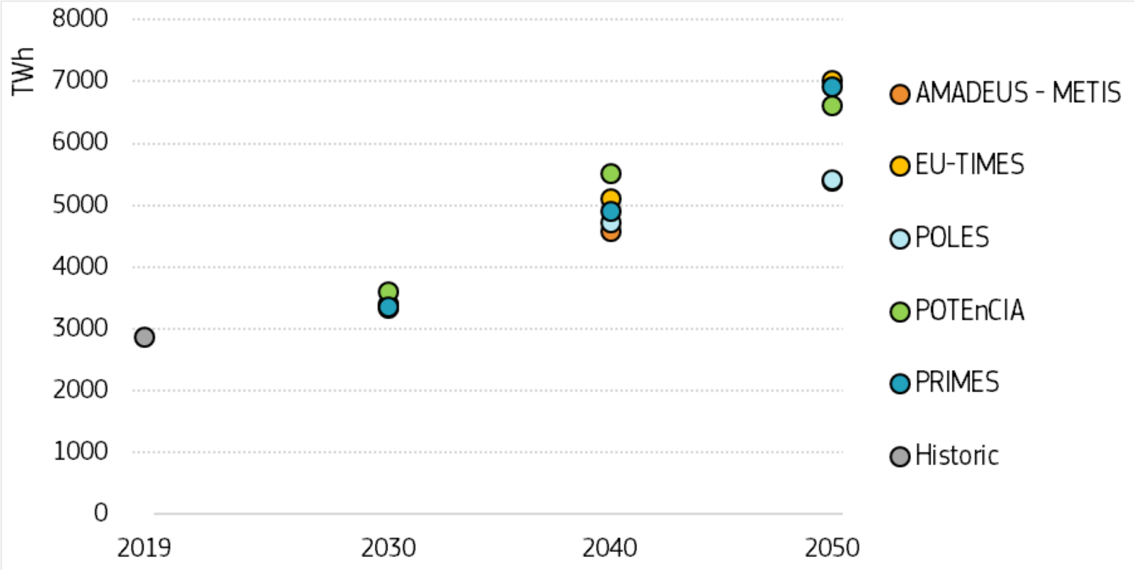
Note: renewables include solar PV, wind, hydro, concentration solar power, biomass, geothermal, tidal and marine.

Sources: AMADEUS-METIS, EU-TIMES, POLES, POTEnCIA, PRIMES.

It is worth noting that while the share of renewables is very similar across the five models, the renewable electricity generation in absolute terms shows a large variation. While all models feature an increase in renewable electricity generation over time, that is more pronounced in PRIMES, POTEnCIA and EU-TIMES – which feature a very similar trajectory – than in POLES and AMADEUS-METIS.

Projections for electricity generation across models show more variability as shown in Figure 26. This happens because energy models have more degrees of freedom in computing indicators such as electricity generation (compared to indicators such as GAE that is constrained by assumptions on economic activity and by emissions reduction targets). For example, in 2040 the POTEnCIA model projects 13% more electricity generation than PRIMES, which is largely due to a higher number of heat pumps deployed by the former model. On the other hand, PRIMES deploys significantly more RFNBOs than POTEnCIA in 2040 and 2050, which results in higher electricity generation in 2050 in PRIMES. POLES and AMADEUS-METIS show the lowest level of electricity production throughout the time horizon and particularly in 2050. This is mainly due to the fact that these models feature the smallest deployment of DAC and the smallest production of e-fuels. Overall, these results highlight the fact that different technology pathways are possible to reach the 2050 carbon neutrality target, which entail different levels of gross electricity generation.

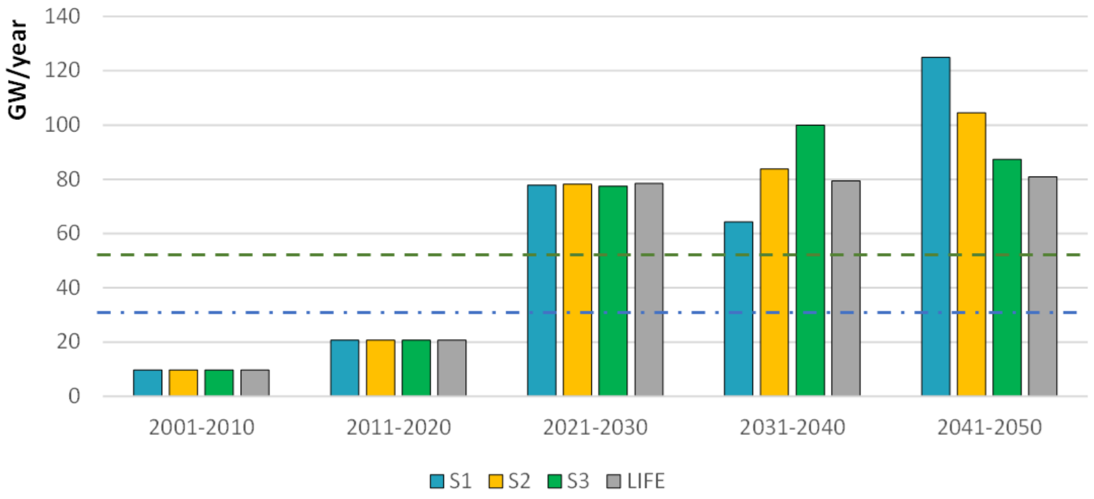
Figure 26: Gross electricity generation in different energy models, 2019-2050



Sources: AMADEUS-METIS, EU-TIMES, POLES, POTEnCIA, PRIMES.

Figure 27 compares annual deployment of wind and PV in different scenarios to the average of recent years (2016-2050, blue line) and to the maximum value reached in 2022 (green line).

Figure 27: Average annual deployment of wind and PV



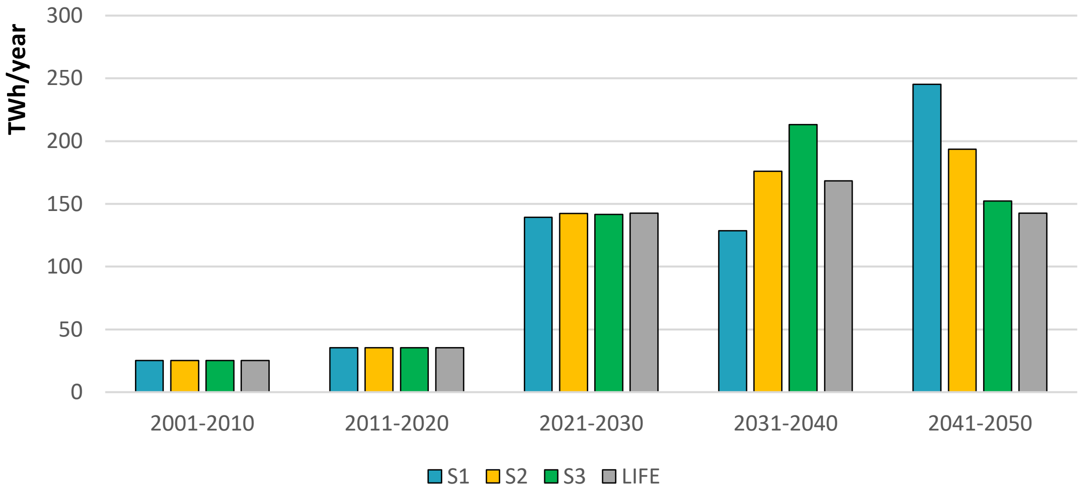
Note: Blue line: average 2016-2020; Green line: max historical deployment (occurred in 2022).

Source: PRIMES

The pace of the energy transition will increase in the 2031- 2040 decade, both compared to recent year and (especially in s ome scenarios) to the projections for 2030. Some patterns emerge across scenarios. The effort in the S1 scenario in the decade between 2030 and 2040 is comparable or slightly lower to that required to reach the 2030 target. However, in the 2041 – 2050 decade, the effort in S1 is significantly higher than in the other scenario (see Figure 28).

On the contrary the S3 scenario anticipates decarbonisation in the years 2031-2040 with lower effort required up to 2050. The S2 scenario lies in between S1 and S3. These trends are repeated for several other key indicators and is particularly noticeable when considering the annual increase in renewable power generation required to electrify the energy system (see Figure 28).

Figure 28: Average change in renewable power generation



Source: PRIMES

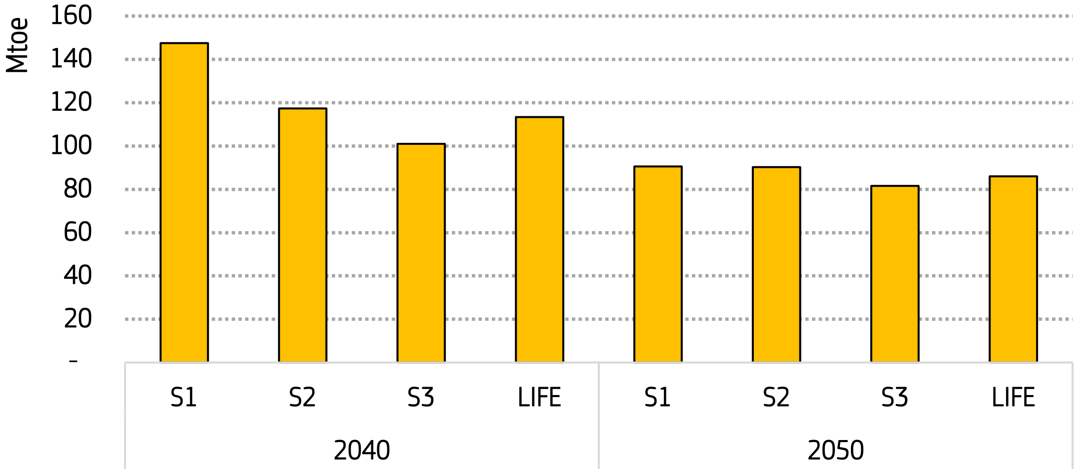
The combined needs of carbon capture, RFNBOs and electrification of final demand will require a very rapid increase in power generation. The rate of change up to 2040 is extreme in the S3 scenario. On the contrary, S1 requires the largest increase by far up to 2050. In this respect the S2 scenario shows a safer trajectory with an effort better balanced between the decades 2031 – 2040 and 2041 – 2050. Notably, LIFE allows to contain the needs for decarbonised power compared to the other scenarios.

1.2.3. Gaseous fuels

The RepowerEU Plan aims at rapidly reducing Europe’s dependence on Russian fossil fuels by fast-forwarding the clean transition and achieve a more resilient energy system. REPowerEU builds on the full implementation of the Fit-for-55 package, but the fast phasing-out of fossil fuel imports from Russia affects the transition trajectory – and how we reach the EU climate neutrality target – compared to previous assumptions. The EU’s consumption of natural gas is expected to reduce at a faster pace than expected before the crisis (*e.g.*, in the Climate Target Plan 2030).

Consumption of gaseous fuels is expected to decrease by between 54% and 68% between 2020 and 2040, reducing from 319 Mtoe in 2020 to 100 to 150 Mtoe in 2040 in S1-S2-S3 (Figure 29). The impact of the LIFE measures is projected to slightly increase the overall consumption of gas. The consumption of gaseous fuels amounts to 100 Mtoe in the S3 scenario. By 2050, gas consumption in the EU is further declines to around 80 Mtoe.

Figure 29: Consumption of gaseous fuels in the gas network, 2040-2050

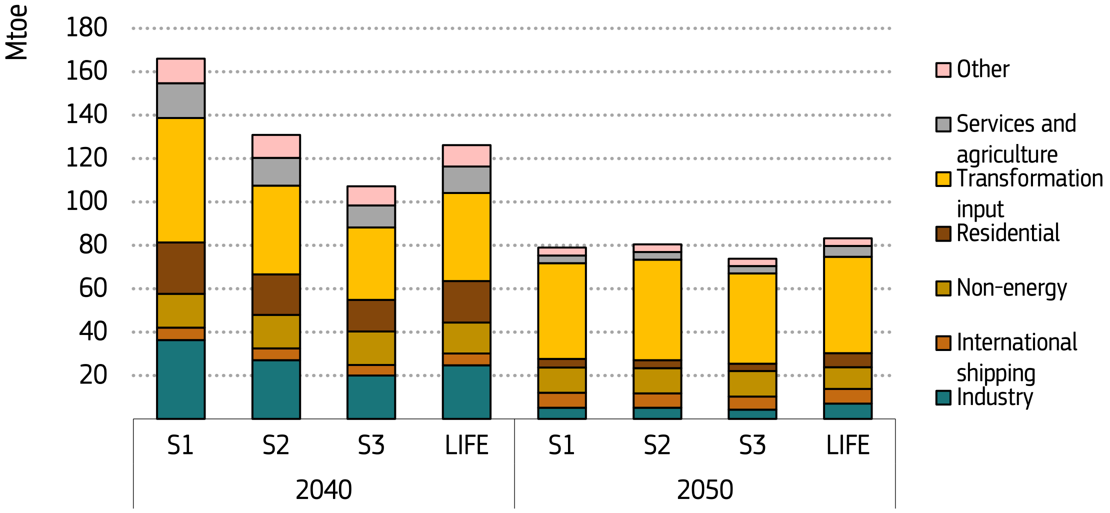


Note: the consumption of gaseous fuels hereby represented refers to gas consumed as transformation input in thermal power stations and district heating plants, consumption of the energy branch, and gas available for final consumption (including final non-energy consumption). It includes natural gas, clean gas and biomethane. Biogas is not covered in this figure and related analysis as it is not injected in the gas network.

Source: PRIMES.

In the gas network, this decrease in the consumption of natural gas is partly compensated by an increase in the consumption of biomethane. The sector with the largest absolute decrease in consumption of gas in the gas networks by 2040 is the residential sector, with -55 Mtoe (-70%) to -64 Mtoe (-82%) between 2020 and 2040. European energy policies encourage building renovation and energy efficiency improvements in the residential and commercial sector reducing the need for heating fuel.

Figure 30: Consumption of gaseous fuels by sector, 2040-2050



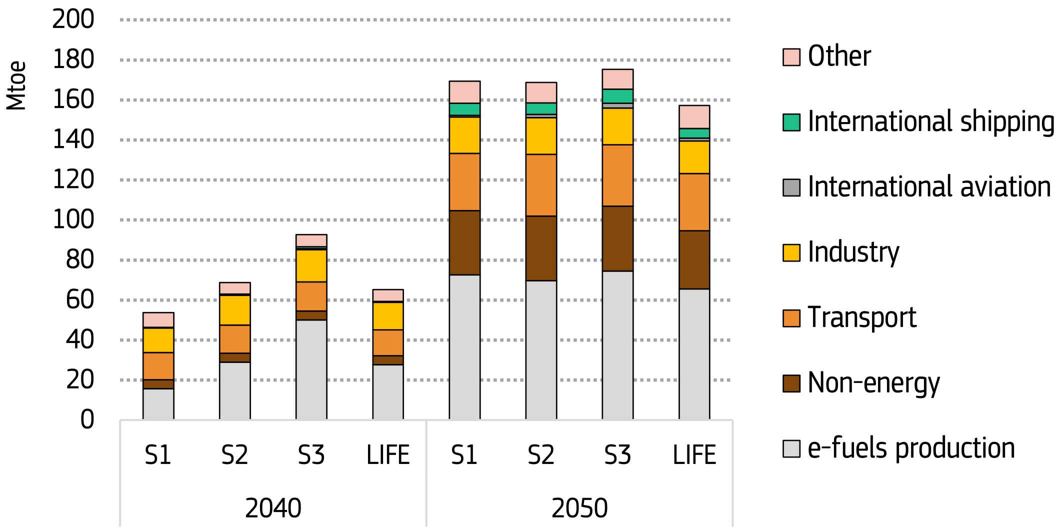
Note: Gaseous fuels include natural gas, biogas and biomethane.

Source: PRIMES.

Consumption of gaseous fuels per sector differs across scenarios in 2040, with notable differences for some sectors. At this time horizon, gas consumption in the industrial sector is higher in S1 compared to S3 (35 Mtoe versus 20 Mtoe). In the residential sector, consumption is also significantly higher in S1 compared to S3 (25 Mtoe versus 15 Mtoe) as well as in agriculture and services (15 Mtoe versus 10 Mtoe).

Renewable hydrogen is a rapidly evolving technology and sector. The modelling results for 2030 reflect the EU RFNBO targets, and associated hydrogen production, as per the revision of the Renewable Energy Directive under the Fit-for-55 package. However, the modelling for the future design of the post-2030 policy framework will take into account the updates of the National Climate and Energy Plans due in June 2024. The consumption of hydrogen as energy vector beyond traditional applications (like the chemical sector and refineries) appears in the EU energy system and contributes to decarbonise the hard-to-abate sectors and to support the operation of the power sector with high shares of variables renewable energies providing seasonal storage. In this decade, the consumption of hydrogen remains limited (see Figure 31), both because hydrogen-based technologies are generally characterised by relatively low maturity level and because the models prioritise the decarbonisation of sectors characterised by lower marginal abatement costs. Hydrogen consumption rapidly scales up, achieving in 2040 55-95 Mtoe in the S1-S2-S3 scenarios. The production of e-fuels (both gaseous and liquid) accounts for the lion’s share of total hydrogen consumption in 2040, followed by industry and – very closely – transport (in the S1, in 2040 the consumption of hydrogen in transport is higher than in industry). These three sectors alone account for more than three-fourths of total hydrogen consumption in 2040 in all scenarios. As a large deployment of e-fuels occurs in S3, this scenario experiences the highest level of hydrogen consumption in 2040 (*i.e.,* about 95 Mtoe) and is characterised by a tremendous growth in hydrogen use in the next decade. The main driver of the higher hydrogen consumption in the S3 scenario is the production of e-fuels, which consumes by itself around 50 Mtoe of hydrogen. In 2050, the consumption of hydrogen doubles with respect to 2040, attaining about 170-175 Mtoe in the S1-S2-S3 scenarios. LIFE measures would reduce the production of hydrogen by around 15 Mtoe. In 2050, the production of e-fuels continues being the main driver of hydrogen use in the EU energy system (70-75 Mtoe across scenarios), followed by non-energy uses (about 30 Mtoe across scenarios), then very closely followed by transport (about 30 Mtoe across scenarios) and finally by industry (20 Mtoe across scenarios).

Figure 31: Consumption of hydrogen by sector, 2040-2050

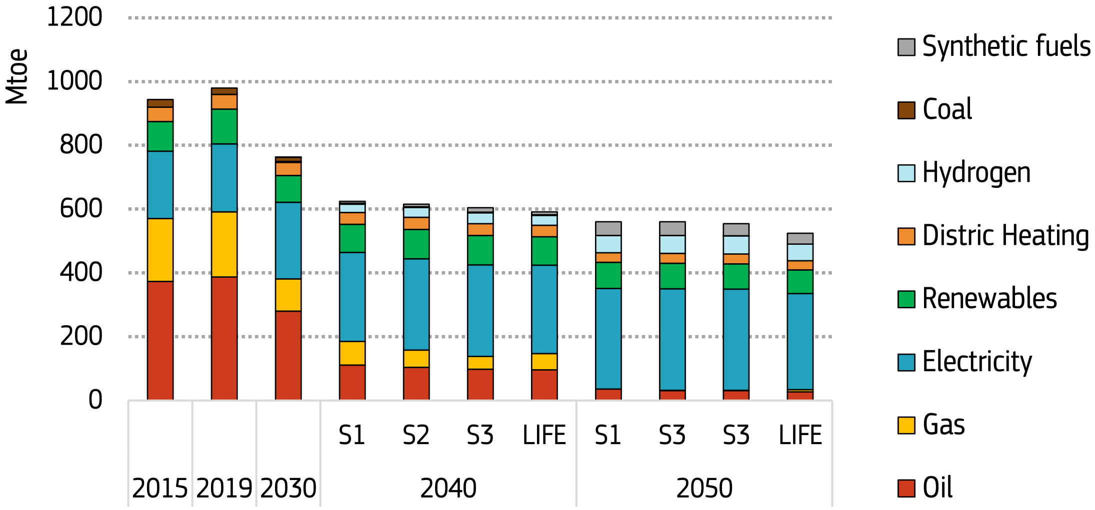


Source: PRIMES.

1.2.4. *Final Energy Consumption*

Final Energy Consumption (FEC) declines steadily, attaining in 2030 the 763 Mtoe targeted by the Energy Efficiency Directive (Figure 32). Then, FEC further reduces to 606-624 Mtoe in the S1-S2-S3 and scenarios. LIFE measures are projected to reduce FEC by additional 12 Mtoe. In 2050, FEC reaches approximately 560 Mtoe. The fuel and sector split of total FEC also changes progressively and the sector-specific drivers and dynamics are described in the relevant sections (Sections 1.3, 1.4 and 1.5).

Figure 32: Final Energy Consumption by fuel, 2015-2050



Source: PRIMES.

The share of fossil fuels in total FEC decreases from above 60% in 2019 to 52% in 2030, between 23% and 30% in 2040 under the various scenarios and 6% in 2050. Coal FEC becomes very small in 2030 and disappears shortly after 2040, driven by phase out in buildings after 2030 (pushed by the policies of several Member States) and by significant reductions in industry after 2030. Encouraged by the gradually more stringent CO_2

emission standards, oil FEC in 2030 reduces by 28% (108 Mtoe) compared to 2019 levels. After 2035, the reduction in oil FEC accelerates in light of the CO_2 emissions standards mandating sales of zero-emission vehicles only: in 2040, oil FEC attains approximately 100-110 Mtoe in the S1-S2-S3 scenarios. Natural gas FEC gradually reduces to only small quantities by 2040 (59). That is mainly due to improved energy performances of the building stock and to fuel switching towards mainly electricity in the building sector and hydrogen and electricity in the industrial sector. Natural gas FEC differs significantly in the S1 and S3 scenarios compared to the S2 scenario (-27% in S1 compared to S3 and -46% for S3), as the three scenarios are underpinned by different renovation rates (see section 1.3.2) and fuel switching to hydrogen and e-fuels. The share of renewable energy in gross FEC increases from 42.5% in 2030 (in line with the Renewable Energy Directive target) to between 65% and 75% in 2040 (with the S3 scenario requiring 10% more renewable energy than S1).

The contribution of electricity in FEC increases across all scenarios, and electricity becomes the dominating energy vector in final energy sectors. From 23% in 2015, the share of electricity in final demand increases to more than 30% in 2030 (240 Mtoe), to above 45% in 2040 across scenarios (280-290 Mtoe). The measures in LIFE reduce the need for electricity in FEC by 9 Mtoe. In 2050, it reaches 57% (320 Mtoe). Such increase is mainly driven by the uptake of electric vehicles in the transport sector, the penetration of heat pumps in buildings and electrification of low and medium temperature industrial processes.

Fossil fuels are also partially replaced by hydrogen and other RFNBOs, whose uptake only scales up at the end of this decade. Renewable hydrogen is a rapidly evolving technology and sector. The modelling results for 2030 reflect the EU RFNBO targets, and associated hydrogen production, as per the revision of the Renewable Energy Directive under the Fit-for-55 package. However, the modelling for the future design of the post-2030 policy framework will take into account the updates of the National Climate and Energy Plans due in June 2024.

Combined, RFNBOs account for 1% of total FEC in 2030 (5 Mtoe), 5-12% in 2040 (about 30-65 Mtoe) and 20% in 2050 (105 Mtoe). Measures from LIFE in 2040 have only a limited impact on the FEC of RFNBOs. Hydrogen is mostly consumed by heavy-duty trucks and in energy intensive industrial processes that can be hardly electrified. Gaseous e-fuels are consumed in almost equal proportions by the industrial sector and by the residential sector, and in lower amounts in the services sector as well. Liquid e-fuels are consumed entirely in the transport sector. Under the S3 scenario, the decline of FEC of oil and natural gas accelerates and in 2040 fossil fuels only account for approximately 23% of total FEC. This acceleration is driven by the need to rapidly reduce emissions in industry, buildings and transport sectors, which should get to almost net zero in early 2040s.

All five energy system models used in this impact assessment project a major increase in the contribution of electricity in total FEC, with high similarity in the overall trend in four of the five models (see Figure 33). In particular, POTEnCIA features a higher level of electrification than the other models from 2035 onwards: in 2040, it reaches 55% share

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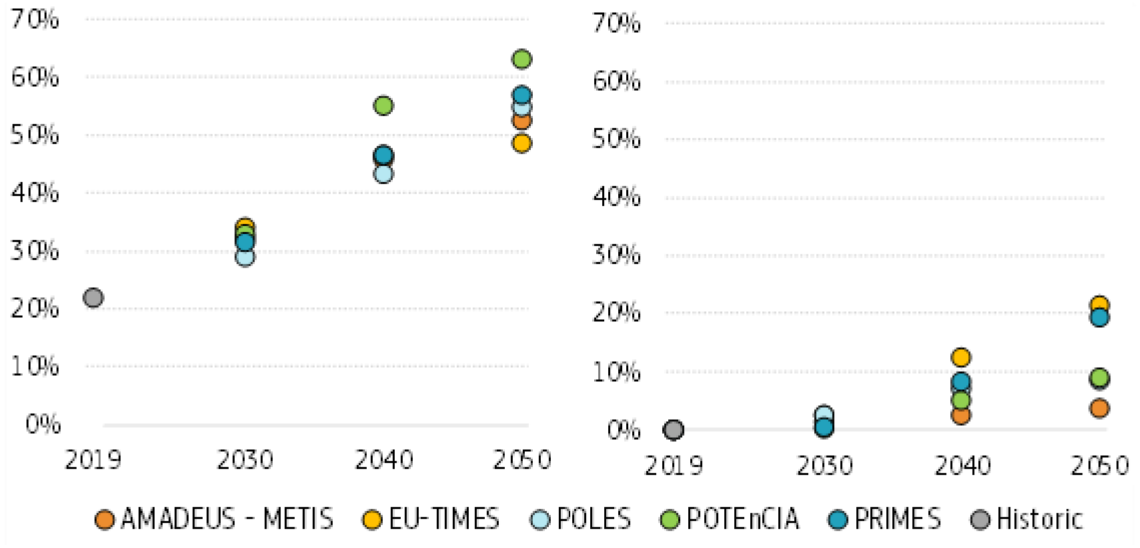
(59) Natural gas is still used as feedstock for the industry after 2040.

of electricity in FEC compared to 43-46% in the other models and in 2050 it reaches 63% compared to 49-57%. The higher electrification rate in POTEnCIA is mainly explained by POTEnCIA's technology choices in the transport and residential sectors, i.e., POTEnCIA features a larger adoption of heat pumps in buildings and higher roll-out of electric vehicles.

Regarding the share of RFNBOs in total FEC, the different models show a larger variability in the results, especially after 2035. In 2030, all five models see the contribution of RFNBOs to total FEC at below 3%. Afterwards, a larger degree of variability emerges in the results, with EU-TIMES showing the largest uptake – at 912 in 2040 and 21% in 2050 - and AMADEUS-METIS the smallest one – 3% in 2040 and 4% in 2050. This suggests that while electrification of end-use sectors is broadly considered a robust pathway for the decarbonisation of the EU energy system, there is more uncertainty on the actual role that RFNBOs are going to play.

Figure 33: Share of electricity (left) and RFNBOs (right) in FEC, 2019-2050



Sources: AMADEUS-METIS, EU-TIMES, POLES, POTEnCIA, PRIMES.

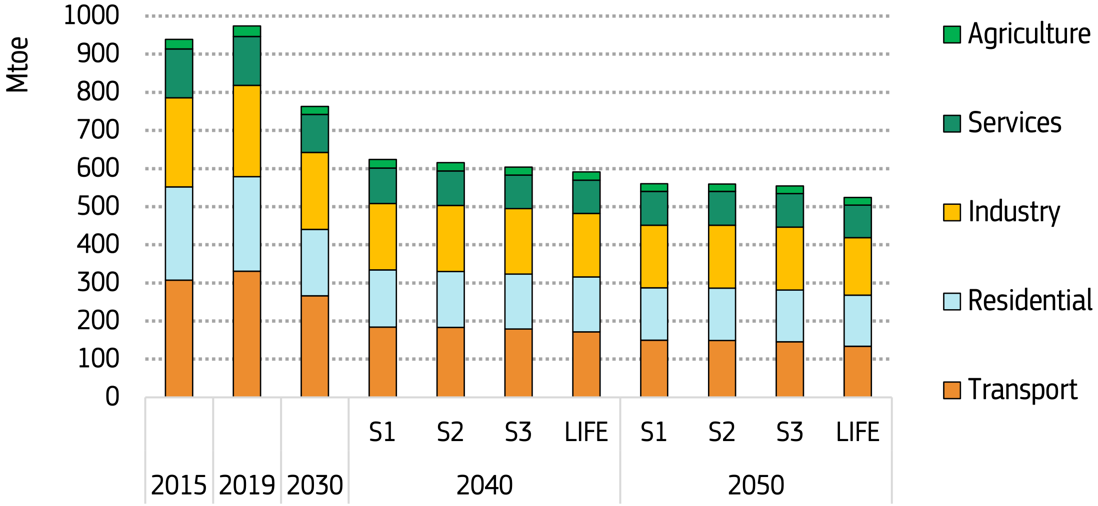
FEC of district heating and renewable heating (solar thermal, biomass and geothermal) in PRIMES slightly reduces over the time horizon, mainly due to better energy performances of the building stock, without particular variations across scenarios. The reduction of renewables FEC is lower than that of total FEC. As a result, the share of renewable heating in total FEC grows from 10% in 2015 to about 15% in 2040 and 2050.

Among the end-use sectors, the residential sector is expected to experience the largest reduction in energy consumption in this decade with almost -30% in 2030 (175 Mtoe) with respect to 2015, triggered by dedicated policies and measures (Figure 34). The residential sector is projected to further reduce its energy consumption by39-41% under the S1-S2-S3 scenarios (around 140-150 Mtoe), up to reducing by 44% in 2050 (140 Mtoe). The measures of LIFE only have a minor impact.

Transport FEC undergoes a markedly different trajectory: the reduction with respect to 2015 is limited to -13% by 2030 (about 270 Mtoe), but afterwards it experiences a steep reduction to reach -42% in 2040 (about 180 Mtoe) across all scenarios and -53% in 2050 (about 150 Mtoe) – the largest reductions across end-use sectors. Such dynamics is largely explained by the CO2 emission standards, which are gradually tightening until

2030 and then from 2035 mandate sales of zero-emission vehicles only (See Section 1.5.3 for more details). The impact of LIFE further reduces FEC in transport by 9 Mtoe n 2040. FEC in services and agriculture combined reduces at slower pace than in the residential sector, attaining -21% in 2030 (about 120 Mtoe) with respect to 2015; -25, -29% under the S1-S2-S3 scenarios, and -29% in 2050 (about 110 Mtoe). Finally, industry undergoes the smallest reduction in FEC of all end-use sectors throughout the time horizon, with -13% in 2030 with respect to 2015 (about 200 Mtoe), -27% in 2030 (about 170 Mtoe) and -39% in 2050 (about 165 Mtoe). Such dynamics are mainly due to the fact activity grows significantly in many energy-intensive sectors. Nevertheless, circular economy measures, as well as material, resource and energy efficiency are able to partially offset the economic growth and still lead to a FEC reduction in the sector (see Section 1.4.2 and 1.4.3 for more details).

Figure 34: FEC by sector, 2015-2050



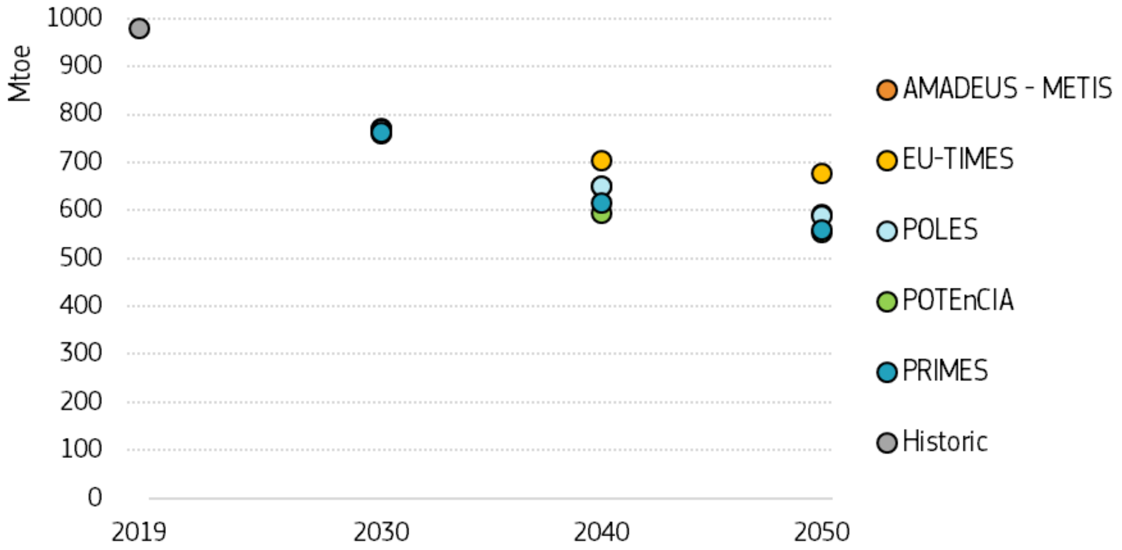
Source: PRIMES.

The above-mentioned sectoral dynamics lead to a different sectoral composition of FEC, with industry and agriculture and services becoming relatively more important over time, while residential and transport are declining.

The different scenario assumptions in the S1-S2-S3 scenarios have a somehow limited effect on energy consumption by sector. For each sector considered, the differences between scenarios are limited to approximately 5%.

Figure 35 compares projections for Final Energy Consumption from different energy system models and finds good alignment between them. In 2030, all models fulfil the target of the Energy Efficiency Directive, but different trends can be appreciated afterwards. EU-TIMES in particular features the slowest pace of reduction in total FEC: its total FEC is 14% and 21% higher than PRIMES’s total FEC in 2040 and 2050 respectively. EU-TIMES’ higher FEC than other models is largely explained by the fact that it features the lowest degree of electrification of end-use sectors and the highest reliance on RFNBOs (see also Figure 33). Results from the PRIMES and POTEnCIA models are very close throughout the time horizon (with a maximum difference below 4% over the 2035 – 2050 period).

Figure 35: Total FEC from different energy models, 2019-2050



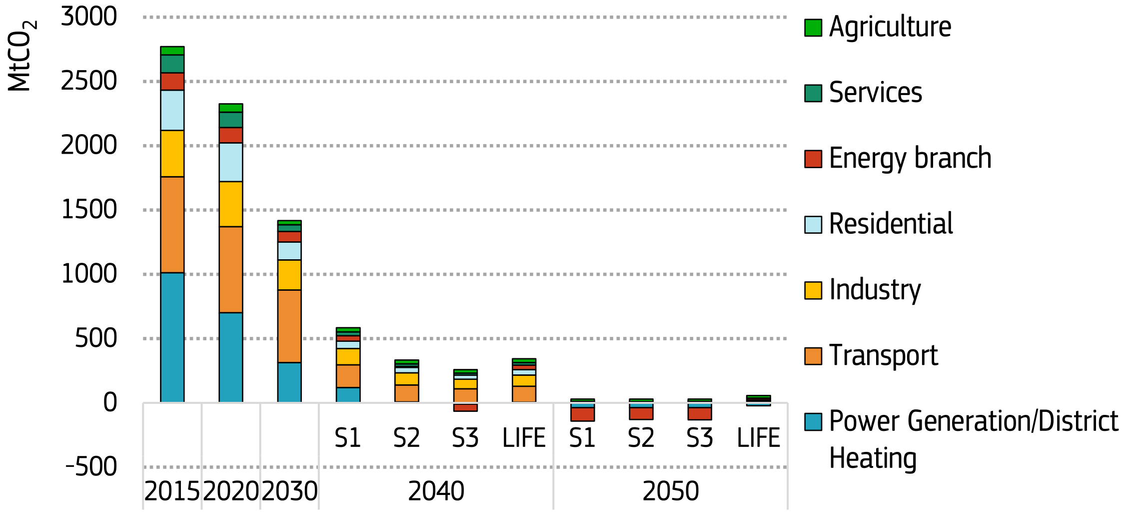
Sources: AMADEUS-METIS, EU-TIMES, POLES, POTEnCIA, PRIMES

1.2.5. Energy related CO_2 emissions

Figure 36 illustrates the energy-related CO_2 emissions profile over the modelling time horizon for the main energy sectors and for all the scenarios assessed. Achieving the climate neutrality objective in 2050 requires energy-related CO_2 emissions in 2040 to be in the range of 200-590 MtCO2 across scenarios. This is equivalent to a reduction in CO2 emissions with respect to 1990 in the range of 83-94%.

Historically, the power generation and district heating sectors were the largest emitter of CO_2 from combustion processes. With about 1 010 $MtCO_2$ emitted in 2015, it accounted for 37% of all energy-related CO2 emissions. However, the power generation and district heating sectors reduce CO_2 emissions at the fastest pace across the energy system and are the first achieving net-zero emissions. This result is in line with the findings of the public consultation on the EU climate targets for 2040, where respondents have most frequently identified “power generation and and district heating" as the first sector to achieve climate neutrality. In 2040, less than 10 MtCO2 are emitted from these sectors in the S2 scenario (99% reduction with respect to 1990) and under the S3 scenario negative emissions are achieved (thanks to BECCS) shortly before 2040. In 2050, these sectors become a negative emitter in all the scenarios analysed, with 30-40 $MtCO_2$ of negative emissions, thus partially offsetting residual emissions from the other sectors. The relatively fast pace in CO_2 emission reductions from the power generation and district heating sectors is explained by the stringency of the emission reduction target and the availability of a broad set of technologies to generate carbon-free electricity backed by proven storage technologies. The reductions in energy-related emissions for the other energy sectors is discussed in dedicated sectoral sections.

Figure 36: Domestic energy-related CO_2 emissions by sector, 2015-2050

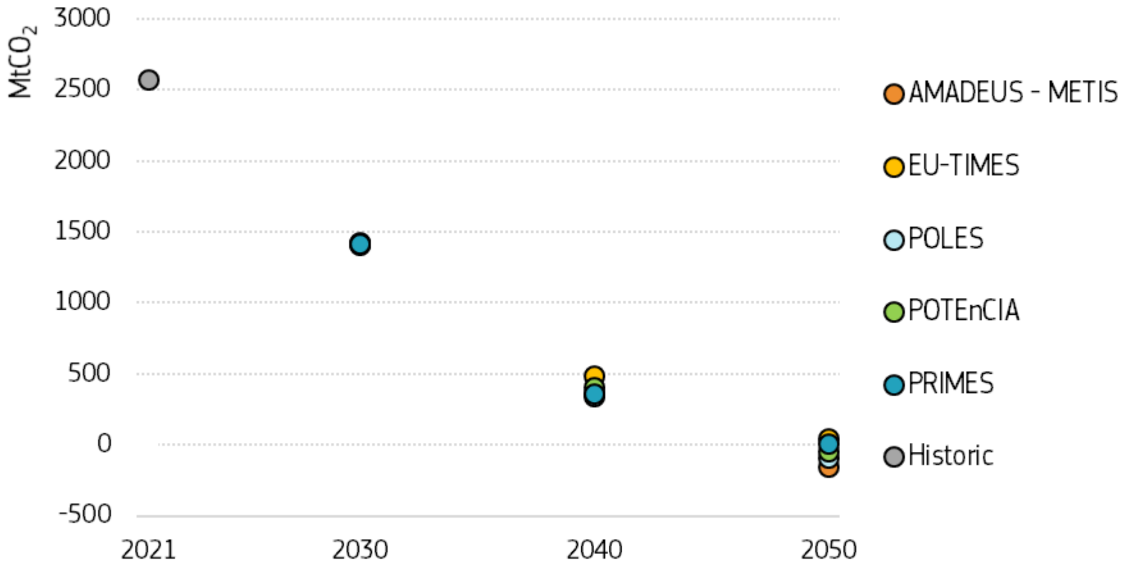


Note: the transport sector covers road, rail, inland navigation, domestic aviation and other transport.

Source: PRIMES.

The energy-related CO_2 emission reduction trajectory is very similar in the S2 scenario across the energy models used in this impact assessment. Overall, there is good agreement among the five energy models in identifying that energy-related CO_2 emissions in 2040 should reduce between 86% and 90% compared to 1990 (Figure 37). The AMADEUS-METIS model attains the largest CO2 emission reductions in 2050 and EU-TIMES is the least ambitious model. In 2050, three models (i.e., AMADEUS-METIS, POLES and POTEnCIA) attain negative energy-related CO_2 emissions, while the other two models achieve almost net-zero emissions.

Figure 37: Comparison of domestic energy-related CO2 emissions, 2021-2050



Note: the figures for the five energy models refer to the S2 scenario.

Sources: AMADEUS-METIS, EU-TIMES, POLES, POTEnCIA, PRIMES.

1.2.6. Raw materials' needs

The manufacturing and deployment of net-zero technologies will increase the needs for Critical Raw Materials (CRMs). With the scenario S3, the deployment of five net-zero technologies (wind turbines, solar PV, batteries, electrolysers and heat pumps) in the decade 2031-2040 would imply the need of up to 500 000 tonnes of copper each year. This compares with a global copper demand of 26 million tonnes in 2022 according to the IEA, including 370 000 tonnes for electric vehicles and 1.2 million tonnes for wind and solar. In 2030, global demand for copper could achieve 261 million tonnes in the Net Zero Emissions by 2050 scenario of the IEA (60).

Wind power on its own would create needs of up to 50 000 tonnes of manganese and 125 000 tonnes of copper per year. Batteries would create needs of up to 900 000 tonnes of aluminium, 80 000 tonnes of lithium and 60 000 tonnes of cobalt per year. Solar PV would also create needs of gallium (50 tonnes per year) and germanium (3 000 tonnes per year). Raw materials' needs would be lower in scenarios S1 and S2, as in 2040, net installed renewable power capacity is lower by 7% in S2 and by 16% in S1 compared with S3. As regards batteries though, deployment is relatively comparable in S1, S2 and S3, as battery capacity in 2040 is lower by only 1% in S2, and by 2.6% in S1 compared with S3. As a comparison, global lithium demand in 2022 was 130 000 tonnes, including 69 000 tonnes for electric vehicles according to the IEA. In 2030, global demand for lithium could be as high as 721 000 tonnes in the Net Zero Emissions by 2050 scenario of the IEA (61).

1.3. Buildings

The building sector (62) (including the residential and services sectors) accounted for 42% of final energy consumption in the EU in 2021 (63). The projections discussed below show that in this decade energy efficiency measures – i.e., renovating the building envelope and adopting minimum energy performance standards – is the main lever for buildings to contribute to the Fit for 55 targets in 2030. By reducing the useful energy needs, energy renovation enables to diminish the size of the heating and cooling equipment, thus reducing related capital and running costs and shielding vulnerable consumers from the impact of increasing energy prices. Fuel switching from fossils to renewable electricity for space heating is a key decarbonisation lever throughout the time horizon and is also essential to contribute to security of supply. In order to achieve climate neutrality by 2050 and to achieve significant emission reductions already in 2040, electrification in buildings needs to be intensified and – to a lower extent - accompanied by fuel switch to low-carbon gases. Besides, the push for high standard renovation must be kept beyond 2030 at higher rates than historically.

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(60) IEA (2023), Critical Minerals Data Explorer, IEA, Paris https://www.iea.org/data-and-statistics/data-tools/critical-minerals-data-explorer. Accessed on 05 December 2023.

(61) Ibid

(62) The model-based analysis is a technical exercise based on a number of assumptions that are shared across scenarios. Its results do not prejudge the future design of the post-2030 policy framework.

(63) Eurostat, *Complete Energy Balances European Union (27 countries) – 2021*, 2023.

1.3.1. Buildings activity

In the residential sector, the total floor area of households is projected to grow by 21% and 26% respectively in 2040 and 2050 with respect to 2015. Although the European population is projected to remain quite stable in the first half of the century (less than 1% reduction in 2050 compared to 2015), the total floor area of households grows due to two concurring dynamics:

- The average number of inhabitants per household is projected to reduce over time, which tends to increase the number of dwellings.
- The average size of the houses is projected to grow, as new houses have significantly larger surfaces than the existing ones.

In the commercial and services sector, the overall floor area of the buildings is projected to slightly reduce reaching in 2040 and beyond a floor area around 5% higher than 2015. These socio-economic dynamics push up the energy consumption in building, which makes the effort to mitigate energy demand and CO_2 emissions of buildings harder.

Heating degree days (HDD) and cooling degree days (CDD) are climate-based indicators commonly used to represent buildings' space heating and cooling needs in energy system models. HDDs and CDDs in historic years are based on EUROSTAT, and projections depart from statistics considering the effect of climate change on these indicators based on the findings of climate models ([64]). Projections of HDDs and CDDs are the same across the S1-S2-S3 scenarios, where - due to rising global average temperature - in the future HDDs are assumed to reduce in all member states with respect to today. In particular, in most member states the reduction in 2050 is in the range of -3/-11% compared to 2022. Consistently, CDDs are assumed to increase in all Member States compared to today. In particular, Member States characterised by colder climates, which today do not use air conditioning or make very limited use of it, are expected to increase CDDs the most in the future in relative terms, in some cases more than tripling compared to today ([65]). LIFE assumes a decrease/increase of the thermostat setpoint for heating and cooling respectively to mimic behavioural change related to thermal comfort. The thermostat setpoint is changed gradually, reaching +/-1.5 degrees in 2040 and remaining at that level until 2050.

1.3.2. Energy efficiency in buildings

Energy efficiency in buildings consists in two main types of action. For existing buildings, it implies renovating the building envelope - in order to reduce the demand for space heating and cooling while ensuring high comfort levels – and deploying renewables and energy efficient equipment for heating, cooling, cooking and appliances.

([64]) Dosio, A, Fischer, E.M. (2018): Will half a degree make a difference? Robust projection of indices of mean and extreme climate in Europe under 1.5°C, 2°C and 3°C global warming, Geophysical Research Letter, 45(2), 935-944, DOI:10.1002/2017GL076222

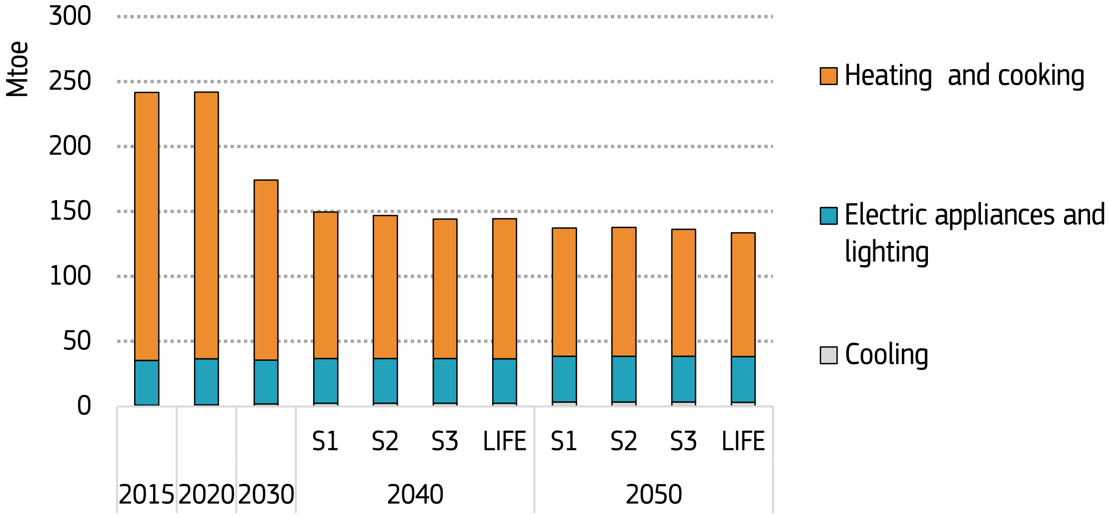
([65]) Energy consumption associated to cooling buildings is much lower than the one associated to heating and thus a large growth in CDDs provides a limited contribution to the overall change in building energy (see Figure and Figure).

For new buildings, it implies sticking to the minimum energy performance standards, as outlined in the Energy Performance of Buildings Directive (EPBD).

The current policy context is expected to significantly reduce energy consumption in buildings already in the course of this decade. Climate neutrality by 2050 requires reductions in buildings' energy demand beyond the levels reached in 2030. Encouraged by several policy initiatives that extend their impact after 2030, as well as by possible long-term effects of current energy crisis and pressure on gas imports, energy savings in buildings reach 35-38% across scenarios in 2040 and 40% in 2050. The residential sector would contribute more than the services sector to the overall energy savings in buildings, with 29% savings in 2030 with respect to 2015 (vs 23% savings in services), 39-41% across scenarios in 2040 (27-32% savings in services) and 44% in 2050 (31% savings in services).

The most important energy use in buildings is for space heating, which in 2015 accounted for more than three-quarters of final energy consumption in buildings.

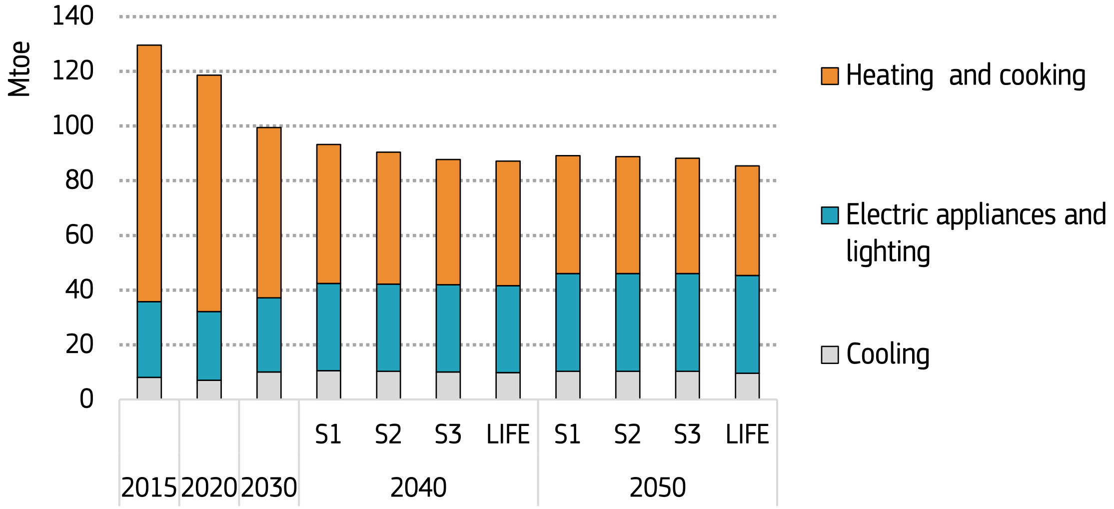
Figure 38: FEC in the residential sector by energy service, 2015-2050



Note: heating refers to both space heating and water heating.

Source: PRIMES.

Figure 39: FEC in the services sector by energy service, 2015-2050



Note: "Heating" refers to both space heating and water heating.

Source: PRIMES.

Final energy consumption related to heating in buildings is projected to reduce by one third in 2030 compared to 2015, by 46-47% across the S1-S2-S3 scenarios and by 51% in 2050, with almost identical dynamics in the residential and services sector (66). Final energy consumption related to cooling buildings accounted for only 2% of the total in 2015, but its share is projected to double by 2040 mainly due to higher comfort needs. The final energy consumption of appliances and lighting accounted for less than 20% of total energy consumption in buildings and the dynamics of this end-use sector are outlined in detail in Section 8.1.3.4 below.

The reduction of energy demand for space heating & cooling is largely achieved via the improvement of the thermal integrity of the building envelopes via increased renovation rates of existing buildings and high energy performance standards for renovated and new buildings. Renovation rates of the building envelope increase significantly in the future compared to historically observed rates. Higher renovation rates are encouraged by existing policies (e.g., the EPBD, ETS2, Energy Efficiency Directive) and increasing material circularity, and assuming that market failures - such as access to finance and split-incentives - that currently limit renovations are addressed.

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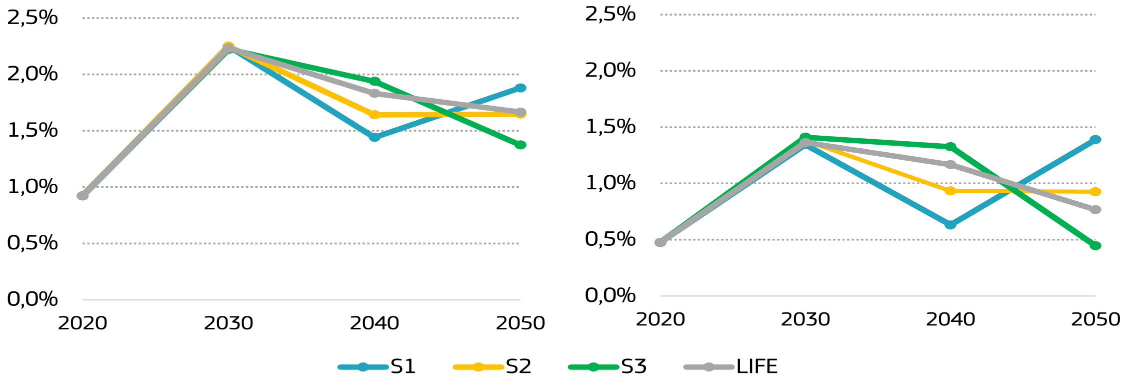
(66) The figures on heating include energy used for space heating, water heating and cooking, although the two latter have minor contributions.

Figure 40: Renovation rates in the residential and services sectors, 2020-2050



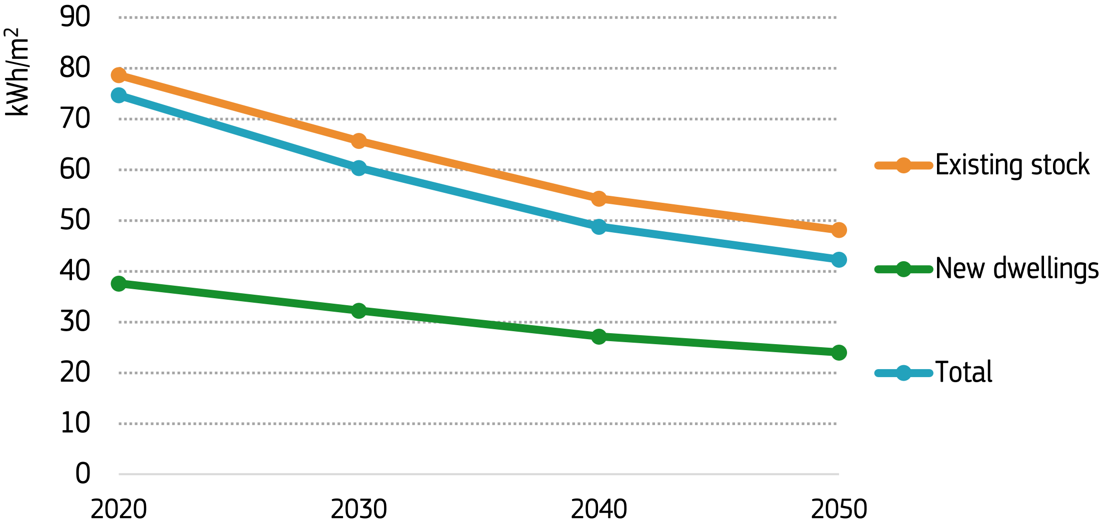
Source: PRIMES

Over the course of this decade, the residential sector doubles the building shell renovation rate, from 0.9% in 2020 to 2.2% in 2030 and 1.4% to 1.9% in 2040. The faster renovation rate of buildings than historically is in line with the findings of the public consultation on the climate target for 2040: 80% of individuals and 64% of organisations claim that the transition to climate neutrality should accelerate up to 2040. In the S3 scenario, the renovation rate in the residential sector changes to 1.6% in 2040 and then stabilises at that level. The S3 and S1 are characterised by opposite dynamics after 2030. The S3 scenario anticipates the renovation effort in the next decade (attaining 1.9% in 2040, the maximum across scenarios) and then limits the renovation in 2050 to a rate of 1.4% (the minimum level across scenarios). On the other hand, the S1 scenario after 2030 reduces substantially the renovation rate (attaining 1.4% in 2040) to then accelerate it in the 2040-2050 decade until 1.9% in 2050 (the highest level across scenarios) to compensate for missed climate action in the earlier decade. Similarly, in the services sector the renovation rate increases from 0.5% in 2020 to 0.6 to 1.3% in 2040. In the S2 scenario it gradually reduces (although at higher levels than historical) to 0.9% in 2040 and finally stabilizes at that level. The S1 and S3 scenarios show similar dynamics as in the residential sector, with the S3 anticipating the renovation effort and the S1 delaying it to the last decade of this analysis.

The renovation rates discussed above lead to 29% of the EU residential buildings fleet having been renovated in 2030, up to 40%-43% in the S1-S2-S3 scenarios) and finally to 55% in 2050. Regarding the services building fleet, 15% get renovated by 2030, 20% in the S2 scenario in 2040 (between 18% and 22% in the S1-S2-S3 scenarios) up to 32% in 2050.

The improvement of the energy performance standards and the renovation of the building fleet contribute to a gradual reduction in the average useful energy consumption for space heating (Figure 41). For new dwellings, the average useful energy for space heating at EU level will be pushed down from 36 kWh/m^2/year in 2015 to 32 in 2030 (-11%), to 27 in 2040 across scenarios (-25% compared to 2015) and 24 kWh/m^2/year in 2050. Existing dwellings will reduce useful energy for space heating from almost 80 kWh/m^2/year in 2015 to 66 in 2030 (-14% compared to 2015), 54-57 in 2040 across scenarios (-25/29% compared to 2015) and approximately 48 kWh/m^2/year in 2050 (-36% compared to 2015).

Figure 41: Average useful energy for space heating (S3)



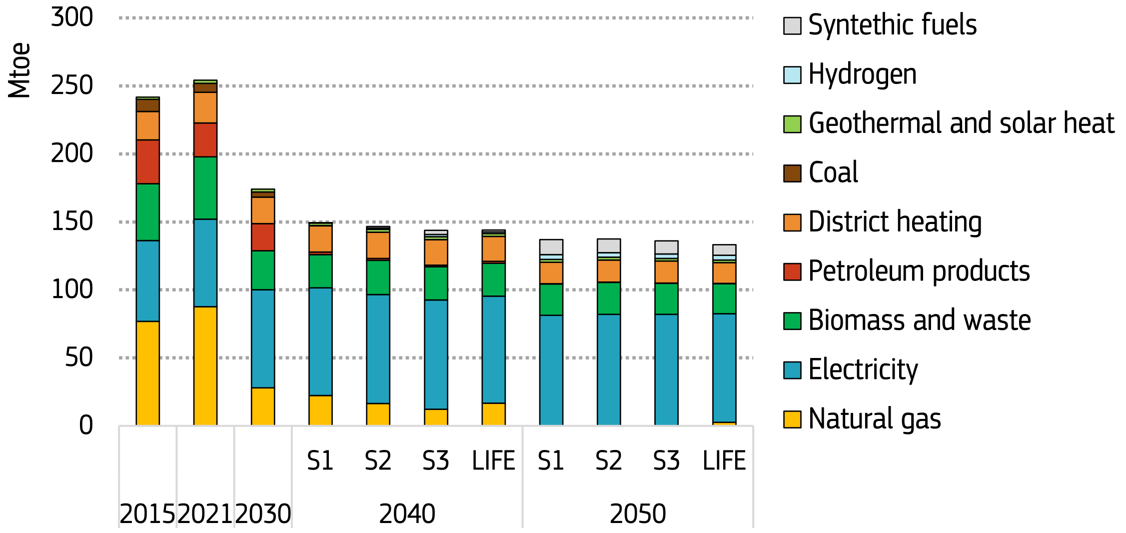
Source: PRIMES.

1.3.3. Fuel mix in buildings

The main trend related to the fuel mix that can be observed in buildings is the rapid growth of electricity consumption and the decrease of fossil fuels (notably natural gas) (see Figure 42 and Figure 43). In 2015, fossil fuels accounted for almost half of the final energy consumption in the buildings sector (about 170 Mtoe), with natural gas giving the largest contribution (about 110 Mtoe). By 2040, fossil fuels account for 9-15% under the S1-S2-S3 scenarios (20-37 Mtoe). In 2040 the consumption of oil and coal in buildings is almost entirely phased-out in all scenarios. By 2050, natural gas is phased-out from buildings as well.

Electricity becomes the backbone of the buildings sector. It increases from one-third of buildings energy demand in 2015 (about 120 Mtoe), to more than half in 2030 (140 Mtoe), up to 61-64% under the S1-S2-S3 scenarios (about 150 Mtoe) in 2040 and 67% in 2050. The electrification pattern is quite different between the residential and services sectors. In the residential sector, the share of electricity is projected to grow from one-fourth today to just above 40% in 2030, 53-56% across the S1, S2 and S3 scenarios in 2040 and up to 60% in 2050. In services, the electricity share today is already much higher: almost 50% and would increase to around two-thirds in 2030, more than 75% in all scenarios in 2040, until achieving almost 80% in 2050.

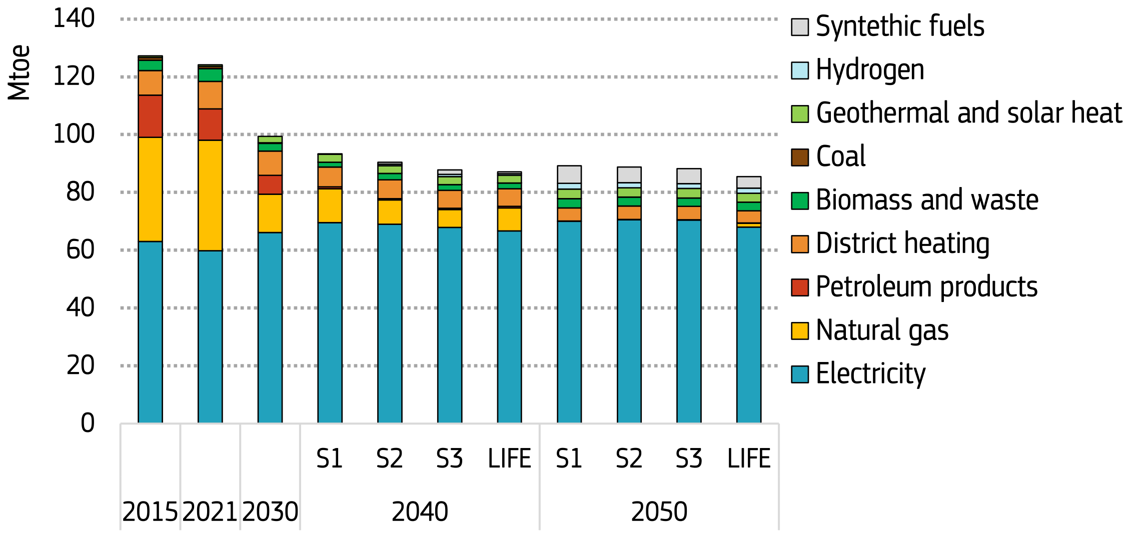
Figure 42: FEC in the residential sector, 2015-2050



Note: Biomass and waste include non-renewable waste. Ambient heat is not shown.

Source: PRIMES.

Figure 43: FEC in the services sector, 2015-2050



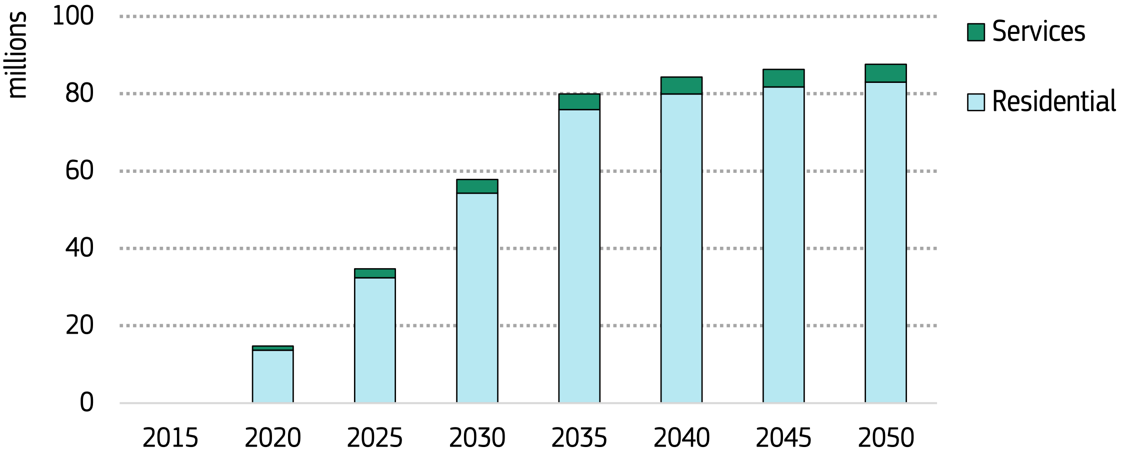
Note: Biomass and waste include non-renewable waste. Ambient heat is not shown.

Source: PRIMES.

Electrification of the buildings sector is characterised by the deployment of efficient electric heating and cooling technologies (notably heat pumps), energy efficient appliances and LED lighting. Efficiency of the electricity use in the buildings sector is well illustrated by the fact that the growing use of equipment consuming electricity is accompanied by limited growth in absolute electricity consumption: from 123 Mtoe in 2015 to almost 140 in 2030 (+12% compared to 2015), almost 150 Mtoe in 2040 across scenarios (+21% compared to 2015) and almost 155 Mtoe (+24%) in 2050.

Since space heating accounts for the lion's share of energy consumption in buildings, fuel switch in buildings' heating services is the key avenue for buildings to contribute to the carbon neutrality objective in 2050 and to curb emissions in 2040. Electrification of space heating and cooling is driven by the uptake of heat pumps (triggered partly by RepowerEU Plan), which experience a tremendous growth especially in the next two decades (see Figure 44).

Figure 44: Stock of heat pumps in the residential and services sector, 2015-2050



Source: PRIMES.

Hydrogen and gaseous e-fuels (67) start featuring an uptake in the buildings sector from 2035 and partially substitute the use of natural gas, thus supporting the phase out of such fossil fuel (see Section 1.2.4). However, the consumption of RFNBOs in the buildings sector remains extremely limited, at 1-3% in the S1-S2-S3 scenarios and below 10% in all scenarios in 2050.

Renewable energy sources (such as geothermal and solar heat) have marginal shares in buildings energy consumption and only experiences a moderate growth during the time horizon. Rather, the use of heat pumps with electricity provided by solar PV is expected be a more competitive technology option underpinned by faster cost reductions. Biomass (used in modern stoves) broadly maintains constant its share of energy consumption in buildings throughout the projections' time horizon. In the residential sector, where biomass accounted for 17% of residential energy consumption in 2015, the consumption of biomass almost halves between 2015 and 2050, at the same pace as total energy consumption in the residential sector. (68) In the services sector, the share of biomass remains stable as well, although at much lower level than in the residential sector - around 3%. District heating increases slightly its share of total energy demand in buildings reaching approximately 11% in 2040 in all scenarios.

It is worth noting that the role of RFNBOs in the decarbonisation of the building sector is highly uncertain. A literature review has found out that hydrogen's role in global energy scenarios is extremely inconsistent: only two out of ten studies reviewed feature a contribution of hydrogen to space heating, which is less than 15% of total space heating

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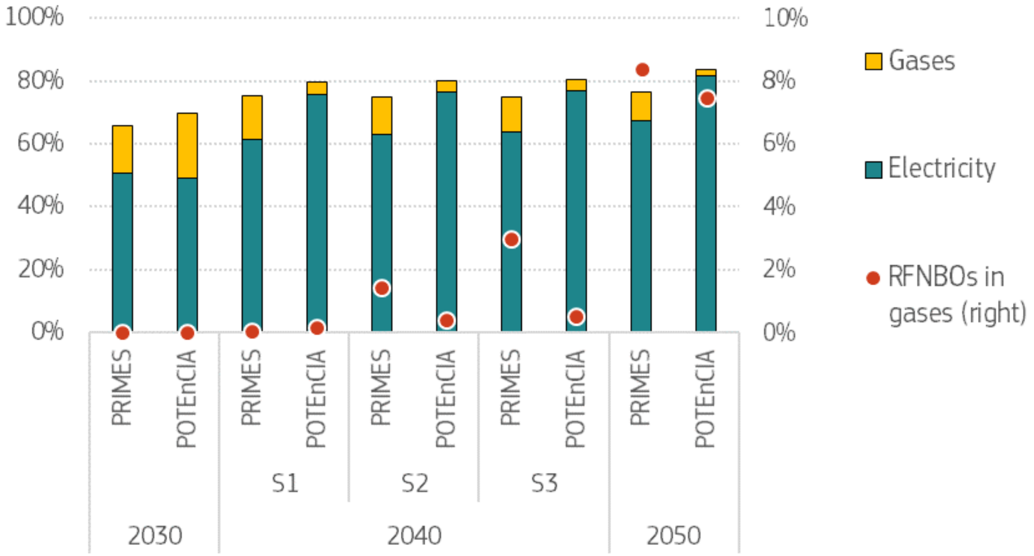
(67) Renewable hydrogen is a rapidly evolving technology and sector. The modelling results for 2030 reflect the EU RFNBO targets, and associated hydrogen production, as per the revision of the Renewable Energy Directive under the Fit-for-55 package. However, the modelling for the future design of the post-2030 policy framework will take into account the updates of the National Climate and Energy Plans due in June 2024.

(68) Future analyses may assume other supply levels of biomass to stay within the sustainability boundaries, in view of the on-going scientific debate.

demand even in the most hydrogen ambitious scenarios in 2050. ([69]). Another recent literature review has found out that few EU energy system models see RFNBOs used in buildings in 2030 (and with a share below 1% of total energy consumption in buildings). In 2040, more models feature hydrogen demand in buildings, which remains below 6% of final demand. In 2050, EU models are characterised by very different levels of RFNBOs consumption in buildings, ranging from nothing or extremely low levels up to 16% of final demand in buildings.

Both PRIMES and POTEnCIA project a similar growing trajectory in terms of combined share of gaseous fuels (natural gas, hydrogen and synthetic gas) and electricity in total buildings' FEC (Figure 45). However, the two models differ in that PRIMES features a higher and longer reliance on the gas network to fulfil buildings' energy needs, while POTEnCIA features a deeper and faster electrification. Such difference is partially explained by the fact that PRIMES reduces the carbon intensity of the gas mix provided to buildings by producing RFNBOs to be injected in the gas network earlier and in larger amounts.

Figure 45: Contribution of electricity and gaseous fuels to buildings' FEC, 2030-2050



Sources: POTEnCIA, PRIMES

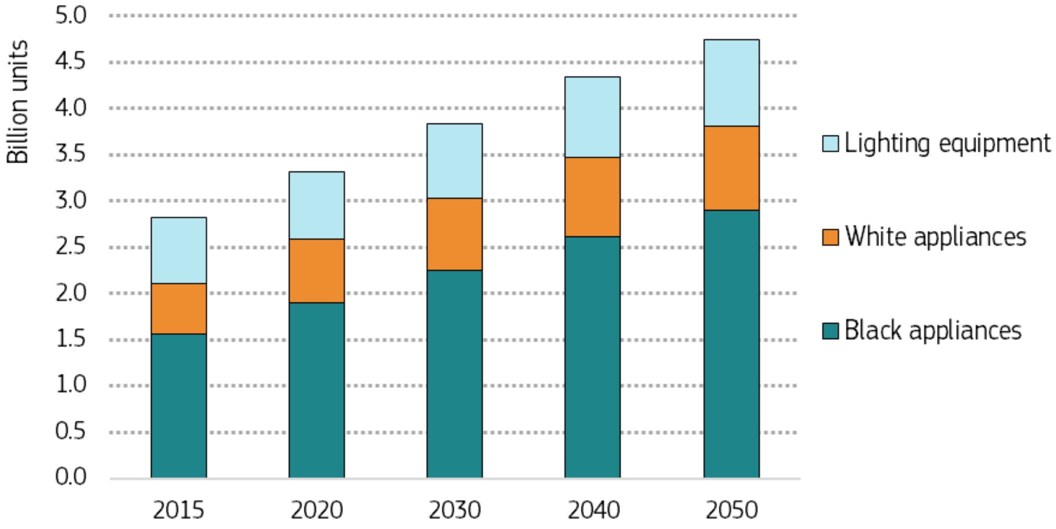
This analysis underlines that a very similar level of decarbonisation of the building sector – as other sectors - can be achieved via different pathways, with the largest differences around 2040. The balance between the use of heat pumps rather than RFNBOs to heat households has important implications on the economics of the gas network and on the sizing of the electricity distribution network.

([69]) Quarton C.J, Tlili O., Welder L., Mansilla C., Blanco H., Heinrichs H., Leaver J., Samsatli N.J., Lucchese P., Robinius M., Samsatli S. (2020), The curious case of the conflicting roles of hydrogen in global energy scenarios, Sustainable Energy Fuels, 4, 80, DOI: 10.1039/c9se00833k

1.3.4. Appliances

The growing number of dwellings (Section 1.3.1), higher GDP and living standards drive up the number of appliances (Figure 46). Compared to 2015, the stock of black appliances grows by 44%, 68% and 86% respectively in 2030, 2040 and 2050 respectively[70]. Information and communication appliances experience the largest growth, more than doubling their stock already in 2030. The stock of white appliances grows at slightly lower pace, by 41%, 55% and 65% respectively in 2030, 2040 and 2050 with respect to 2015 ([71]). The growth of the stock of lighting equipment is more limited compared to that of appliances.

Figure 46: Stock of black and white appliances and of lighting equipment, 2015-2050



Note: the stock of appliances and of lighting equipment does not vary across scenarios.

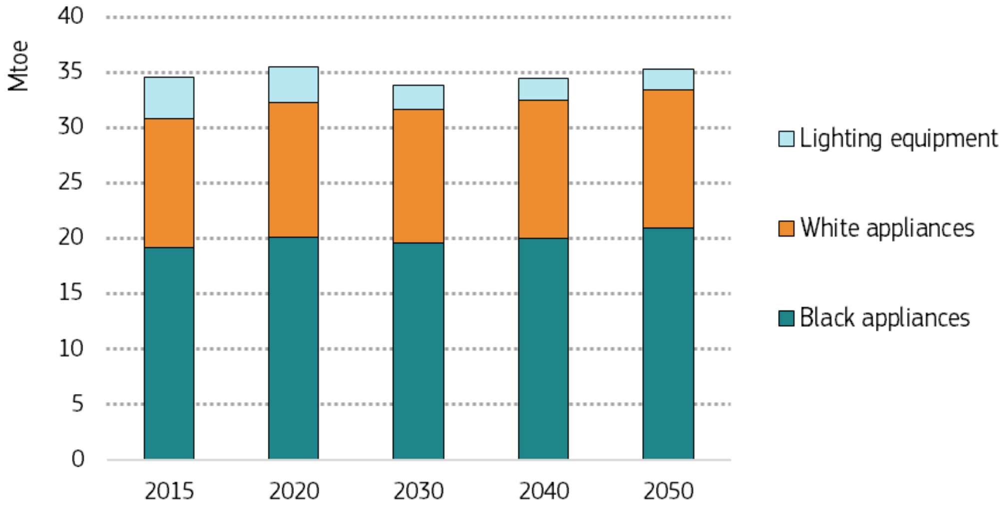
Source: PRIMES.

Such ever increasing number and use of appliances is moderated by energy efficiency measures (such as eco-design and energy labelling legislation targeting the energy efficiency of appliances) resulting in almost constant electricity demand from appliances and lighting, at around 35 Mtoe throughout the projections' time horizon (see Figure 47). Since energy demand for space heating is projected to reduce significantly, the share of energy demand for appliances out of total energy demand in buildings grows from 14% in 2015 to 19% in 2030, 23% in 2040 and 26% in 2050 across scenarios.

([70]) Black appliances refer to vacuum cleaners, small appliances, information and entertainment appliances.

([71]) White appliances refer to dishwasher, dryers, freezers, refrigerators and washing machines.

Figure 47: Electricity demand associated to appliances and lighting, 2015-2050

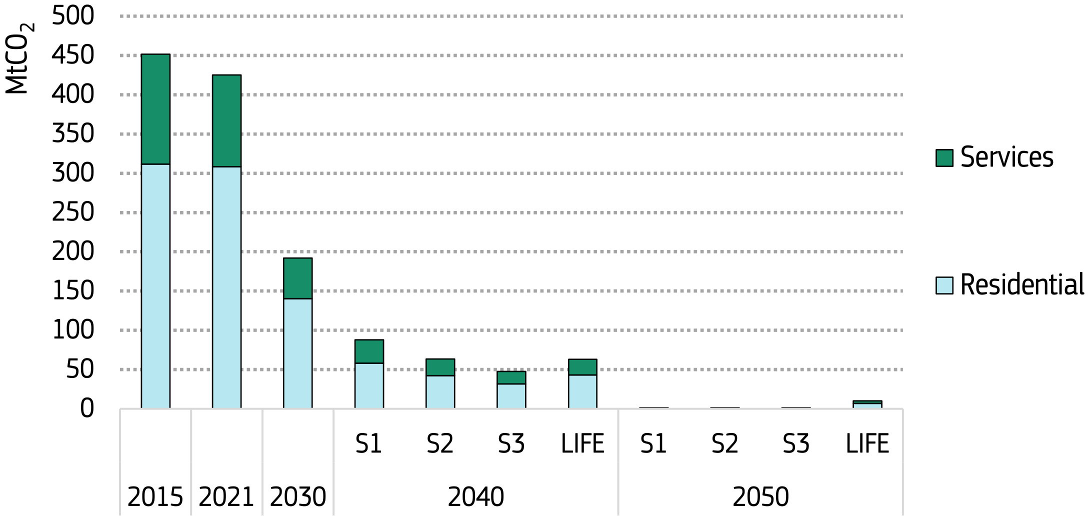


Source: PRIMES.

1.3.5. *CO_2 emissions from buildings*

Direct CO_2 emissions from buildings experience a rapid decrease already in this decade, from about 450 $MtCO_2$ in 2015 to 190 $MtCO_2$ in 2030, i.e., -57% (Figure 48). Then, CO_2 emissions further reduce to about 50-90 $MtCO_2$ under the S1-S2-S3 scenarios in 2040 and reach almost zero emissions in 2050 for all scenarios. The residential and services sectors face a similar pace of CO_2 emission reductions throughout the projection time horizon. This is largely explained by the fact both sectors rely on essentially the same mitigation options, which have very similar costs, and are triggered by the same policy measures.

Figure 48: Buildings CO2 emissions trajectory by sector, 2015-2050



Note: CO_2 emissions shown in the figure are only direct emissions, i.e., related to the combustion of fuels consumed in the building sector. Emissions related to the production of the electricity and RFNBOs consumed in the buildings sector are accounted in the upstream sectors.

Source: PRIMES.

The CO_2 emissions discussed above only account for direct CO_2 emissions, i.e., those directly related to the combustion of fuels consumed in the building sector. Instead, emissions associated to the production of electricity and RFNBOs consumed by buildings are accounted in the upstream sectors. Given that the buildings sector is expected to experience a significant electrification (see Figure 42 and Figure 43) and to consume – to a lower extent – RFNBOs, the building sector is responsible for significant amounts of indirect CO_2 emissions as well. However, the power generation sector is set to decarbonise rapidly and become completely carbon neutral by around 2040.

The reduction in CO_2 emissions from buildings is achieved mainly via the faster rate of renovation of the buildings' envelopes, which reduces the overall energy consumption, and by the replacement of fossil fuels space heating equipment with heat pumps. The deployment of renewables and the blending of low-carbon gases in the gas network also contributes to lower emissions. As discussed in detail in Sections 1.3.2 and 1.3.3, these transformations are largely driven by climate policies extending their impact beyond 2030, such as the ETS2. Finally, CO_2 emission reductions are also achieved by reducing energy consumption from heating, cooling and cooking equipment and appliances – driven by the eco-labelling policy.

1.4. Industry

1.4.1. Introduction

According to IEA, global industry **(**[72]**)** accounts for one-third of total final energy consumption, and the CO2 emitted (9 GtCO2) represents one-quarter of all energy and process CO2 emissions ([73]). In the EU, industrial emissions have been decreasing steadily since 1990, overcoming also the rebound due to the restart of economic activity after the COVID-19 pandemic ([74]), and in 2020, they represented 26% of total net GHG emissions ([75]).

No silver bullet exists to decarbonise industry, and different solutions are to be implemented to the various subsectors to achieve climate neutrality. Reduction of raw materials demand, for instance by implementation of circular economy and demand-side actions, can reduce emissions by 20% in 2040 ([76]). Energy efficiency, together with indirect and direct electrification can reduce emissions by 25% ([77]), acting on the industry energy needs. Replacement of fossil fuels by bio- and e-fuels can contribute to decarbonisation where electrification is not technically possible and carbon capture can be implemented where low carbon alternative processes have limited potential. Literature

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([72]) The model-based analysis is a technical exercise based on a number of assumptions that are shared across scenarios. Its results do not prejudge the future design of the post-2030 policy framework.

([73]) IEA, (2022). Achieving Net Zero Heavy Industry Sectors in G7 Members.

([74]) COM/2022/514 final

([75]) McKinsey, (2020). Net-Zero Europe Decarbonization pathways and socioeconomic implications.

([76]) Kalcher, L. et al., (2023). The post-2030 climate target debate starts now, *Strategic Perspectives and Climact*. https://strategicperspectives.eu/the-post-2030-climate-target-debate-starts-now/

([77]) Madeddu, S., et al. (2020). The CO2 reduction potential for the European industry via direct electrification of heat supply (power-to-heat). *Environmental Research Letters, 15*(12), 124004.

shows that combining all approaches can reduce industrial emissions by 86% in 2050 compared to 2019 (78).

1.4.2. Activity

The activity in the three main scenarios build on a continuation of trends of sector-specific material demand and associated production. LIFE illustrates how a more efficient use of materials resources, through technological innovations and a higher circularity of the EU's economy, can impact positively sectoral CO2 emissions.

Future production of steel in EU is likely to maintain current levels (79), and this trend is reflected in the main scenarios, where sector decarbonisation happens mainly through the increase of electric arc furnace share and a larger use of hydrogen in the reduction of iron ore (80). A more efficient use of steel and an increasing recycling rate could lead to a decrease in primary production and an increased share of secondary steel, reducing overall demand by up to 15-17% in the period 2040-2050 compared to the most recent years (77)(78). LIFE follows this approach and projects a decrease in demand of around 15% in 2050 (25% of primary) compared to the main scenarios.

According to BNEF (79), global production for aluminium is projected to increase by around 40% by 2050, intensifying especially secondary aluminum. Studies also show that a more efficient use of this material, especially in terms of scrap recycled and lifetime extension of products, can instead maintain production level to similar values as today (77). In S1, S2 and S3, an increase of aluminum production of around 35% until 2050 is assumed, while LIFE models an optimisation of material use resulting in a reduction of 20% of production when compared to the main scenarios.

The paper sector is expected to moderately increase production, as the decline in printing-related paper production is outweighed by growth in packaging and sanitary paper products (81). The high recyclicling rates of today are projected to increase further (82), expanding the secondary share of production and unlocking the possibility to reduced paper demand of up to 14% in 2050 (vs 2015) (78). The modelling captures these trends, projecting a 5% increase of production by 2050 in S1, S2 and S3 and a decrease in LIFE of around 20% in 2050 (40% for primary), thanks to higher recycling rates and material efficiency, and implementation of reusable packaging.

Production of cement (including clinker) in EU is assumed to increase by around 20% in the main scenarios by 2050 (79). However, low-carbon cement alternatives, high share of recycled cement in concrete, and changes in lifetime and utilisation rate of buildings could decrease demand, with estimates showing lower demand by 25% in 2040

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(78) CLEVER, (2023). Climate neutrality, Energy security and Sustainability: A pathway to bridge the gap through Sufficiency, Efficiency and Renewables, *Final Report*. https://clever-energy-scenario.eu/wp-content/uploads/2023/06/clever_final_report-exec_summary.pdf

(79) BNEF, (2023). New Energy Outlook: Industry.

(80) Agora Industry and Wuppertal Institute, (2023). 15 insights on the global steel transformation.

(81) IEA, (2023). Tracking Clean Energy Process, Tracking Pulp and Paper.

(82) Directive 94/62/EC (Amended by Directive(EU) 2018/852).

compared to 2019 (77) or by 38% in 2050 compared to 2015 (78). LIFE assumes a demand-driven production around 25% lower in 2050.

The global demand for petrochemicals, including a larger share of chemically recycled feedstock, is projected to double by 2050 compared to 2021, with the EU representing around 4% of market share by mid-century (79). In the main scenarios, an increase of demand for organic chemical and petrochemicals in end-user products of around 23% with respect to the average production in 2015-2020 is assumed, taking also into account a steep increase in recycling rate. According to literature, additional demand-side actions could lead to an optimisation of production of chemicals, with savings of up to around 28% of olefins and ammonia in 2040 (vs 2019) (77) and up to 23% in 2050 (vs 2015) when encompassing all chemicals (78). Introduction of additional measures in LIFE such as a ban of single use water bottles and strong reduction of plastic-packaging are projected to save approximately 15% of primary input material in 2050.

Table 8 summarises the variation of industrial production assumed in the analysis.

Table 8: Assumptions on evolution of industrial domestic production for selected materials

	S1, S2, S3	**LIFE**
	2050 vs 2015	vs S1, S2, S3 in 2050
Steel	0%	-15% (-25% primary)
Aluminum	35%	-20%
Paper	5%	-20% (-40% primary)
Cement (including clinker)	20%	-25%
Petrochemicals and organic materials	25%*	-15%

*Note: *Value calculated with respect to the 2015-2020 average production.*

1.4.3. Final Energy Consumption

As result of improved energy efficiency and changes in activity, energy consumption (83) in the industrial sector decreases by around 20% in the 2031-2040 decade and by 7 additional percentage point in 2041-2050 (vs 2030) in the main scenarios, showing that a significant part of the mitigation potential allocated to efficiency improvement is attained already by 2040. LIFE shows for 2040 a nearly identical value as the other scenarios and for 2050 an additional reduction of few percentage points (Figure 49).

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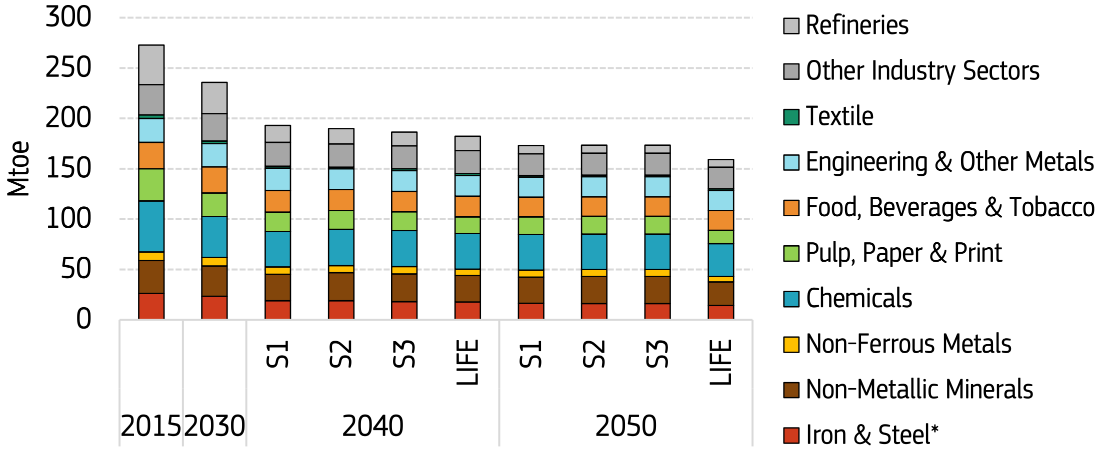
(83) Final energy consumption (FEC) and consumption in refineries

Figure 49: Final Energy Consumption in industry by sector



*Note: *The iron and steel sector includes blast furnaces.*

Source: PRIMES.

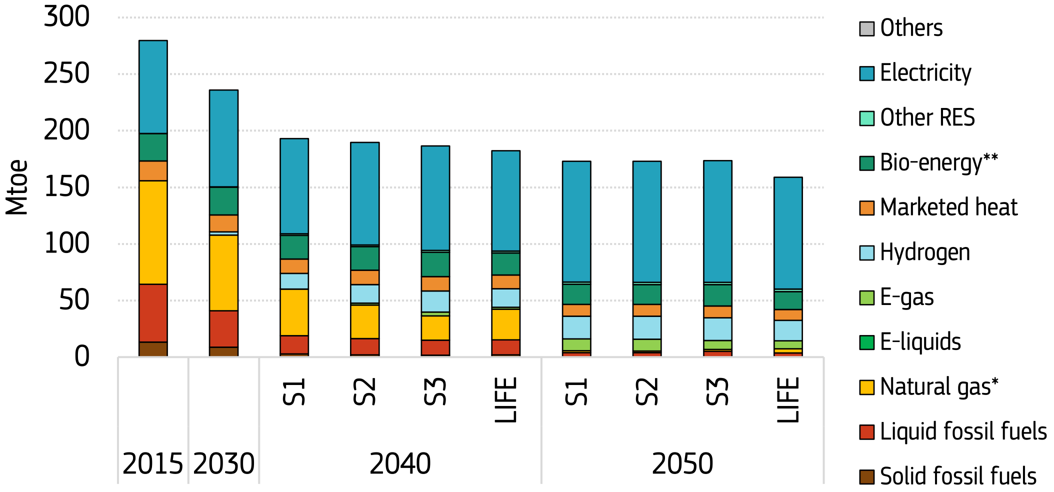
When looking at the share of the different fuels in industry consumption (Figure 50), the model shows an increasing electrification trend in all scenarios. Electrification share reaches around 48% in 2040 and 62% in 2050 from around 21% in 2021 ([84]), in line with figures of around 50% in 2040 and 60% in 2050 projected by Eurelectric ([85]). The model also shows a progressively higher contribution of RFNBOs, representing around 1%, 10% and 18% of FEC in 2030, 2040 and 2050. Electrification share in Final Energy Consumption (FEC-E) varies little across scenarios, indicating that it is based on a number of commercial technologies and consolidated trends already available in S1 and deployed similarly across S1, S2 and S3. Fossil fuels, in particular natural gas, are replaced partially by biofuels and mostly by an increasing amount of RFNBOs, in particular hydrogen, whose share in FEC-E increases from 7% to 9% and 12% when moving from S1 to S2 and S3 (Eurelectric shows hydrogen shares of around 10-15% ([86])). LIFE shows a use of RFNBOs in line with S2 and more moderate compared to S3: additional emission reductions in sectors outside energy and industry slightly delays the need for extensive deployment of e-fuels. In 2050, almost all fossil fuels disappear, as result of complete fuel switch in furnaces and introduction of alternative heating processes.

([84]) Eurostat, (2023). Complete Energy Balances European Union (27 countries) – 2021.

([85]) Eurelectric (2023). Decarbonisation speedways: Accelerating Europe’s journey to net zero with realistic 2040 targets. Slide 19. https://www.eurelectric.org/publications/decarbonisation-speedways-full-report

([86]) Ibid

Figure 50: Energy Consumption in industry by fuel



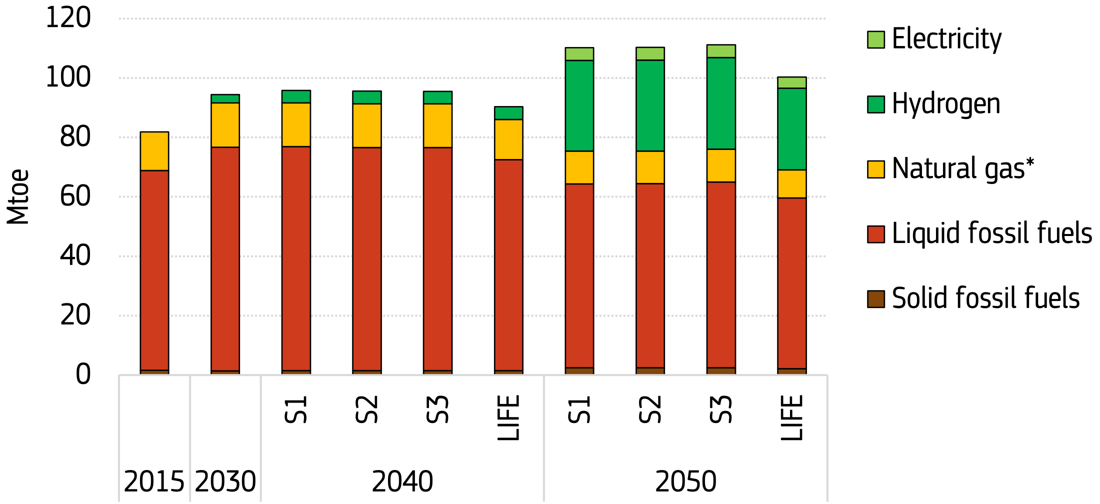
Note: The energy consumption includes the final energy consumption plus the consumption in refineries.
**Natural gas including manufactured gas (coke-oven gas, blast furnace gas & gasworks gas), but not e-gas.*
***Bioenergy including bio-solids, biofuels, biogas (including waste gas and biomethane) and solid waste.*

Source: PRIMES.

1.4.4. Final Non-Energy Consumption

Figure 51 shows the evolution non-energy consumption in industry, representing fuels that are used as raw materials (for instance oil transformed in plastics or bitumen used in road construction). In 2031-2040, total consumption is maintained around 2030 levels, while significant changes occur in 2041-2050: fossil fuels which represents around 90% of the industrial feedstock until 2040 decrease by 15 Mtoe and are partially replaced by hydrogen and electricity. In the same decade, hydrogen increases of around 25 Mtoe. Negligible differences can be found between S1, S2 and S3. A small decrease in non-energy consumption in LIFE is projected in around 5% in 2040 and 10% in 2050, as result of decrease in activity in the petrochemical and other industrial sectors.

Figure 51: Final Non-Energy Consumption in industry by fuel



*Note: *including manufactured gas (coke-oven gas, blast furnace gas & gasworks gas), but not e-gas.*

Source: PRIMES.

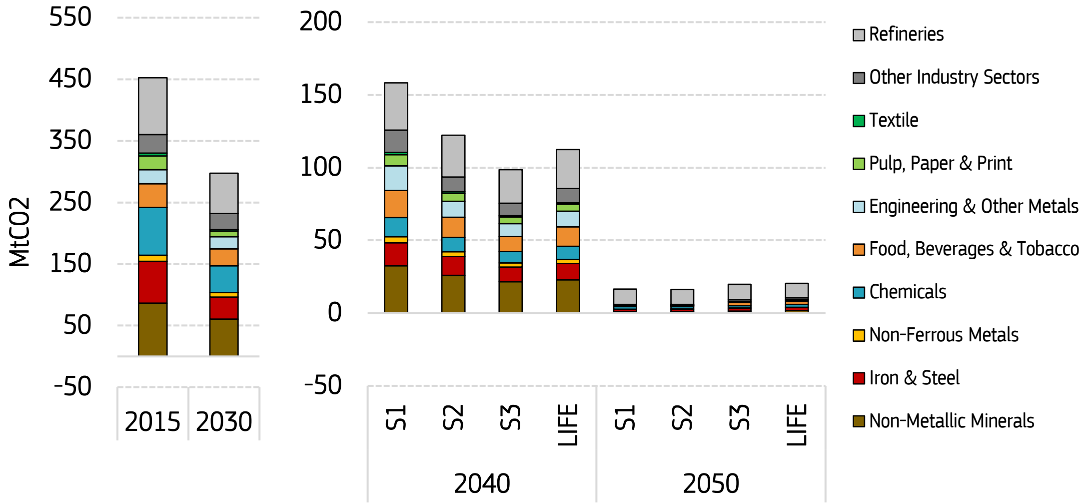
1.4.5. CO2 emissions from industry

1.4.5.1.Energy-related CO2 emissions

Significant reduction of the energy-related CO2 industrial emissions appears in the decade 2031-2040: -47% in S1, -63% in S2 and -80% in S3 (Figure 52). Emissions reduce in all sectors, as result of electrification process and gradual uptake of RFNBOs and carbon capture technologies. The variation across scenarios for all main sectors ranges between 12 and 32 percentage point, with the chemical sector achieving the highest reduction in 2040 (down to 82% below 2030 level). The iron and steel emissions achieve around -55% in S1, -65% in S2 and -70% in S3 when compared to 2030 levels. These values result from an increased electrification occurring in S1, on top of which carbon capture and RFNBOs deploy progressively in S2 and S3. In 2050, an even higher share of electricity and RFNBOs in industrial consumption (see Figure 49), together with larger development of carbon capture, reduce or eliminate further residual emissions in all sectors in a similar way across the three scenarios.

LIFE shows emissions higher than S3 and in line with S2 in 2040, since the additional reductions in non-CO2 and the LULUCF allow for less constraints in the energy and industrial emissions. This translates into a lower use of RFNBOs in 2040 (see also Figure 50) and a lower amount of carbon captured in 2050.

Figure 52 : Energy-related CO_2 emissions in industry by sector

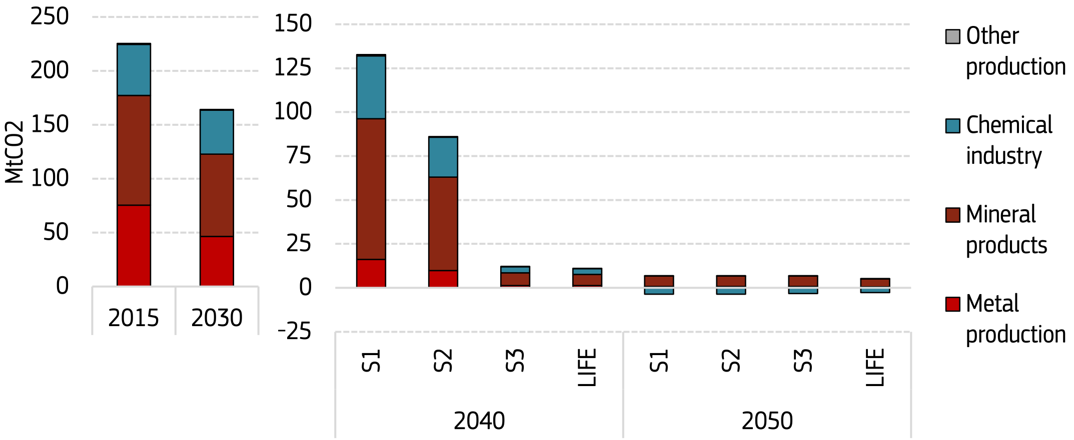


Source: PRIMES.

1.4.5.2.Process-related CO_2 emissions

Figure 53 shows that process-related CO2 emissions, are projected to decreased by around 30% in 2030 compared to 2015. In 2040, emissions amount respectively to around 135, 85 and 10 MtCO2 in S1, S2 and S3, i.e., reducing approximately between 20% and 95% (vs 2030). By 2050, all scenarios show negligible residual emissions.

Figure 53: Process CO2 emissions in industry by sector



Note: Metal production includes both ferrous and non-ferrous materials. For 2050, S1 and S2 values are similar to S3 and not represented.

Source: PRIMES

The role of carbon capture ([87]) is pivotal to explain differences on total net process emissions across scenarios in 2040 and the negligible emissions in 2050 (Figure 54). In S1

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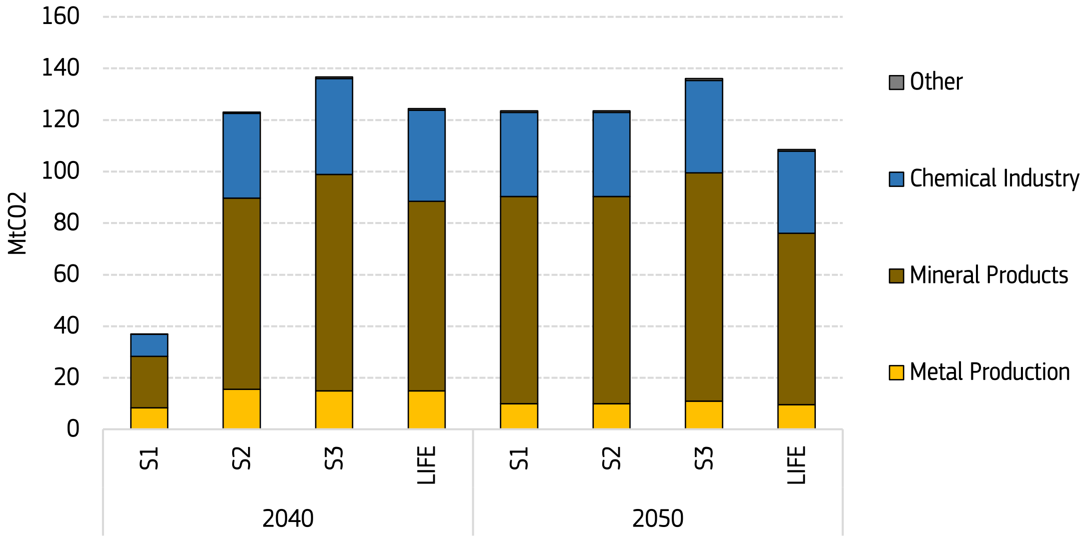
[87] Industrial challenges explained in 1.1.3.2 are associated to the development of carbon capture, but these challenges are assumed to be overcome in the projections.

only around 40 MtCO2 are projected to be captured in 2040, in line with the limited uptake of capture technologies. This value leaps to around 120 MtCO2 in S2, of which around 65% goes to e-fuel production and 35% goes to underground storage (see Figure 11 section 1.1.3.2). The stored CO2 is not considered as emitted, and total net industrial process emissions reduce by a corresponding amount. In S3, the carbon captured increases moderately compared to S2, but it is mostly stored underground or in materials and not dedicated to e-fuels productions, reducing further the net process emissions. By 2050, the amount of total carbon captured increases for S1, and it is similar to 2040 values for S2, but in both scenario it is fully stored either underground or in materials, reducing net emission further than in 2040 and reusing CO2 within the industry. In S3, a similar amount of carbon is captured yearly between 2040 and 2050, resulting in limited reduction in net emissions in the 2041-2050 decade. In LIFE, carbon capture falls short to S3 in 2040 and 2050, as result of more emission reductions elsewhere (see 1.4.2 in this Annex).

Figure 54: Carbon captured in industrial processes.



Note: Metal production includes both ferrous and non-ferrous materials.

Source: PRIMES

The different reduction rates and residual emissions shown by the iron and steel, the chemical and the mineral product sectors are explained by the different availabilities of decarbonisation technologies in each sector (in addition to carbon capture). In the steel sector, options exist today ([88]): a large implementation of hydrogen-based alternative steelmaking process reduces emissions between 65% and 80% (before carbon capture and depending on the scenario) by 2040, when compared to 2015. Carbon capture completes then the decarbonisation process. The chemical sector relies almost exclusively on carbon capture by 2040 while implementation of low-carbon processes by replacement of fossil fuel feedstock and use of fossil-fuel free CO2 as feedstock occurs only in 2041-2050. In the 2041-2050 decade, capture still plays a prominent role in chemistry, leading to even negative emissions in 2050, as result of improved flow of CO2 within the industrial sector and storage in materials of carbon coming from non-fossil fuel feedstock ([89]). Production

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([88]) BNEF, (2021). Decarbonizing steel – Technologies and Costs.

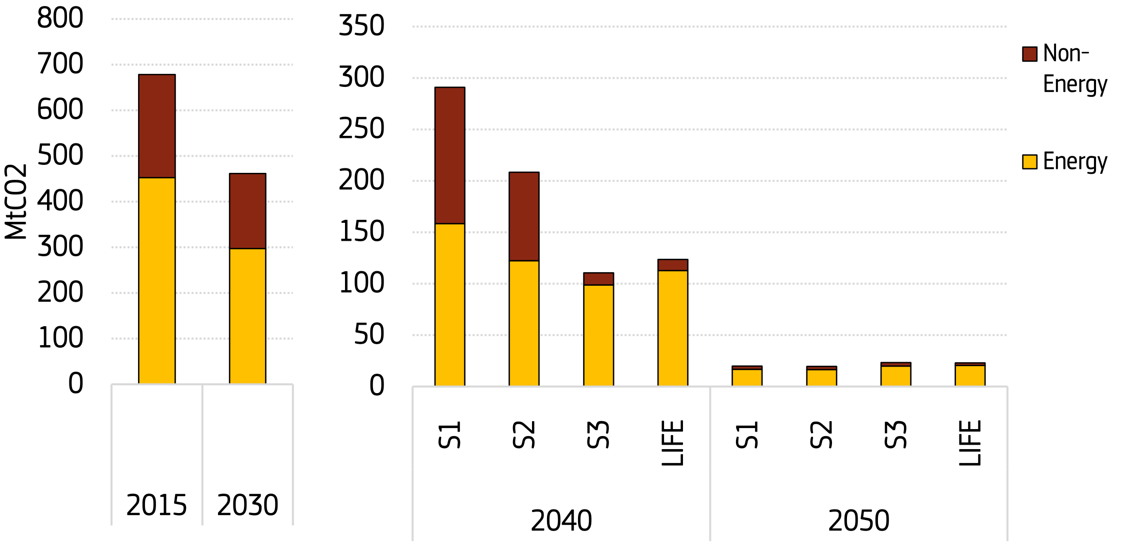
([89]) CEFIC, (2021). Shining a light on the EU27 chemical sector's journey toward climate neutrality.

of minerals, such as cement, are the hardest to decarbonise: literature shows that residual emissions from cement in 2050 can be as high as 25% of 2017 levels ([90]), and massive deployment of carbon capture and storage is projected to be the most common options for decarbonisation of the sector.

1.4.5.3. Total CO2 from industry

Figure 55 summarises the energy and process related CO2 emission from the industrial sector, showing that total net CO2 reduces by 37%, 55% and 76% in S1, S2 and S3, in 2040 compared to 2030 ([91]). This correspond to a decrease between 60% and 90% in comparison with 1990 levels, well aligned with literature: a report from the NAVIGATE project comparing the results of seven IAM states that industrial emissions should reduce by at least 55% in 2040 vs 2020 to be compatible with the 1.5°C case ([92]), report from the CLEVER project show how industry can reduce emissions by 86% in 2050 vs 2019 ([93]) and Ecologic illustrates that the industrial sector should reach emissions between -78% and -91% in 2040 vs 1990 to comply with climate neutrality ([94]). Acceleration of the decarbonisation of the industry is also supported by the public consultation results, where almost 48% of respondents, and a number of position papers indicated "Industrial processes and waste" as one of the sectors that can do more to reduce emissions.

Figure 55: CO2 Emissions from industrial sector



Source: PRIMES

([90]) McKinsey, (2020). Laying the foundation for zero-carbon cement.

([91]) Carbon capture from DACCS not included.

([92]) Kriegler, E. et al., (2023). The EU's 2040 target Insights from the NAVIGATE project, *NAVIGATE*.

([93]) CLEVER, (2023). Climate neutrality, Energy security and Sustainability: A pathway to bridge the gap through Sufficiency, Efficiency and Renewables, *Final Report*. https://clever-energy-scenario.eu/wp-content/uploads/2023/06/clever_final_report-exec_summary.pdf

([94]) Ecologic and Oeko-Institut, (2023). Designing the EU 2040 climate target.

1.4.6. Complementary analysis

1.4.6.1.Introduction

Circular Economy (CE) actions can contribute significantly to decarbonise industrial sectors, especially in fields where other mitigation options are under development or available but still come at a cost premium (e.g., electrification of high temperature heat or hydrogen). One of the key channels through which CE actions can support industrial decarbonisation is by reducing the demand for primary production of industrial outputs through the extension of the lifetime of products and materials as well as the substitution of primary with less carbon-intensive, secondary materials. Literature reports 20% GHG emission saving potential in the EU due to CE actions until 2050 (95), that can go up to 25% in certain Member States (96). More ambitious estimates, which also include sufficiency actions can go beyond that level (97), (98). CE can also bring several additional co-benefits e.g., reducing the environmental pressure associated with natural resource consumption nd increasing strategic autonomy of the EU by derisking supply chain for critical and other raw materials (see section 1.9.4).

The following complementary analysis investigates the impact of a limited group of relevant CE actions on the decarbonisation of iron and steel, aluminum, paper and pulp, cement, ethylene, and glass sectors. It shows results on future material production, GHG emissions and energy demand. A broad circular economy approach and the overall impact of CE actions across the whole economy fall outside the scope of this study (99),(100), and is taken into account in S1, S2, S3 and LIFE analysis.

1.4.6.2.Methodology

The complementary analysis focuses on a subset of materials produced by energy-intensive industries EIIs (Iron and Steel, Cement, Aluminium, Glass, Ethylene and Pulp and Paper). It projects future material production, and by mean of the FORECAST tool, (see Annex 6), it models GHG emissions and energy demand in two different decarbonisation scenarios: CIRC (after circularity) and STD (after standard). While the

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(95) Ellen MacArthur Foundation, Completing the picture: How the circular economy tackles climate change (2019). 20% GHG emission saving potential due to CE actions until 2050.

(96) Agora Industrie, Systemiq (2023): Resilienter Klimaschutz durch eine zirkuläre Wirtschaft: Perspektiven und Potenziale für energieintensive Grundstoffindustrien. Agora estimates circular economy potential to be around 25% until 2050 for Germany.

(97) Ramboll. Fraunhofer ISI, Ecologic Institute (2020). *Quantification methodology for, and analysis of, the decarbonisation benefits of sectoral circular economy actions*. Final Report.

(98) IRP (2020). Resource Efficiency and Climate Change: *Material Efficiency Strategies for a Low-Carbon Future*. Hertwich, E., Lifset, R., Pauliuk, S., Heeren, N. A report of the International Resource Panel. United Nations Environment Programme, Nairobi, Kenya.

99) Ellen MacArthur Foundation, Completing the picture: How the circular economy tackles climate change (2019). 20% GHG emission saving potential due to CE actions until 2050.

(100) Agora Industrie, Systemiq (2023): Resilienter Klimaschutz durch eine zirkuläre Wirtschaft: Perspektiven und Potenziale für energieintensive Grundstoffindustrien. Agora estimates circular economy potential to be around 25% until 2050 for Germany.

STD assumes the partial implementation Circular Economy Action Plan (CEAP) ([101]), the CIRC includes additional selected CE actions that are listed in Table 9. The main common assumptions of the CIRC and STD are in line with the main scenarios S1, S2, S3 with some signficiant differences. For instance, in STD and CIRC, deployment of carbon capture is limited to industrial processes in sectors where residual emissions are projected in 2050 (the cement industry ([102]) ([103])), and removal compensation outside EII sectors (DACCS), are not considered. Moreover, the CIRC scenario only reflects selected CE action, without considering a large circular economy framework including sufficiency or shared economy measures. Finally, the analysis focuses on the decarbonisation of industrial sectors and is limited to the savings that could be achieved only during production stage. It does not take into account decarbonisation in the other sectors leading to EU economy-wide climate neutrality, thus, allowing only for comparison in relative terms with scenarios S1, S2 and S3. These limitations need to be taken into account when interpreting the magnitude of the modelled impacts. More details on the methodology can be found elsewhere ([104]).

([101]) The STD scenarios implements actions from the CEAP (COM/2020/98) that have been legislated or agreed until March 2023.

([102]) McKinsey, (2020). Laying the foundation for zero-carbon cement.

([103]) Cembureau, (2023). Cementing the European Green Deal. Reaching climate neutrality along the cement.

([104]) Herbst, A. et al. (2023): Role of the circular economy as a contributor to industry decarbonisation beyond 2030. Report prepared for DG CLIMA: Job number 330301101. Fraunhofer ISI & ICF.

Table 9: List of circular economy actions applied to the CIRC scenario

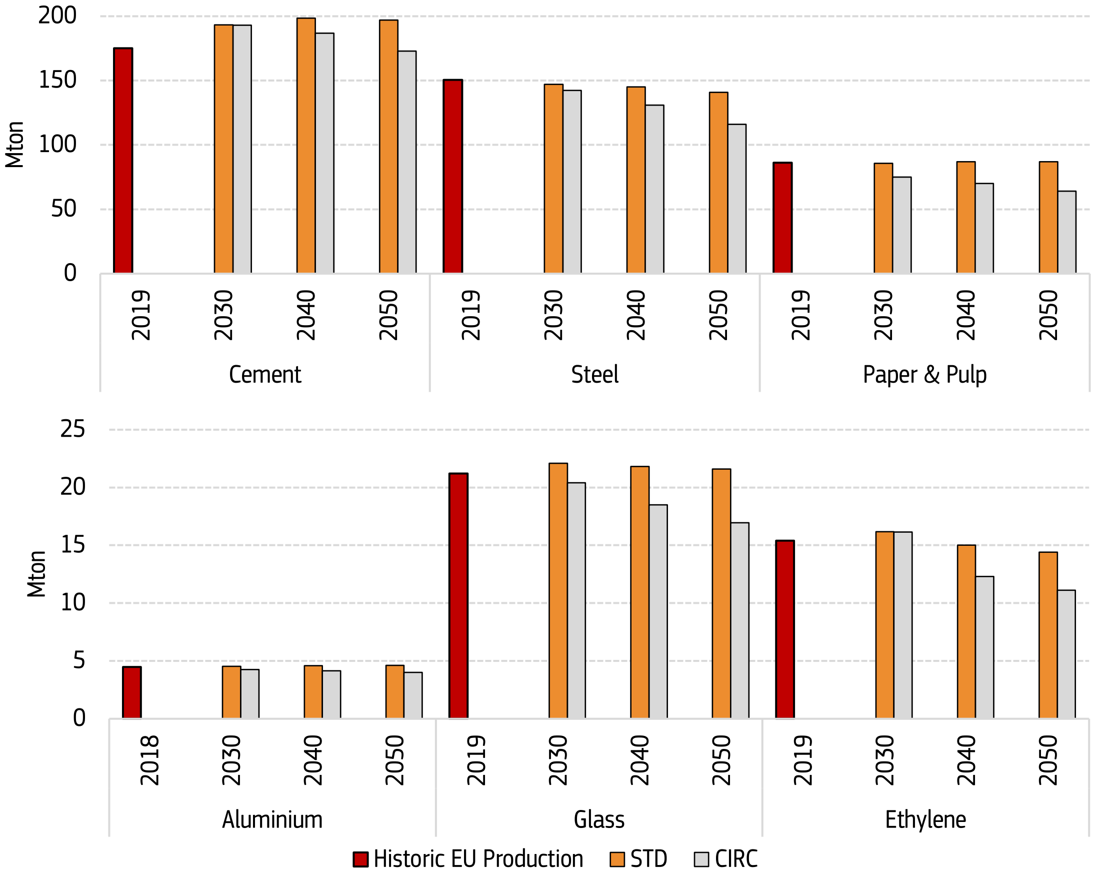
MATERIAL	CE ACTION
Aluminium	Increased aluminium recycling from buildings (increase collection rate from 96 to 100% by 2045)
	Increased recycling of aluminium cans (reduce losses and disposal to 0 by 2030)
	Reduction of scrap exports (to 0 by 2050)
	Reduction of exports of EoL cars (to 0 by 2050)
	Alloy sorting of post-consumer scraps (reduce input of primary aluminium for dilution of scrap from 20 to 5%)
	Lifetime extension of cars (increasing from 15 to 20 years on average)
	Lifetime extension of buildings (decreasing building demolition by up to 30%)
	Lifetime extension of machinery (from 25 to 30 years on average)
Cement	Using up to 20% recycled cement in buildings
	Use innovative binders as substitute for ordinary cement (market share of up to 10%)
	Lifetime extension of buildings (decreasing building demolition by up to 30%)
	Design for building disassembly, and make standardised building elements (reusing up to 38% of prefab building elements)
	Reducing use of structural concrete at design stage by up to 41%
	Using cement with lower clinker shares (reducing average from 0.73 to 0.7)
Ethylene	Redesign multi-material packaging of different layers to ensure recyclability from the year 2030
	Increasing the recycled content in plastic bottles
	Reduction in single-use plastics packaging from supermarkets by 50%
	Ban single use water bottles
Glass	Recycling of municipal waste to increase to 55%, 60% and 65% by weight by 2025, 2030 and 2035 respectively
	Increase share of reusable glass bottles and containers
Iron and Steel	Reduction of scrap exports from 28Mt in 2020 to 0 in 2050
	Reduction of exports of EoL cars from 72600 cars in 2020 to 0 in 2050
	Alloy sorting of post-consumer scraps to increase the quality of recycled steel which enables the European usage of formerly exported and downcycled steel scrap
	Lifetime extension of cars (increasing from 15 to 20 years on average)
	Lifetime extension of buildings (decreasing building demolition by up to 30%)
	Lifetime extension of machinery (increasing from 22 to 27 years on average)
	Reusing up to 6% structural steel from buildings
	Design for building disassembly, and make standardised building elements (reusing up to 38% of prefab building elements)
	Lightweighting of steel-intensive products (depending on product, reduction of 5-10% product weight by 2050)
	Reducing use of structural steel at design stage (reducing overspecification up to 41%)
Paper and Pulp	Recycling of municipal waste to increase to 55%, 60% and 65% by weight by 2025, 2030 and 2035 respectively
	Increase paper recycling
	Increase the market share of reusable packaging to 40% by 2050
	Lightweighting of paper packaging (Decreasing paper packaging weight by 20% in 2050 compared to 2020)

Note: This list only applies to the CIRC scenario. The actions listed in the Circular Economy Action Plan are assumed to be already implemented up to the cutoff date of March 2023 both in the STD and the CIRC scenarios.

1.4.6.3.Activity

Figure 56 summarises the projections of the total demand for the different materials in the STD and the CIRC scenario and includes historical data of the material production in EU as reference.

Figure 56: Historical EU production and future demand for specific materials



Note: 2019 is taken as the calibration year for the FORECAST model. In case 2019 historic values are not available, first previously available year is represented (e.g., 2018 for Aluminum).

Source: FORECAST production database, FORECAST model.

For all materials, the material demand reduces, leaving a gap between the two scenarios that increases over time in the period 2030-2050. Around 5% and 10% of total cement are saved in CIRC in 2040 and 2050 compared to STD, which in 2050 splits into around 10% of reduction of conventional cement and 10% replacement of conventional cement by low-carbon cement. Building lifetime extension and demand reduction through reuse, preparing for re-use, and modification of overspecification has the highest optimisation potential among the actions analysed, followed by the substitution of conventional cement by wood and low carbon cement produced using alternative cement constituents ([105]), ([106]). The use

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([105]) Le Den, et al., (2020). Quantification methodology for, and analysis of, the decarbonisation benefits of sectoral circular economy actions. Final report.

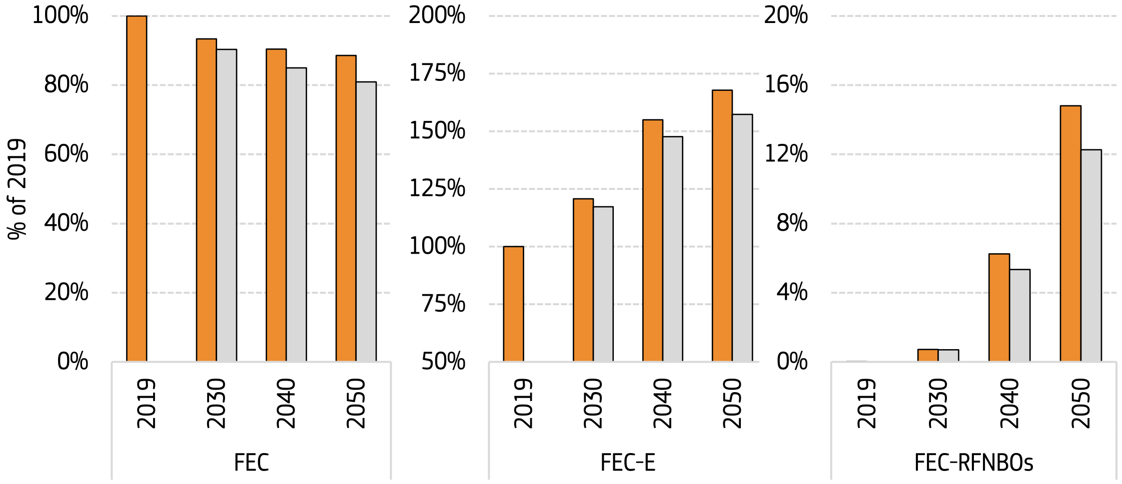
([106]) Rehfeldt, M. et al., (2020). Modelling circular economy action impacts in the building sector on the EU cement industry. *ECEEE Industrial Summer Study Proceedings*, 133–143.

of wood has been restricted only to certain construction elements and in single family houses (107), largely in line with sustainable use of biomass and limiting its possible negative impact on the LULUCF net removals. Total steel and aluminium demand reduce around 15%-20% in 2050 compared to STD: this reduction affects mostly primary production, which reduced for the two materials by around half, while secondary production remains stable or increases due to higher availability of scrap and higher recyclability. Ethylene demand, which already decreases in STD due to the high recycling rates, shows a possible additional reduction of around 20% in CIRC. The demand in the paper and pulp sector by around 20-25% until 2050 in CIRC, driven mostly by an increase market share of reusable packaging and light weighting of paper packaging.

1.4.6.4.Final Energy Consumption

The resulting FEC, FEC-E and FEC-RFNBOs (hydrogen + e-fuels) in STD and CIRC scenarios are shown in Figure 57.

Figure 57: FEC, FEC-E and FEC-RFNBOs as % of 2019



Note: 2019 is taken as the calibration year for the FORECAST model.

Source: FORECAST.

A significant decrease in FEC in STD occurs until 2040 (around -10% vs 2019) and stabilises until 2050. This decline is given mainly by efficiency gains from the electrification of processes or the shift to hydrogen-based production, which in part compensate for the assumed growth in industrial value added. Additional savings of 3%, 5% and 8% in 2030, 2040 and 2050 are achieved in CIRC compared to STD, leading to an overall decrease of around 20% in 2050 compared to 2019. This trend is attributed to additional energy and material efficiency measures, as well as the increase in recycling-based processes, and confirm that impact of CE actions becomes more visible on the long term. Electricity and RFNBOs consumptions in the sector under analysis increase considerably both in STD and CIRC. In STD, FEC-E grows by around 21%, 55% and 68% in 2030, 2040 and 2050 compared to 2019, and FEC-RFNBOs rises from 0 to 1%, 6% and 15% in the same years. CIRC allows for lower consumption, leading to

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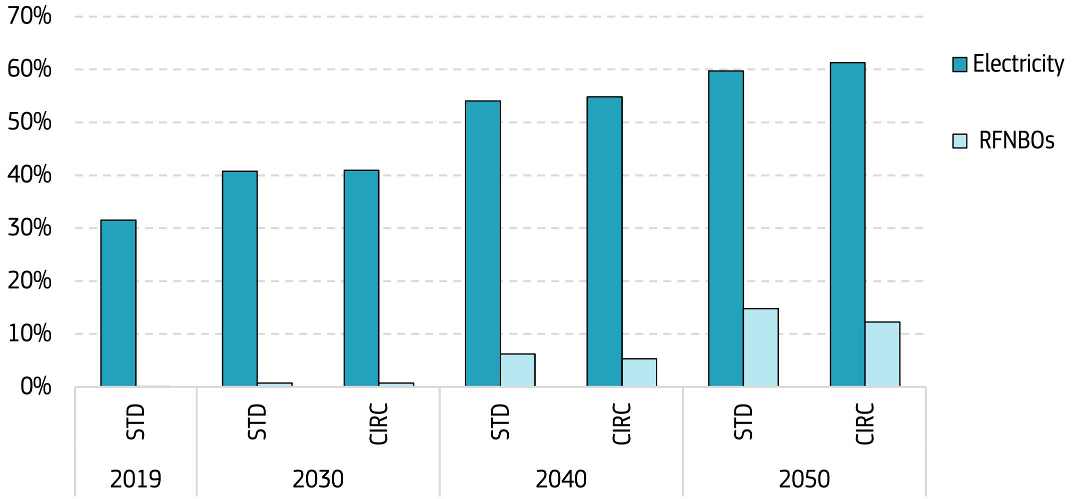
(107) Nemry, F.; Uihlein, A. (2008): Environmental Improvement Potentials of Residential Buildings (IMPRO-Building).

electricity savings of around 3-4% in 2030-2040 and up to 6% in 2050, and RFNBOs savings of around 1% in 2040 and 3% in 2050 (with respect to STD).

The share of FEC across energy carriers also changes (Figure 58). As result of decrease of FEC and increase of FEC-E, electricity becomes the dominant energy carrier, growing from around 30% of FEC share in 2019, to above 50% already in 2040 and up to around 65% in 2050. To replace fossil fuels in processes where electrification is currently not viable, the amount of RFNBOs increases in absolute terms and as share of FEC, growing from around 1% in 2030, to above 5% in 2040 and above 10% in 2050. When comparing the two scenarios in relative terms ([108]), the shares for the two energy carriers behave differently: in CIRC, CE actions boost electricity share by around 1% in 2040 and 2050 when compared to the shares of the same years in STD, while share of RFNBOs reduces by 1% and 3% respectively in 2040 and 2050. This indicates that CE actions, in addition to reducing overall FEC, especially contributes to reduce the final energy demand (and relative FEC shares) for carriers that are more expensive or more complex to implement, like hydrogen and e-fuels. A similar effect of reduction of hydrogen and e-fuels due to circular economy actions could be witnessed also in the final non-energy consumption (see 1.4.4 in this Annex).

Figure 58: Share of electricity and RFNBOs in FEC



Note: STD and CIRC shows different FEC, meaning that the comparison between FEC shares in STD and CIRC can only apply in relative terms. A phase out of fossil fuel to less than 3% share of FEC in 2050 is projected, and the rest of FEC is covered by other RES sources. 2019 is taken as the calibration year for the FORECAST model.

Source: FORECAST.

1.4.6.5.GHG Emissions

Figure 59 shows the evolution of GHG emissions in the industrial sector. In STD, net GHG emissions reduce by 29%, 69% and 90% in 2030, 2040 and 2050 compared to

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([108]) Comparison in absolute terms is not possible since the total FEC in CIRC and BENCH is different.

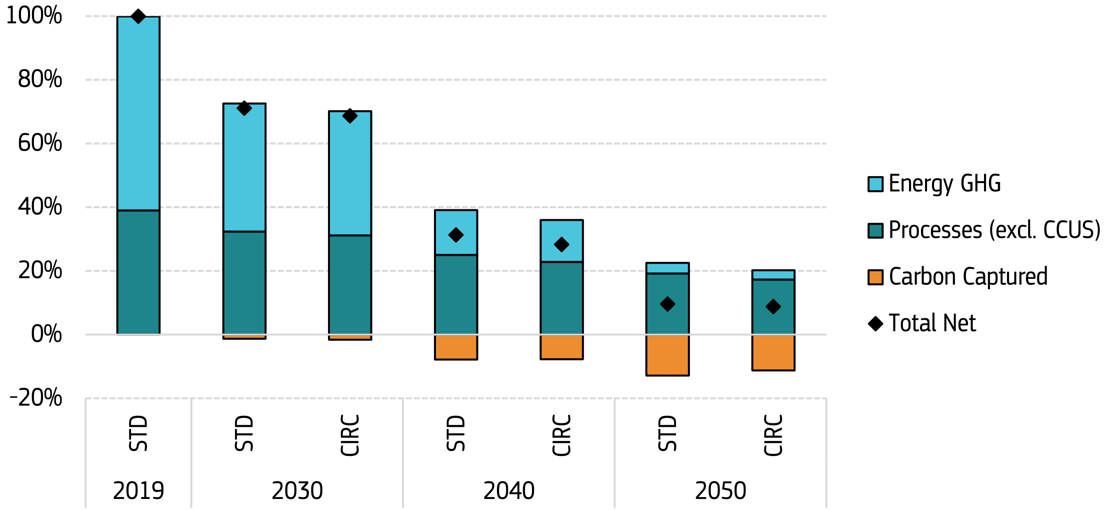
2019. GHG emissions in the CIRC scenario reduce by 31%, 72% and 91% for the same years.

Energy-related emissions decrease in STD in line with the strong electrification of the power system and the reduction of energy needs. In an already well decarbonised sector, the CIRC assumptions can further decrease energy-related emissions by around 7% and 12% compared to STD in 2040 and 2050. The use of alternative processes also reduces significantly process emissions in comparison with today level: process changes in the steel and chemical industries, reduced use of hydrofluorocarbons (HFCs) and additives or low-CO2 binders in cement and lime production can cut by around 50% process-related emissions (excl. carbon capture) in 2050 compared 2019 in the industrial sector considered. Implementation of the selected list of CE action leads to additional savings in 2040-2050 compared to STD of around 10%. Carbon capture also plays a role in the decarbonisation of process emissions, and CE actions help slightly reduce the carbon capture needs.

The differences in GHG emissions between STD and CIRC only capture a fraction of the positive impact of CE on the decarbonisation of the economy for two main reasons. First, part of the CE impact is already covered in the STD, which assumes implementation of the CEAP; second, the additional CE actions apply into an already well decarbonised energy system, limiting their potential to cut emissions. The contribution to emission reduction of the CE actions can be disaggregated from the one of the decarbonisation of the energy system by assuming a constant carbon intensity in the period from the year of reference (2019) until 2050. In constant carbon intensity settings, the analysis shows that selected list of CE actions could reduce industrial emissions in the sectors under scrutiny by around 20% in the CIRC scenario with respect to STD (in 2050).

Net residual emissions of around 10% of 2019 values are projected in 2050 (see Figure 59). This is explained mainly by the assumptions taken on the role of carbon capture in these scenarios, which has been applied only to the emissions of processes where other mitigation strategies (e.g., fuel and process switch) are lacking today, i.e., in the cement sector. Residual emission confirms that a larger deployment of carbon capture in additional (e.g., steel, chemical) and emerging (e.g., DACC) sectors, or compensation of emission by other sectors (e.g. LULUCF) are be needed to reach climate neutrality in industry.

Figure 59: GHG emissions by type in % of 2019 values



Note: 2019 is taken as the calibration year for the FORECAST model.

Source: FORECAST.

1.5. Transport

1.5.1. Introduction

All the decarbonisation pathways for the transport sector (109) analysed in this impact assessment show a sustained growth in transport activity at EU level, as well as a modal shift to rail, from now to 2040 and 2050 (see Section 1.5.2). Nevertheless, as explained in Section 1.5.3, the total amount of energy consumed by the EU's transport sector is projected to decline significantly because of large-scale electrification (notably in road transport) and implementation of technological and operational measures to improve energy efficiency (notably in maritime and air transport). Furthermore, the fuel mix of the transport sector is projected to undergo a deep transformation characterised by a significant reduction in the consumption of fossil fuels, which are largely replaced by zero- and low-emission energy carriers (i.e., electricity, advanced liquid biofuels and biogas, e-fuels and hydrogen) by 2040 and almost fully replaced by them by 2050. In terms of decarbonisation options deployed, road and rail transport are largely electrified over time, whereas the maritime and air transport sectors, which are hard to electrify, deploy measures to improve energy efficiency combined with a significant uptake of zero- and low-emission fuels, particularly liquid biofuels, biogas and e-fuels (see Section 1.5.4). Consequently, direct CO2 emissions from the EU's transport sector are projected to decrease dramatically in the next decades, especially after 2030 (see Section 1.5.5). Road and maritime transport are the modes reducing their CO2 emissions the most by 2040, and most of the transport-related emissions remaining in 2050 are projected to come from the international aviation sector.

The decarbonisation pathways for the transport sector are in line with the results of the public consultation. The participants to the "expert section" of the public consultation think that the transport sector will be one of the key sectors affected by the green transition after 2030, particularly because of the transition to electric vehicles and

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(109) The model-based analysis is a technical exercise based on a number of assumptions that are shared across scenarios. Its results do not prejudge the future design of the post-2030 policy framework.

alternative fuels (this is mentioned by 20% of the respondents). The results of the public consultation also show that, amongst all economic sectors, the respondents give the highest priority to reduce emissions caused by the transport sector, particularly “aviation and maritime transport” (with an average priority of 4.42 between 1 and 5, 5 being the highest priority level) and “road transport” (with an average priority of 4.39 between 1 and 5). However, overall, the respondents think that “aviation and maritime transport” will be the last economic sectors to become climate neutral, compared to “production of electricity and district heating”, “industrial processes and waste”, “buildings”, “agriculture, forestry and other land use” and “road transport”.

1.5.2. Activity

A sustained growth in transport activity at EU level is observed in all scenarios, following the post-COVID recovery. Total **passenger transport** activity (expressed in passenger-km, excluding international navigation and extra-EU aviation), increases to a similar extent in the main scenarios (S1, S2 and S3). As shown in Figure 60 and Figure 61, in these scenarios, total activity increases by 26-27% (depending on the scenario) in 2040 and 32% in 2050 compared to 2015. However, there are differences between transport modes with respect to activity growth. The modes showing the greatest increase in activity relative to 2015 are rail (65-67% in 2040 and 83-86% in 2050), driven mainly by the revision of the TEN-T Regulation, CEF funding, the proposal for the increase in railway capacity use and the action plan to boost long-distance and cross-border passenger rail, and intra-EU aviation (56-57% increase in 2040 and 74% increase in 2050), driven by the sustained economic growth and the post-COVID recovery. Road transport activity grows by 20-21% between 2015 and 2040 (see Figure 61) and then mostly stabilises (between 2015 and 2050, activity grows by 23%, see Figure 60). Domestic navigation activity is projected to increase by 12-17% in 2040 and by 20-23% in 2050, relative to 2015 (110). There are slight differences between the three main scenarios. The S3 scenario shows the highest increase in rail transport activity and the lowest increase in road and air transport activity over time, whereas the S1 scenario shows the lowest increase in rail transport activity and the highest increase in road and air transport activity.

In LIFE, total passenger transport activity (excluding international navigation and extra-EU aviation) still increases over time, but less than in the three main scenarios (111). As shown in Figure 60 and Figure 61, total passenger activity increases by 22% in 2040 and 27% in 2050 compared to 2015 (i.e., 4-5 and 5-6 percentage points less than in the other scenarios, respectively). If one looks at the activity per mode, intra-EU aviation shows much lower activity growth rates relative to 2015 than the other scenarios (42% in 2040, i.e., 15-16 pp less than in S2 and S3, and 47% in 2050, i.e., 27 pp less), driven by the assumed substitution of some business trips with video conferences, reduction in the

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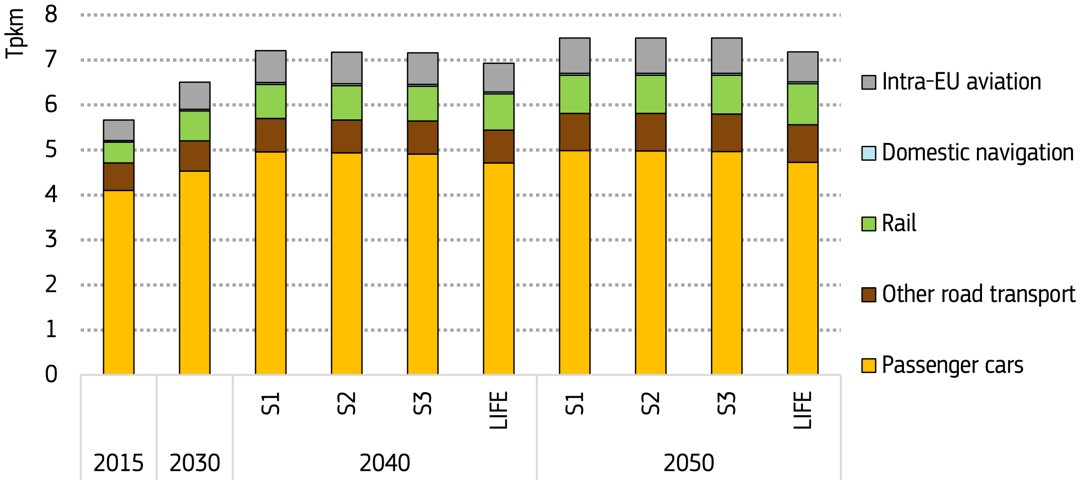
(110) In this impact assessment, the term *domestic navigation* includes inland waterway transport and national maritime transport. These two waterborne transport modes are grouped together because a split between inland waterway and national maritime transport is currently not available in the official energy statistics, so the PRIMES model takes them together.

(111) Other analyses look at much stronger changes in mobility patterns. For instance, the CLEVER scenario published in “*Energy security and Sustainability: A pathway to bridge the gap through Sufficiency, Efficiency and Renewables”* projects a 21% reduction in passenger traffic between 2019 and 2050. However, the costs associated to these changes are not assessed.

distance travelled for trips for personal purposes, and modal shift towards high-speed rail where available. Passenger road transport also shows lower activity growth rates relative to 2015 than in the other scenarios (15% in 2040 and 18% in 2050, i.e., 4-5 pp less than in S2 and S3 in both years). Note that it is assumed that part of this difference in road transport activity growth is replaced by an increased use of active modes, which is not represented in the PRIMES model. Instead, passenger rail activity increases much more than in the other scenarios (74% in 2040, i.e., 7-9 pp more than in S2 and S3, and 97% in 2050, i.e., 10-13 pp more). Domestic navigation activity is projected to increase by 12% in 2040 and by 22% in 2050, relative to 2015, that is to say, similarly to the main scenarios. Consequently, in LIFE, air transport represents a lower share of the total passenger transport activity (9% in 2040 and 2050) than in the other scenarios (10% in 2040 and 2050), whereas rail transport represents a higher share of the total passenger transport activity (12% in 2040 and 13% 2050) than in the other scenarios (11% in 2040 and 2050). This indicates a modal shift to rail.

International extra-EU aviation activity (expressed in passenger-km) increases by 62% in 2040 and 80-81% in 2050 compared to 2015 in the three main scenarios (S1, S2 and S3), whereas in LIFE it increases to a lesser extent (46% in 2040 and 57% in 2050 relative to 2015, i.e., 16 and 23-24 percentage points less than in S2 and S3 in 2040 and 2050, respectively) (112).

Figure 60: Passenger transport activity in the EU disaggregated by mode



Note: The y-axis label ("Tpkm") stands for trillion passenger-kilometres.

Source: PRIMES.

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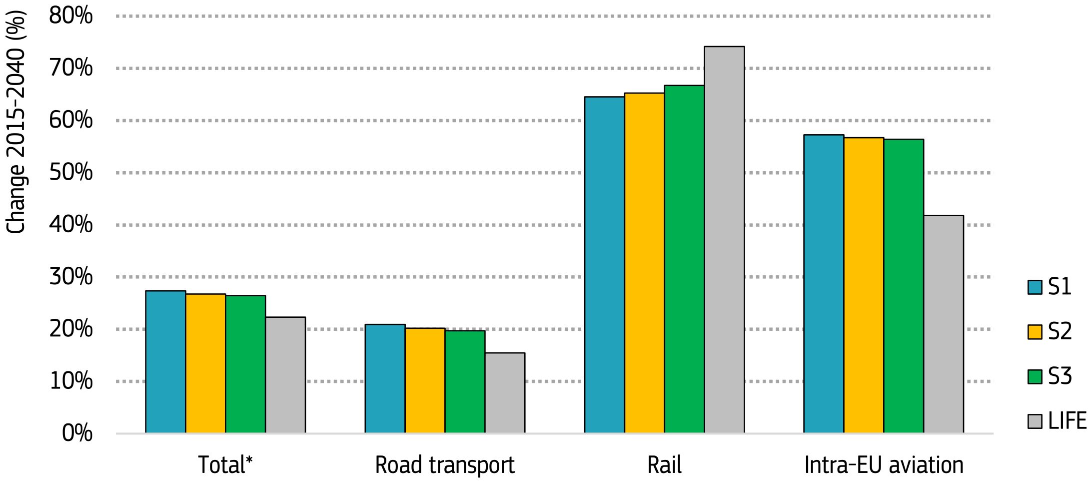
(112) In its "Aviation Outlook 2050 – Main Report, 2022" report EUROCONTROL looks at scenarios on the evolution of the number of flights in Europe between 2019 (the year with the highest number of flights) and 2050, reaching +44% in the "base" (or most-likely) scenario, ranging from +54% in the "high" scenario to +20% in the "low" scenario.

Figure 61: Change in passenger transport activity between 2015 and 2040 by mode



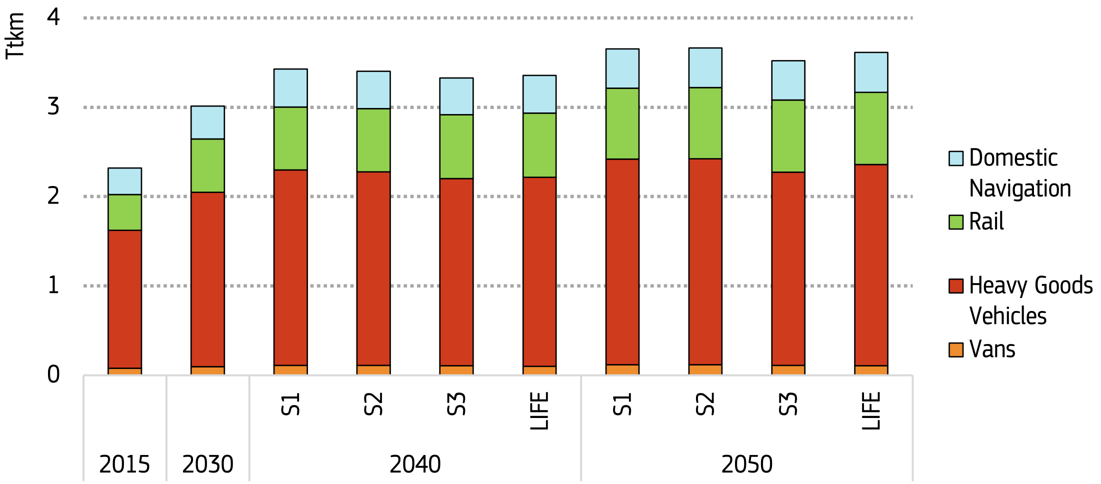
*Note: *The total passenger transport activity excludes international navigation and extra-EU aviation.*

Source: PRIMES.

Total **freight transport** activity (expressed in tonnes-km, including international shipping), also increases to a similar extent in the S1, S2 and S3 scenarios. As shown in Figure 63, in these scenarios, total activity increases by 35-36% in 2040 and 51% in 2050 compared to 2015. Note, however, that there are significant differences in activity growth between transport modes. The activity of international navigation increases by 34% in 2040 and by 50-51% in 2050 compared to 2015, and the activity growth is slightly higher in the S3 scenario than in the S1 and S2 scenarios. Rail shows the greatest increase in freight transport activity relative to 2015 amongst all modes (77-79% in 2040 and 99-102% in 2050), driven mainly by the revision of the TEN-T Regulation, CEF funding, the proposal for the increase in railway capacity use, and the proposed revision of the Combined Transport Directive. The S3 scenario shows the highest increase in rail transport activity over the 2015-2040 and 2015-2050 periods, and the S1 scenario shows the lowest increase over the same periods (see Figure 62 and Figure 63). Regarding road transport, the S3 scenario shows a lower increase in activity over the 2015-2040 and 2015-2050 periods (36% and 40%, respectively) than the S1 and S2 scenarios. Instead, the S1 scenario shows the highest growth in activity between 2015 and 2040 (41%). Road transport activity increases to a similar degree over the 2015-2050 period in the S1 and S2 scenarios (49%), which is greater than that of the S3 scenario. All three scenarios reflect the proposed revision of the Weights and Dimensions Directive. Domestic navigation activity is projected to grow by 40-44% over the 2015-2040 period and by 48-51% over the 2015-2050 period.

In LIFE, the increase in total freight transport activity (expressed in tonnes-km) is similar to the other scenarios. However, there are small differences between modes. As shown in Figure 63, road transport shows an increase in activity compared to 2015 that is lower than in S2 but higher than in S3 (36% in 2040 and 45% in 2050, i.e., 4 percentage points less than S2 in both years, 1 pp more than in S3 in 2040 and 5 pp more than in S3 in 2050). Instead, rail transport shows slightly higher activity growth rates relative to 2015 than the S2 scenario (80% in 2040 and 102% in 2050, i.e., up to 2 pp more than S2 and S3 in both years). Furthermore, the increase in domestic navigation activity between 2015 and 2040 is also slightly higher in LIFE than in S2 and S3. This indicates a modal shift to rail and domestic navigation.

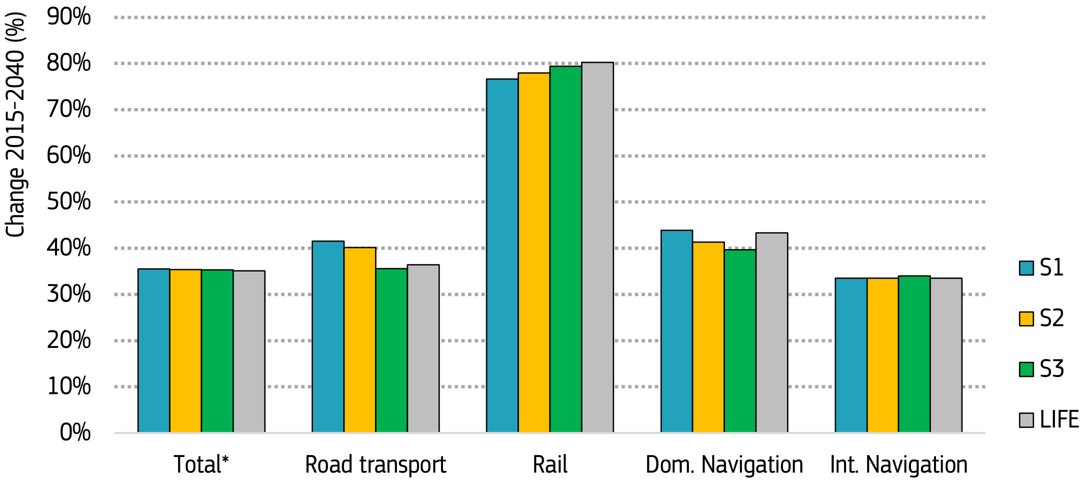
Figure 62: EU freight transport activity by mode (excluding international navigation)



Note: The y-axis label ("Ttkm") stands for trillion tonne-kilometres.

Source: PRIMES.

Figure 63: Change in EU freight transport activity between 2015 and 2040 by mode



*Note: *The total freight transport activity includes international navigation.*

Source: PRIMES.

1.5.3. Energy consumption and fuel mix

The total amount of energy consumed by the transport sector in the EU significantly decreases between 2015 and 2050 in all scenarios (even though transport activity increases over that period, as discussed in Section 1.5.2), thanks to major energy consumption reductions in road transport. The main reasons are electrification (113) (notably in road transport) and energy efficiency improvements. As shown in Figure 64 and Figure 65, in the S1, S2 and S3 scenarios, total energy consumption (expressed in Mtoe, including international aviation and navigation) decreases by 33-35% in 2040 and

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(113) In general, electric engines are 3-4 times more energy-efficient than internal combustion engines.

by 42-44% in 2050 compared to 2015. The greatest reduction is observed in the S3 scenario, whereas the lowest reduction is observed in the S1 scenario.

There are significant differences between transport modes. As shown in Figure 64 and Figure 65, a large reduction in energy consumption is observed in **road transport** (by 52-53% in 2040 and 65-67% in 2050 relative to 2015, depending on the scenario). The main reason is the large-scale electrification of the fleet. As a result, the percentage of the total energy consumption in the transport sector attributable to road transport drops from 74% in 2015 to 53-54% in 2040 and around 44% in 2050. The decrease in energy consumption is especially significant for passenger cars: roughly 105 Mtoe in 2040 compared to 2015 (i.e., 60% reduction) and 135 Mtoe in 2050 relative to 2015 (i.e., around 75% reduction). For trucks, the reduction is significant but more moderate, because of lower levels of electrification (see Figure 64).

All **modes other than road transport** increase their energy consumption. These are modes for which the shift to electrification is less prominent than for road transport (114), so their energy consumption increases mainly because of the increased transport activity. However, in relative terms, the increase in energy consumption is significantly lower than the increase in transport activity (see Section 1.5.2), which indicates important energy efficiency gains over time in these transport modes.

In LIFE, the total amount of energy consumed by the transport sector decreases over time a bit more than in the other scenarios, mainly because of a different transport activity pattern (including a higher shift to rail transport, which is a very energy-efficient mode, and to active modes). As shown in Figure 64 and Figure 65, total energy consumption drops by 37% in 2040 and 46% in 2050 compared to 2015 (i.e., 1-3 percentage points more than in S2 and S3 in 2040, and 3-4 pp more in 2050). Road transport shows a slightly greater decrease in energy consumption relative to 2015 than the other scenarios (55% in 2040 and 69% in 2050, i.e., 2 pp more than in S2 and S3 in 2040 and 2-3 pp more than in S2 and S3 in 2050), while aviation shows a much lower increase (6% in 2040, i.e., 11 pp less than in S2 and S3, and 0.5% in 2050, i.e., 16-17 pp less). Instead, energy consumption in rail transport increases more in LIFE than in the other scenarios (by 48% in 2040, i.e., 4-5 pp more than in S2 and S3, and by 54% in 2050, i.e., 4-6 pp more), driven by the higher increase in activity.

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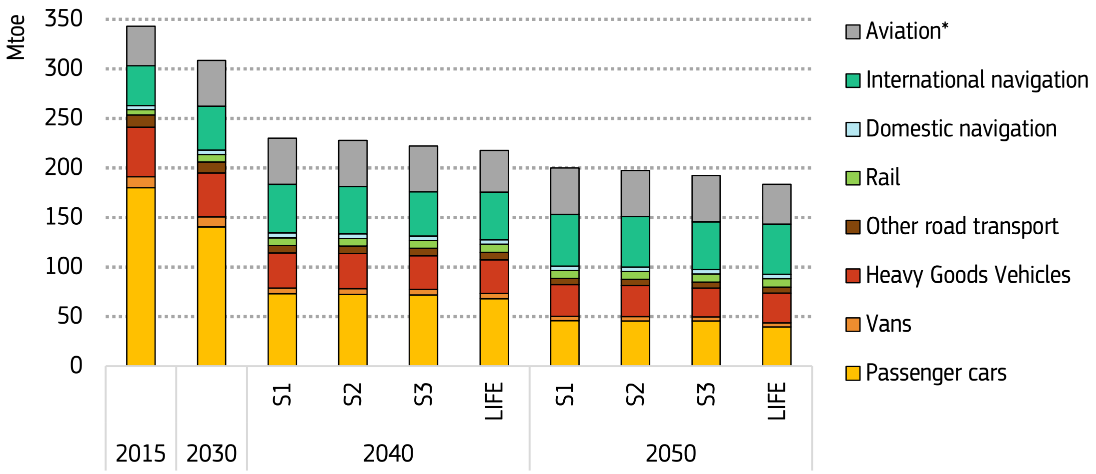
(114) In the case of rail transport, the shift to electrification is less prominent than for road transport only because currently the sector is already largely electrified.

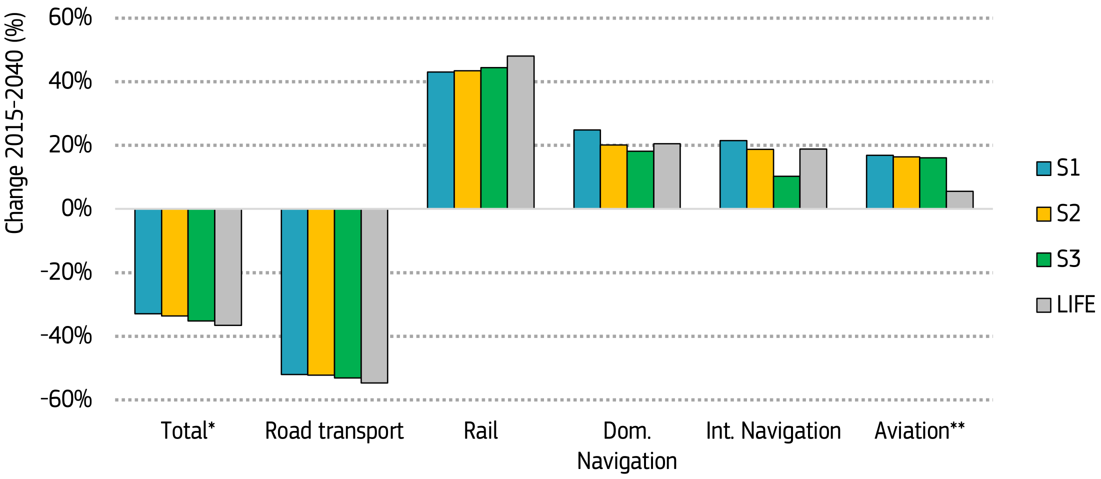
Figure 64: EU energy consumption in the transport sector by mode



*Note: *Aviation includes domestic aviation as well as international intra-EU and extra-EU aviation.*

Source: PRIMES.

Figure 65: Change in EU energy consumption between 2015 and 2040 by mode



*Note: *The total energy consumption includes international transport. **Aviation includes domestic aviation as well as international intra-EU and extra-EU aviation.*

Source: PRIMES.

The analysis of the fuel mix in the transport sector shows a significant reduction in the consumption of fossil fuels (i.e., oil products and natural gas) between 2015 and 2050, which are partially replaced by electricity, advanced liquid biofuels and biogas, e-fuels and hydrogen. As shown in Figure 66, in the S1, S2 and S3 scenarios, fossil fuel consumption in the EU drops from almost 326 Mtoe in 2015 to 12-16 Mtoe in 2050 (i.e., 95-96% reduction). Most of the fossil fuel consumption remaining in 2050 occurs in the aviation sector. In 2040, fossil fuel consumption is 68% to 77% lower than in 2015, depending on the scenario (68% in S1, 74% in S2 and 77% in S3). Fossil fuel consumption constituted 95% of the total energy consumption in 2015, but this share drops to 33-45% in 2040 and 6-8% in 2050, depending on the scenario.

Instead, electricity consumption in the EU's transport sector increases from less than 5 Mtoe in 2015 to 42-43 Mtoe in 2040 and 53-54 Mtoe in 2050 in the S1, S2 and S3 scenarios (see Figure 66). This represents 15-16% of the EU's total final electricity consumption across all sectors in 2040 and around 17% in 2050 (with small differences between the scenarios). The main driver is the electrification of road transport; however, it should be noted that electricity consumption in rail transport also increases significantly (it almost doubles between 2015 and 2050). As a result, the share of electricity in the total energy consumption of the transport sector increases from around 1% in 2015 to 19% in 2040 and 27-28% in 2050, depending on the scenario (the highest shares are observed in S3, and the lowest shares are observed in S1).

Hydrogen consumption in the EU's transport sector increases from almost zero in 2015 to 14-16 Mtoe in 2040 and 35-40 Mtoe in 2050 in the S1, S2 and S3 scenarios (see Figure 66). Based on the assumptions on hydrogen production pathways and efficiency, producing this amount of hydrogen will require around 17-19 Mtoe of (renewable) electricity in 2040 and 42-48 Mtoe in 2050. In 2040, almost all hydrogen used in the transport sector (more than 90%) is consumed by road transport alone. In 2050, this percentage drops to 75-80% (depending on the scenario), because the navigation and aviation sectors also consume significant amounts of hydrogen. The use of hydrogen in rail transport is more limited; it is mainly used where electrification is not possible. In the S1, S2 and S3 scenarios, the share of hydrogen in the total energy consumption of the transport sector increases from almost zero in 2015 to 6-7% in 2040 and 18-21% in 2050 (the highest shares are observed in S3, and the lowest shares are observed in S1).

As shown in Figure 66, the consumption of liquid biofuels and biogas increases from around 13 Mtoe in 2015 (mostly bioliquids used in road transport) to 48-52 Mtoe in 2040 in the three main scenarios, mainly because of increased consumption in the navigation and aviation sectors (115), which are generally considered hard to decarbonise through electrification. In 2050, instead, the consumption of liquid biofuels and biogas decreases to 41-47 Mtoe, depending on the scenario. The main reason is a strong reduction in liquid biofuel consumption in the road transport sector relative to 2040 (due to growing electrification and use of hydrogen), even if consumption in the navigation and aviation sectors continues to rise. In the S1, S2 and S3 scenarios, the consumption of liquid biofuels and biogas represents 21 to 23% of the total energy consumption of the transport sector (depending on the scenario) in 2040, and 22-23% in 2050. Bioliquids dominate, but the importance of biogas, which is mostly used in the navigation sector, grows over time: biogas use constitutes 7-8% of the total consumption of bioliquids and biogas in 2040 (depending on the scenario), but this share increases to 16% in 2050 (in all three main scenarios).

In the S1, S2 and S3 scenarios, the consumption of e-fuels (including e-gas and e-liquids (116)) in the EU rises from zero in 2015 to 22-40 Mtoe in 2040 and 45-49 Mtoe in 2050 (depending on the scenario), which are mainly consumed by road transport, navigation and aviation (117). Based on the assumptions on e-fuel production pathways and efficiency, producing this amount of e-fuels will require around 38-69 Mtoe of (renewable) electricity in 2040 and 76-84 Mtoe in 2050. Note that there are significant differences in e-fuel use between scenarios in 2040: 22 Mtoe in S1, 34 Mtoe in S2 and 40

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(115) Only bioliquids are used in aviation.

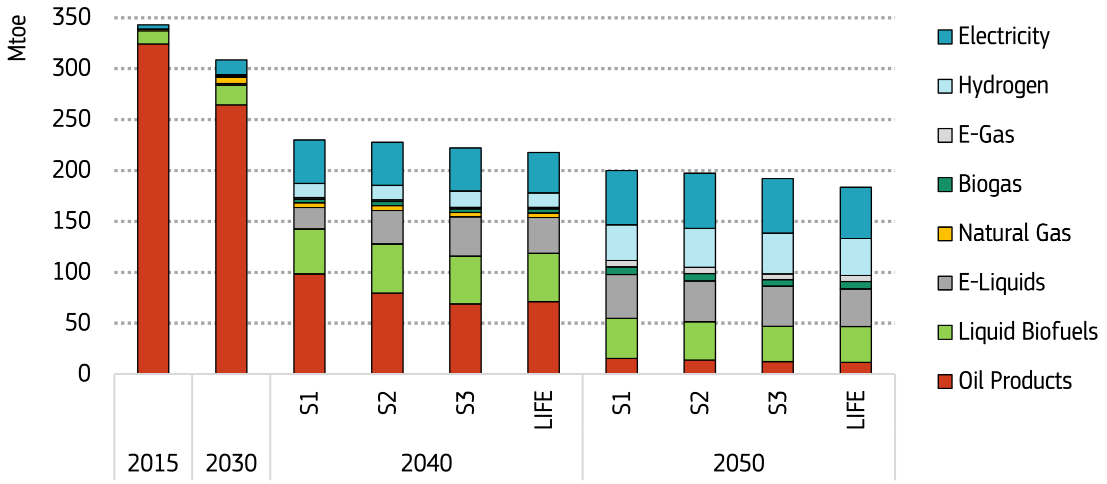
(116) E-liquids include e-ammonia and e-methanol.

(117) Only e-liquids are used in aviation.

Mtoe in S3 (see Figure 66). These differences are caused mainly by differences in e-fuel consumption in the road transport sector, in which reduced consumption of fossil fuels in the most ambitious scenarios is mostly compensated by increased consumption of e-fuels. E-fuel consumption in road transport in 2040 is rather small in the S1 scenario (roughly 3 Mtoe), but it is significantly higher in the S2 and S3 scenarios (12 and 17 Mtoe, respectively). As a result of the above, in the S1, S2 and S3 scenarios, the share of e-fuels in the total energy consumption of the transport sector increases from zero in 2015 to 10-18% in 2040 and 23-25% in 2050. The consumption of liquid e-fuels is much higher than that of gaseous e-fuels. However, the importance of e-gas, which is mostly used in the navigation sector, increases over time: 4-6% of e-fuel consumption in 2040 corresponds to e-gas, depending on the scenario, whereas in 2050 this share is 13-14%.

In LIFE, the total amount of energy consumed by the transport sector decreases over time a bit more than in the other scenarios, mainly because of the different transport activity pattern, as already explained above. However, in relative terms, the fuel mix of the transport sector is very similar to that of the S2 and S3 scenarios (see Figure 66). More specifically, in LIFE, in 2040, fossil fuel and e-fuel shares are in between those observed in S2 and S3, whereas electricity, hydrogen and liquid biofuel and biogas shares are similar in S2, S3 and LIFE.

Figure 66: EU energy consumption in the transport sector by fuel/energy carrier type



Note: Energy consumption including international aviation and navigation.

Source: PRIMES.

1.5.4. Technology developments per transport mode

1.5.4.1. Passenger cars and vans

A deep transformation of the EU's car and van fleet occurs between 2015 and 2050, driven mainly by the new regulation strengthening the CO2 emission performance standards applicable to these types of vehicles. In 2015, the fleet consists practically only of conventional ICE cars and vans. Over time, however, the share of ICE vehicles rapidly declines, and these vehicles are replaced by battery-electric vehicles and, to a lesser degree, fuel-cell and plug-in hybrid vehicles (118) (119). As a result, the EU's car and van fleet goes from consuming almost only fossil fuels in 2015 to consuming energy mostly in the form of electricity and hydrogen in 2050.

As shown in Figure 67, in the S1, S2 and S3 scenarios, the share of ICE **passenger cars** (including diesel, gasoline, LPG and CNG vehicles) in the EU's car stock declines from practically 100% in 2015, to 26% in 2040 and 2% in 2050. These vehicles are substituted by battery-electric, fuel-cell and plug-in hybrid cars. The share of battery-electric cars increases to 57-58% in 2040 and 79-80% in 2050 (depending on the scenario), and the share of fuel-cell cars increases to 5% in 2040 and 14% in 2050. The share of plug-in hybrids increases to 11% in 2040, which indicates that this technology has a role to play in the transition away from fossil fuels. However, in 2050, the share of plug-in hybrids decreases to 5%, as zero-emission powertrains become dominant. As a result of the above, the passenger car fleet goes from consuming mostly only fossil fuels in 2015 (95% of the total amount of energy consumed by cars) to consuming mostly electricity and hydrogen (91% of the total energy consumption) and almost no fossil fuels in 2050 (see Figure 68). Finally, it should be noted that the total energy consumption by cars drops from around 180 Mtoe in 2015 to 72-73 Mtoe in 2040 and 45-46 Mtoe in 2050 (which means it decreases by roughly 60% and 75% in 2040 and 2050, respectively, relative to 2015). This occurs even if transport activity by car (expressed in passenger-km) increases by 20-21% and 21-22% over the 2015-2040 and 2015-2050 periods, respectively (see Section 1.5.2). This can be explained by the significant energy efficiency gains related to electrification.

The picture looks similar for **vans**, although in this case the switch to alternative drivetrains is slightly more moderate than for cars in 2040. In the S1, S2 and S3 scenarios, the share of ICE vehicles in the EU's van stock declines from virtually 100% in 2015, to 38% in 2040 and 3% in 2050, as ICE vans are replaced by battery-electric, fuel-cell and plug-in hybrid vans. The share of battery-electric vehicles increases to 39-40% in 2040 (depending on the scenario) and 74% in 2050, and the share of fuel-cell vans rises to 5% in 2040 and 15-16% in 2050. As a result, the van fleet goes from consuming mostly only fossil fuels in 2015 (94% of the total amount of energy consumed by vans) to consuming mainly electricity and hydrogen (91% of the total energy consumption) and almost no fossil fuels in 2050, similarly to passenger cars. Also, the total amount of energy consumed by vans in the EU drops by 47-48% in 2040 and by 60-63% in 2050, relative to 2015, even though transport activity by vans actually increases

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(118) The electric passenger car and van market is growing rapidly. According to IEA's 'Global EV Outlook 2023', in Europe, electric passenger car sales increased by more than 15% in 2022 relative to 2021 to reach 2.7 million units (including battery-electric and plug-in hybrid cars). As a result, 21% of all new cars sold in Europe in 2022 were electric, up from 18% in 2021, 10% in 2020 and less than 3% prior to 2019. Electric van sales increased by around 50% in 2022 relative to 2021 to reach 95 000 units (including battery-electric and plug-in hybrid vehicles). As a result, 5% of all new vans sold in Europe in 2022 were electric, up from 3% in 2021 and less than 2% prior to 2020. Note that, in IEA's study, "Europe" includes the EU countries, Iceland, Israel, Norway, Switzerland, Türkiye, and the UK.

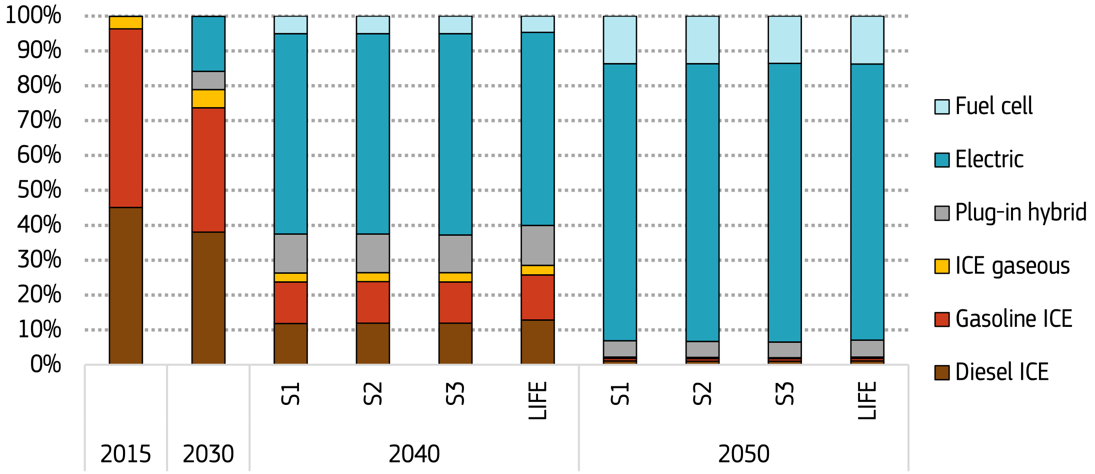
(119) The share of electric vehicles (including battery-electric and plug-in hybrid vehicles) in the annual amount of cars and vans sold in Europe is expected to continue rising in the next years, reaching more than 40% in 2026 (according to BNEF's 'Electric Vehicle Outlook 2023') and around 60% in 2030 (according to IEA's 'Global EV Outlook 2023', in the Stated Policies Scenario).

over the same periods (see Section 1.5.2). Again, this can be explained by the significant energy efficiency gains related to electrification.

It should be noted that the carbon intensity of the fuels used by ICE cars and vans is significantly lower in 2040 and 2050 than in 2015, owing to the increased consumption of liquid biofuels, biogas and e-fuels relative to fossil fuels. This is particularly important in 2040, with significant differences between the S1, S2 and S3 scenarios (see Figure 68). The total amount of fossil fuels, liquid biofuels, biogas and e-fuels consumed by passenger cars and vans in 2040 is similar in the three main scenarios (45-46 Mtoe). However, disaggregating per fuel shows that, in 2040, fossil fuel consumption is higher, and liquid biofuel and e-liquid consumption is lower in the S1 scenario than in the S2 and S3 scenarios. Instead, the S3 scenario shows a lower consumption of fossil fuels and a greater consumption of liquid biofuels and e-liquids than the S1 and S2 scenarios. Biogas and e-gas consumption is similar in the three main scenarios. This implies that the carbon intensity (expressed in tCO2/toe) of fuels used by the ICE passenger cars and vans remaining in the fleet in 2040 is highest in the S1 scenario (21% lower intensity than in 2015) and lowest in the S3 scenario (49% lower intensity than in 2015). In 2050, the carbon intensity is 89-93% lower than in 2015 in the main scenarios, with S3 scenario showing the largest decrease (93%).

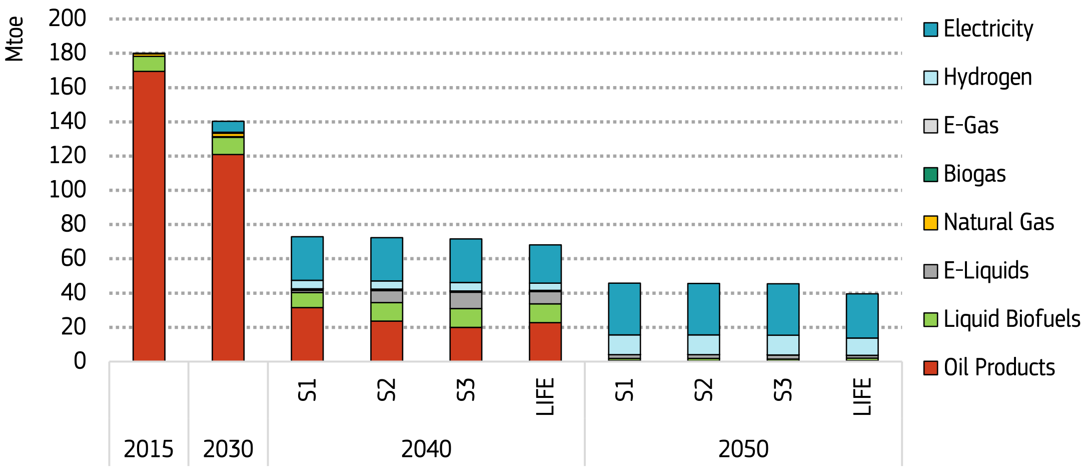
In LIFE, the total amount of energy consumed by cars and vans decreases over time a bit more than in the other scenarios, mainly because of the lower transport activity (expressed in passenger-km for cars, and in tonnes-km for vans). For passenger cars, total energy consumption drops by 62% in 2040 and by 78% in 2050 compared to 2015 (i.e., 2 percentage points more than in the S2 and S3 scenarios in 2040, and 3 pp more in 2050). For vans, energy consumption drops by 52% in 2040 and 63% in 2050 compared to 2015 (i.e., 4-5 pp more than in the S2 and S3 scenarios in 2040, and 1-3 pp more in 2050). In 2040, both for cars and vans, the fuel mix is similar to that of the S2 scenario (in relative terms).

Figure 67: Distribution of the EU passenger car stock per type of drivetrain



Source: PRIMES.

Figure 68: EU energy consumption by passenger cars by fuel/energy carrier type



Source: PRIMES.

1.5.4.2. Heavy Goods Vehicles (HGVs)

The EU's HGV stock undergoes a deep transformation between 2015 and 2050, driven mainly by the proposed revision of the regulation on CO2 emission standards for heavy duty vehicles ([120]). In 2015, the fleet consisted almost entirely of diesel conventional ICE vehicles, but over time their share is projected to decline, and these vehicles are largely replaced by battery-electric vehicles and hydrogen vehicles (the latter, mostly for long-haul transport) ([121]). Consequently, the EU's HGV fleet goes from consuming almost only fossil fuels in 2015 to consuming mostly electricity and hydrogen in 2050.

As shown in Figure 69, in the S1, S2 and S3 scenarios, the total share of diesel conventional, diesel hybrid ([122]), LPG and LNG vehicles in the EU's HGV stock drops from virtually 100% in 2015, to 62-64% in 2040 and 21-29% in 2050 (depending on the scenario). These vehicles are replaced mostly by battery-electric and hydrogen HGVs. The share of battery-electric vehicles in the HGV stock increases to 24-25% in 2040 and 45-48% in 2050, and the share of hydrogen HGVs increases to 12-14% in 2040 and 26-31% in 2050. As already mentioned above, however, there is still a significant percentage of diesel conventional, diesel hybrid and ICE gaseous vehicles left in 2050 (21-29% of the HGV stock, depending on the scenario). The differences between scenarios, particularly observed in 2050, are mainly due to different assumptions on HDV CO2 standards from 2040 onwards (see Annex 6). S1 is the scenario assuming the least

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([120]) COM(2023) 88 final.

([121]) Electric truck sales are currently low, but this market is growing. According to IEA's 'Global EV Outlook 2023', 0.5% of all new trucks sold in Europe in 2022 were electric (including battery-electric and plug-in hybrid vehicles). This is a small share, but an increasing trend is observed in the last years (the share of electric truck sales was almost zero in 2017 and 0.2% in 2020). Furthermore, the share of electric truck sales is projected to continue rising in the next years, reaching 10% in Europe and 13% in the EU in 2030 (in the Stated Policies Scenario). Note that, in IEA's study, "Europe" includes the EU countries, Iceland, Israel, Norway, Switzerland, Türkiye, and the UK.

([122]) Here, diesel hybrid vehicles include plug-in hybrids. The share of plug-in hybrids in the HGV stock is limited (below 2% of the fleet in all years up to 2050).

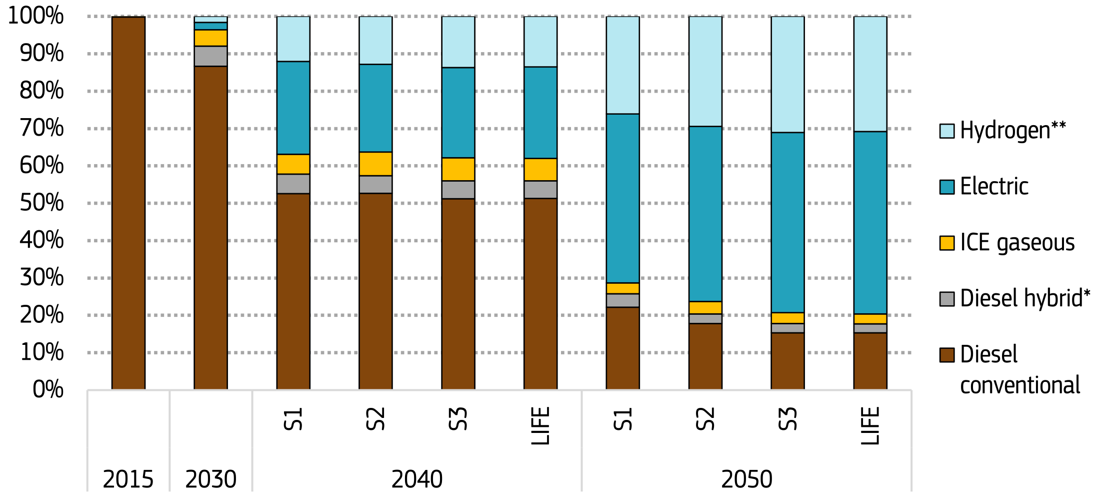
stringent CO2 standards in the 2040-2050 period, and S3 is the scenario assuming the most stringent ones. This is why the S1 scenario shows the largest share of diesel conventional, diesel hybrid and ICE gaseous vehicles (29%) and the smallest share of battery-electric and hydrogen vehicles (71% taken together) in 2050, whereas S3 is the scenario showing the smallest share of diesel conventional, diesel hybrid and ICE gaseous vehicles (21%) and the biggest share of battery-electric and hydrogen vehicles that year (79% in aggregate).

As a result of the fleet transformation described above, the HGV fleet goes from consuming mostly only fossil fuels in 2015 (94% of the total amount of energy consumed by HGVs) to consuming mostly hydrogen and electricity (70-84% of the total energy consumption, depending on the scenario) and almost no fossil fuels in 2050 (see Figure 70). Moreover, as in the case of passenger cars and vans, the diesel conventional, diesel hybrid and ICE gaseous vehicles remaining in the fleet in 2040 and 2050 use fuels that have a significantly lower carbon intensity than in 2015, owing to the increased consumption of liquid biofuels, biogas and e-fuels relative to fossil fuels. This is particularly important in 2040, with significant differences in carbon intensity between the S1, S2 and S3 scenarios. More specifically, the carbon intensity of fuels used by diesel conventional, diesel hybrid and ICE gaseous vehicles in 2040 is highest in the S1 scenario (24% lower intensity than in 2015) and lowest in the S3 scenario (52% lower intensity than in 2015). In 2050, instead, the remaining diesel conventional, diesel hybrid and ICE gaseous vehicles use almost no fossil fuels in all three scenarios (see Figure 70); hence, the carbon intensity is similar in the three main scenarios (95-98% lower than in 2015).

Furthermore, it should be noted that the total amount of energy consumed by HGVs in the EU, which is almost 50 Mtoe in 2015, decreases by 29% in S1 and S2 and 32% in S3 in 2040, and by 36% in S1, 37% in S2 and 42% in S3 in 2050, compared to 2015 (see Figure 70). This occurs even if the HGV transport activity (expressed in tonnes-km) increases by 35-41% and 40-49% (depending on the scenario) over the 2015-2040 and 2015-2050 periods, respectively (see Section 1.5.2). This is mostly explained by the energy efficiency gains linked to electrification.

In LIFE, the total amount of energy consumed by HGVs decreases over time a bit more than in the S1 and S2 scenarios, mainly because of a slightly lower level of HGV transport activity (expressed in tonnes-km), due to a shift to other modes, such as rail. However, the total energy consumption in LIFE is slightly higher than in S3, mainly because of the somewhat higher level of HGV transport activity. More specifically, the total energy consumption drops by 32% in 2040 and 40% in 2050 compared to 2015 (i.e., 3 percentage points more than in S1 and S2 in 2040 and 3-4 pp more in 2050, and 0.1 pp less than in S3 in 2040 and 2 pp less in 2050). In 2040, the fuel mix in LIFE has similar characteristics to the fuel mix of both the S2 and S3 scenarios (in relative terms).

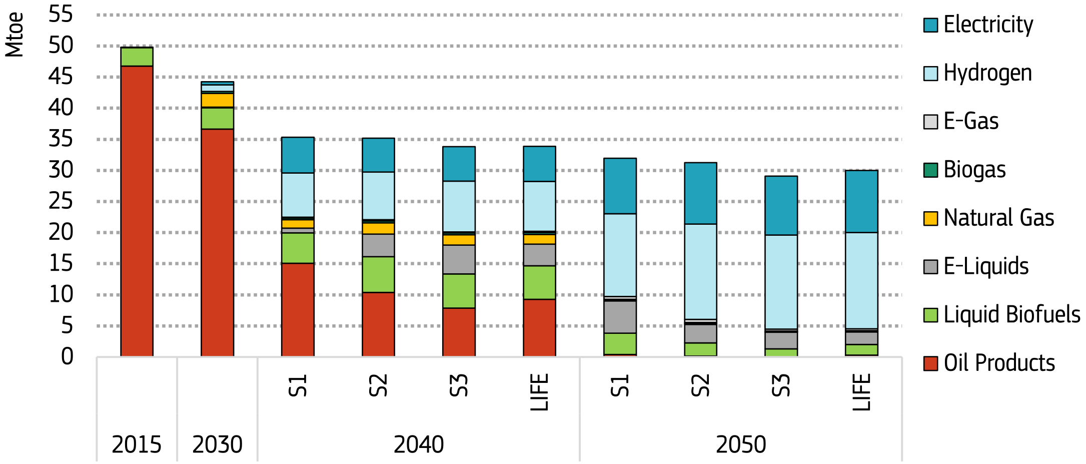
Figure 69: Distribution of the EU HGV stock by type of drivetrain



*Note: *Diesel hybrid vehicles include plug-in hybrids. **Hydrogen vehicles include fuel-cell vehicles and hydrogen ICE vehicles.*

Source: PRIMES.

Figure 70: EU energy consumption by HGVs by fuel/energy carrier type



Source: PRIMES.

1.5.4.3. Other road transport

The EU’s fleet of buses and coaches is projected to undergo significant changes between 2015 and 2050, driven mainly by the proposed revision of the regulation on CO2 emission standards for heavy duty vehicles (123). In 2015, the fleet consisted almost entirely of diesel ICE vehicles. However, battery-electric and hydrogen vehicles are expected to largely replace this type of vehicles by 2050 (124). Buses are used mostly

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(123) COM(2023) 88 final.

(124) Electric bus and coach sales are growing. According to IEA’s ‘Global EV Outlook 2023’, around 9% of all new buses and coaches sold in Europe in 2022 were electric (including battery-electric and plug-in hybrid vehicles), up from around 7% in 2021, 4% in 2020 and less than 3% prior to 2019. Furthermore, the share of electric bus and coach sales is projected to continue rising in the next years,

within urban areas, where battery-electric vehicles are generally a fully viable alternative, and this allows high shares of this type of vehicles. Instead, coaches are mainly used for long inter-urban trips, which imposes operational limitations on the use of battery-electric vehicles; as a result, the share of hydrogen vehicles in the fleet is higher for coaches than for buses. In the S1, S2 and S3 scenarios, the share of battery-electric vehicles in the bus and coach fleet increases to 36-37% in 2040 and 43-44% in 2050, while the share of hydrogen vehicles reaches 15-16% in 2040 and 32-37% in 2050 (the exact share depends on the scenario). It is important to note that, even though the total share of diesel conventional, diesel hybrid (125) and ICE gaseous buses and coaches is projected to decline over time, their share remains significant in 2040 and 2050. More specifically, the share of diesel conventional, diesel hybrid and ICE gaseous vehicles in the EU's bus and coach fleet is 47-49% in 2040 and 20-25% in 2050. Note that the exact fleet composition shares differ per scenario. In particular, significant differences can be observed in 2050, which is mainly due to different assumptions on CO2 emission standards for coaches from 2040 onwards (see Annex 6). As a result of the fleet transformation described above, the EU's bus and coach fleet goes from consuming almost only fossil fuels in 2015 (94% of the total energy consumption) to using mostly alternative energy carriers in 2050 (electricity, hydrogen, liquid biofuels, biogas and e-fuels represent 95-96% of the total energy consumption in that year).

The EU's fleet of powered 2-wheelers becomes largely electrified between 2015 and 2050 (126). In the S1, S2 and S3 scenarios, the share of ICE 2-wheelers in the EU's stock declines from virtually 100% in 2015, to 32% in 2040 and 10% in 2050, as ICE vehicles are rapidly replaced by battery-electric vehicles. On the other hand, the share of battery-electric vehicles increases to 68% in 2040 and 90% in 2050. As a result, the 2-wheeler fleet goes from consuming mostly only fossil fuels in 2015 (97% of the total energy consumption) to consuming mainly electricity (78-79% of the total energy consumption) and almost no fossil fuels in 2050.

It should be noted that the total amount of energy consumed by buses, coaches and powered 2-wheelers taken together decreases by 39-40% in 2040 and 49-51% in 2050 compared to 2015. This occurs even if transport activity (expressed in passengers-km) by these transport modes taken together increases by 19-21% and 35-36% over the 2015-2040 and 2015-2050 periods, respectively (see Section 1.5.2). This can be explained by the significant energy efficiency gains related to electrification.

Finally, the diesel conventional, diesel hybrid and ICE gaseous buses and coaches and the ICE 2-wheelers that remain in the fleet in 2040 and 2050 use fuels that have a significantly lower carbon intensity than in 2015, due to the increased consumption of

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reaching 40% in Europe and 55% in the EU in 2030 (in the Stated Policies Scenario). Note that, in IEA's study, "Europe" includes the EU countries, Iceland, Israel, Norway, Switzerland, Türkiye, and the UK.

(125) Diesel hybrid vehicles include plug-in hybrids.

(126) The electric two- and three-wheeler market is growing. According to IEA's 'Global EV Outlook 2023', in Europe, 8% of all new powered two-wheelers and 7% of all new powered three-wheelers sold in 2022 were electric, up from around 5% and 4%, respectively, in 2020. The share of electric two- and three-wheeler sales is projected to continue rising in the next years, reaching more than 90% in 2040 (according to BNEF's 'Electric Vehicle Outlook 2023').

liquid biofuels, biogas and e-fuels relative to fossil fuels. This is particularly important in 2040, with significant differences in carbon intensity between scenarios. More specifically, the carbon intensity of fuels used by ICE vehicles in 2040 is highest in the S1 scenario (22% lower intensity than in 2015) and lowest in the S3 scenario (51% lower intensity than in 2015), while in 2050 the carbon intensity is similar in all scenarios (88-91% lower intensity than in 2015).

In LIFE, the total amount of energy consumed by buses, coaches and 2-wheelers taken together is similar to that of the other scenarios both in 2040 and 2050 (around 8 and 6 Mtoe, respectively). Furthermore, in 2040, the combined fuel mix for all these modes is similar to that of the S2 scenario.

1.5.4.4. Rail

The EU's rail transport sector is projected to undergo significant further electrification between 2015 and 2050. In 2015, around 67% of the rolling stock used for passenger transport was already electric, while in the case of freight transport this share was a bit lower (55%). The remainder was internal combustion rolling stock. The proportion of electrified lines in use in the EU is increasing gradually (56% in 2015, 57% in 2020), and the share of electric rolling stock is projected to increase considerably by 2040 and 2050. More specifically, in the S1, S2 and S3 scenarios, the share of electric rolling stock used for passenger transport increases to 85-86% in 2040 and 95% in 2050, and the share of electric rolling stock used for freight transport increases to 76-77% in 2040 and 88-89% in 2050 (the exact shares differ slightly per scenario). At the same time, the share of internal combustion rolling stock used for passenger transport drops to 12-13% in 2040 and 4% in 2050, and in the case of freight rail transport, it goes down to 21-22% in 2040 and 10% in 2050. The share of hydrogen rolling stock is projected to be limited; it will be mainly used where electrification is not possible. This transformation requires substantial investments in electric rolling stock as well as significant efforts to largely electrify the European rail infrastructure by 2050 (127), and it is supported by the assumed completion of the core TEN-T network by 2030 and the comprehensive TEN-T network by 2050.

As a result of the transformation described above, in the S1, S2 and S3 scenarios, the EU's rail transport sector transitions from meeting 25% of its energy demand with fossil fuels in 2015 (the remainder being electricity), to using almost only electricity and no fossil fuels in 2050 (see Figure 71). Note that, although the share of internal combustion rolling stock is projected to decline over time, there is still some left both in 2040 and in 2050; however, in these two years, and particularly in 2050, the internal combustion rolling stock uses a fuel blend that has a significantly lower carbon intensity than in 2015, due to the increased consumption of liquid biofuels and e-fuels relative to fossil fuels (see Figure 71). More specifically, in 2040, this carbon intensity is 26% lower in S1, 46% lower in S2 and 56% lower in S3 than in 2015. In 2050, it is more than 95% lower than in 2015 in all three scenarios. Furthermore, it should be noted that the total amount of energy consumed by rail transport in the EU increases by around 43-44% in 2040 and 48-51% in 2050 compared to 2015 (see Figure 71), mainly due to increased rail transport activity (see Section 1.5.2). However, these energy consumption growth rates

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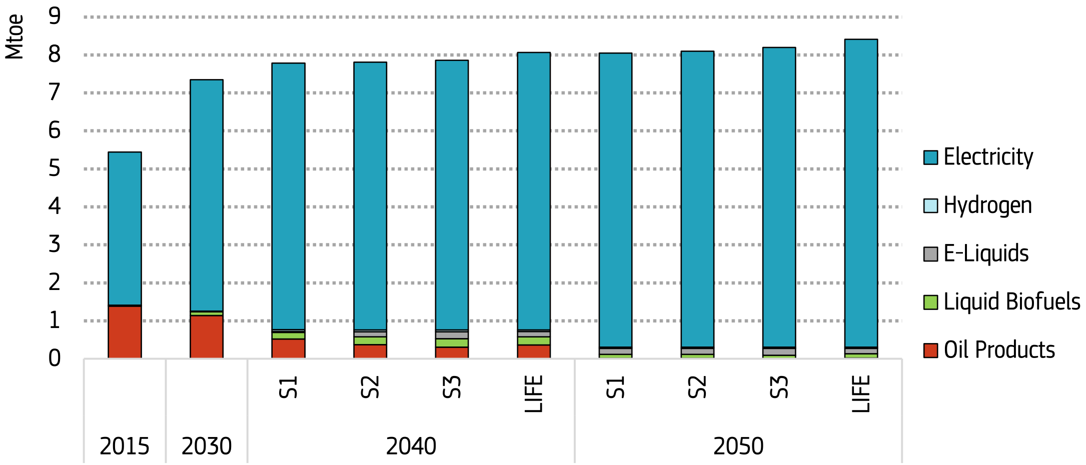
(127) The investment costs corresponding to the electrification of the rail network are not included in the modelling. Instead, the investment costs related to rolling stock are included.

are lower than the activity growth rates observed over the same period. The main reason is that the rail sector is projected to be further electrified during the next decades, which brings significant energy efficiency gains.

In LIFE, the total amount of energy consumed by the rail sector increases over time a bit more than in the S1, S2 and S3 scenarios, mainly because of a higher level of rail transport activity (both in passenger-km and tonnes-km) due to a higher shift from other modes to rail. The total energy consumption increases by 48% in 2040 and 54% in 2050 compared to 2015 (i.e., 4-5 percentage points more than in the core scenarios in 2040, and 4-7 pp more in 2050). Nevertheless, the fuel mix remains similar to that of the core scenarios (in relative terms), particularly S2 and S3.

Figure 71: EU energy consumption in the rail sector by fuel/energy carrier type



Note: Energy consumption including passenger and freight rail transport.

Source: PRIMES.

1.5.4.5. Domestic navigation

As explained in Section 1.5.2, in this impact assessment, the term *domestic navigation* includes inland waterway transport and national maritime transport (128). The composition of the vessel fleet used for domestic navigation in the EU is projected to undergo significant changes between 2015 and 2050, in a similar way across all scenarios. In 2015, the fleet consisted almost entirely of conventional vessels powered by liquid fossil fuels (i.e., diesel, gasoline and fuel oil). However, the share of vessels using alternative propulsion technologies is expected to grow in the next decades. More specifically, in the S1, S2 and S3 scenarios, the share of battery-electric vessels in the fleet increases to 14% in 2040 and 24% in 2050, while the share of fuel-cell ships, which are deployed only after 2040, becomes 6% in 2050. Furthermore, the share of vessels using gaseous fuels grows over time, reaching 8% of the fleet in 2040 and 11-12% in 2050. It is important to note that, even though the share of vessels equipped with

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(128) These two waterborne transport modes are grouped together because a split between inland waterway and national maritime transport is currently not available in the official energy statistics, so the PRIMES model takes them together.

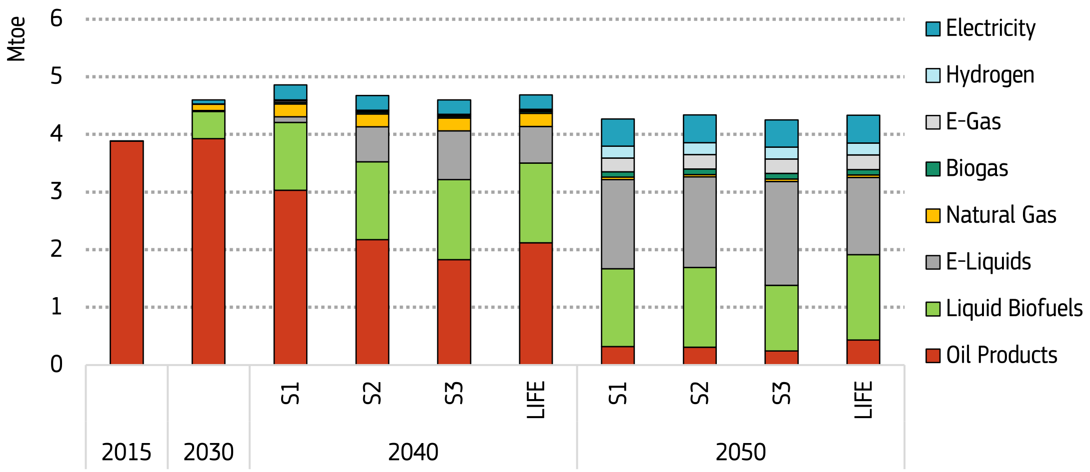
conventional propulsion systems using liquid fuels is projected to decline over time, this ship type remains the predominant one, representing 78% of the EU fleet in 2040 and 58% in 2050.

As a result of the fleet composition changes described above, along with a significant uptake of liquid biofuels, biogas and e-fuels after 2030, the EU's fleet goes from consuming almost only fossil fuels in 2015 to using mostly zero- and low-emission energy carriers in 2050. In the S1, S2 and S3 scenarios, projections show that liquid oil products and natural gas represent only 6-7% and 1% of the total amount of energy consumed by domestic navigation in 2050, respectively (see Figure 72). Instead, liquid biofuels, biogas and e-fuels (in gaseous or liquid form) are projected to represent 76-77% of the total energy consumption in 2050, while the share of electricity and hydrogen taken together reaches 16%. Note that the fuels used by conventional vessels have a significantly lower carbon intensity in 2040 and 2050 than in 2015, due to the increased consumption of liquid biofuels, biogas and e-fuels (both in gaseous and liquid form) relative to fossil fuels (see Figure 72). This is particularly important in 2040, with significant differences in carbon intensity between scenarios. More specifically, the carbon intensity of fuels used by conventional vessels in 2040 is highest in the S1 scenario (31% lower intensity than in 2015) and lowest in the S3 scenario (54% lower intensity than in 2015), while in 2050 it is 91-93% lower than in 2015 in the three main scenarios.

Furthermore, it should be noted that, in S1, S2 and S3, the total amount of energy consumed by domestic navigation in the EU increases by around 18-25% in 2040 and 9-11% in 2050 compared to 2015 (see Figure 72). This occurs in parallel to the deployment of technological and operational measures to improve energy efficiency (e.g., hull design, slow steaming, optimisation of cargo capacity utilisation, etc.) as well as the energy efficiency gains linked to the partial electrification of the fleet.

In LIFE, the total amount of energy consumed in the domestic navigation sector evolves over time in the same way as in the core scenarios (reaching almost 5 Mtoe in 2040 and a bit more than 4 Mtoe in 2050). In 2040, the fuel mix is similar to that of the S2 scenario.

Figure 72: EU energy consumption in domestic navigation by fuel/energy carrier type



Note: Including passenger and freight transport. The category «E-Liquids» includes e-methanol, e-ammonia, synthetic diesel and synthetic fuel oil.

Source: PRIMES.

1.5.4.6. International navigation

The composition of the vessel fleet used for international maritime transport in the EU is projected to change considerably between 2015 and 2050. The transformation is driven by policy measures aimed at decarbonising this sector adopted by the EU (e.g., FuelEU Maritime) and by the International Maritime Organisation (see Annex 6). In 2015, the EU's fleet consisted almost entirely of vessels with conventional engines powered by liquid fossil fuels (i.e., diesel and fuel oil). However, the number of ships using alternative propulsion technologies is projected to grow in the next decades. More specifically, in the S1, S2 and S3 scenarios, the share of battery-electric vessels in the fleet increases to 2-3% in 2040 and 6-7% in 2050, while the share of fuel-cell ships increases to 3-7% in 2040 and 21-29% in 2050 (depending on the scenario), as shown in Figure 73. Furthermore, the share of vessels powered by engines that can use gaseous fuels (which are gradually decarbonised over time) grows significantly until 2040 (reaching 20-21% in 2040) and it remains relatively stable after that year (reaching 21-23% in 2050). It is important to remark that, even though the share of vessels equipped with conventional propulsion systems using liquid fuels is projected to decline over time, this ship type remains the predominant one, representing 71-74% of the EU fleet in 2040 and 44-49% in 2050 (depending on the scenario). Note also that the fleet composition is similar in the S1 and S2 scenarios, whereas in the S3 scenario it shows slightly lower shares of ships with conventional engines along with slightly higher shares of fuel-cell vessels (see Figure 73).

As a result of the fleet composition changes described above, combined with a significant uptake of liquid biofuels, biogas and e-fuels (129) after 2030, the EU's fleet goes from consuming almost only liquid fossil fuels in 2015 to using almost exclusively zero- and

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(129) Including e-ammonia, e-methanol and other e-fuels.

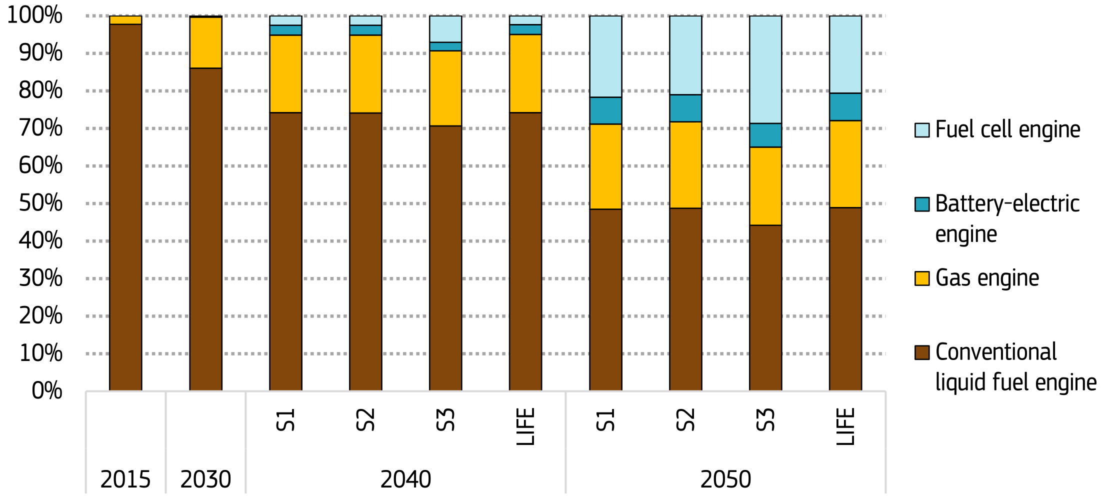
low-emission energy carriers in 2050 ([130]). In the S1, S2 and S3 scenarios, liquid oil products are projected to represent almost 0% of the total amount of energy consumed by international navigation in 2050 (see Figure 74). The use of gaseous fuels (LNG, biogas and e-gas) is projected to increase gradually this decade and the next one, reaching 23-24% of the total energy consumption in 2050. It should be noted that gaseous fuels are gradually decarbonised over time: biogas and e-gas taken together represent 63-70% of the consumption of gaseous fuels in the international navigation sector in 2040, whereas in 2050 this share is close to 100%, as biogas and e-gas progressively replace LNG (see Figure 74). Liquid biofuels and e-liquids are projected to represent 61-62% of the total energy consumption in 2050, whereas electricity and hydrogen represent the remaining 14-16%. Note that the fuels used by vessels equipped with conventional liquid fuel engines or engines that can use gaseous fuels have a significantly lower carbon intensity in 2040 and 2050 than in 2015, due to the increased consumption of liquid biofuels, biogas and e-fuels (both in gaseous and liquid form) relative to fossil fuels. This is particularly important in 2040, with significant differences in carbon intensity between scenarios. More specifically, the carbon intensity of liquid and gaseous fuels in 2040 is highest in the S1 scenario (73% lower intensity than in 2015) and lowest in the S3 scenario (82% lower intensity than in 2015). In 2050, the carbon intensity of these fuels is projected to be almost zero in all scenarios, due to the very low share of fossil fuels in the fuel blend.

It should be noted that the total amount of energy consumed by international navigation in the EU increases by around 10-21% in 2040 and 19-30% in 2050 compared to 2015 in the S1, S2 and S3 scenarios (see Figure 74). However, these growth rates are lower than the increase in international navigation activity projected over the same period (see Section 1.5.2). This can be explained mainly by the deployment of technological and operational measures to improve the energy efficiency of maritime transport (e.g., hull design, slow steaming, optimisation of cargo capacity utilisation, increased vessel size, etc.). The energy intensity of international navigation (expressed in toe/tkm) decreases by 9-18% between 2015 and 2040 and by 13-21% between 2015 and 2050 (the exact rate depends on the scenario), mostly as a result of these measures. Note that there are significant differences between scenarios, with S3 showing the lowest increase in total energy consumption relative to 2015 (see Figure 74), although it is the scenario with the highest level of transport activity (see Section 1.5.2). The main reason for this difference is a larger deployment of energy efficiency measures compared to the S1 and S2 scenarios.

In LIFE, the total amount of energy consumed in the international navigation sector evolves over time in the same way as in S2. However, in 2040, the fuel mix is similar to that of the S3 scenario (in relative terms).

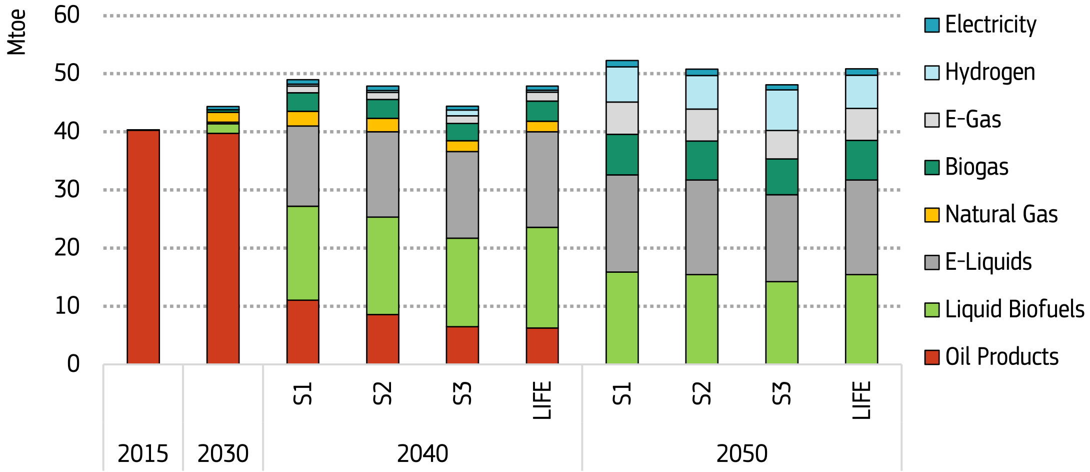
([130]) Projections made by other studies also show an increasing use of zero- and low-emission energy carriers over the next decades. For example, IEA's 'Net Zero Road Map' (2023 update) shows an increase in the use of bioenergy, hydrogen and e-fuels in international shipping at global level, with bioenergy representing 8% and 19% of the energy consumed in 2030 and 2050, respectively, hydrogen representing 4% and 19% in 2030 and 2050, respectively, and e-fuels (mostly, ammonia), representing 7% and 47% in the same years. Similarly, DNV's 'Energy Transition Outlook 2023' argues that the main decarbonisation opportunity for the international maritime sector is switching to low- and zero-carbon fuels such as ammonia, e-methanol, e-methane, and various forms of biofuel.

Figure 73: Composition of the EU vessel fleet used for international navigation



Source: PRIMES.

Figure 74: EU energy consumption in international navigation by fuel/energy carrier type



Note: The category «E-Liquids» includes e-methanol, e-ammonia, synthetic diesel and synthetic fuel oil.

Source: PRIMES.

1.5.4.7. Aviation

The European aviation sector is projected to undergo a significant transformation over the next decades, driven by policy measures aimed at decarbonising this sector, such as the EU Emissions Trading System and ReFuelEU Aviation, which mandates the supply of Sustainable Aviation Fuels (SAF) (see Annex 6). This transformation is multi-dimensional, mainly driven by significant improvements in energy efficiency and a large uptake of zero- and low-emission fuels (such as liquid biofuels and e-fuels) (131), along with a moderate deployment of battery-electric and fuel-cell-electric aircraft.

In the S1, S2 and S3 scenarios, the total amount of energy consumed by the aviation sector in the EU (including domestic and international intra-EU and extra-EU aviation) is projected to increase by around 16-17% between 2015 and 2040, remaining relatively stable after 2040 (see Figure 75). This increase is much lower than the growth in air transport activity (expressed in passenger-km) over the same period (see Section 1.5.2). There is a decoupling between energy consumption and market growth. The difference between transport activity growth and energy consumption growth is mainly due to the large-scale deployment of technological and operational measures to improve energy efficiency (e.g., measures related to aircraft structure design and aerodynamics, propulsion system technology, and transport capacity utilisation). The energy intensity of air transport (expressed in toe/pkm) decreases by 27-28% between 2015 and 2040, and by 34-35% between 2015 and 2050, mostly as a result of these measures.

Furthermore, the S1, S2 and S3 scenarios show an increasing use of zero- and low-emission energy carriers (particularly after 2030), which partially replaces the consumption of fossil fuels in the EU aviation sector. In this respect, the sector transitions from consuming almost only fossil fuels (kerosene) in 2015 to using mostly zero- and low-emission energy carriers in 2050. As shown in Figure 75, oil products are projected to represent 62-66% of the total amount of energy consumed by the aviation sector in 2040, and 24-30% in 2050 (the exact shares depend on the scenario). Thanks to the mandates in ReFuelEU Aviation, the share of liquid biofuels in the total energy consumption increases to 24% in 2040 and 35% in 2050, and the share of e-fuels grows to 10-13% in 2040 and 33-34% in 2050. In addition, hydrogen is projected to represent 0.2-1.1% of the aviation fuel mix in 2040 and 1.6-6% in 2050. The use of electricity as an energy carrier in the aviation sector remains limited to very specific niche markets; consequently, it represents a very small share of the total amount of energy consumed by the aviation sector by 2050 (see Figure 75). Note that the fuel mix in 2040 and 2050 differs between scenarios: S1 is the scenario showing the highest share of oil products and the lowest shares of e-fuels and hydrogen, whereas S3 shows the lowest share of oil products and the highest shares of e-fuels and hydrogen. The liquid biofuel shares in 2040 and 2050, instead, are almost the same across scenarios.

It is important to remark that the aviation fuel blend (excluding electricity and hydrogen) is projected to have a considerably lower carbon intensity in 2040 and 2050 than in 2015, mainly because of the increased consumption of liquid biofuels and e-fuels relative to fossil fuels. There are significant differences between scenarios; more specifically, the carbon intensities are highest in the S1 scenario (34% lower intensity in 2040 than in

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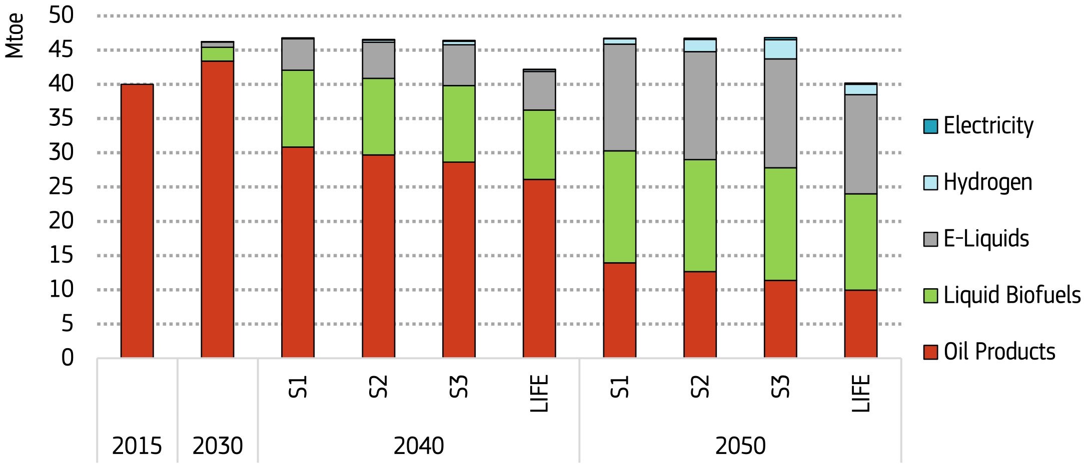
(131) Projections made by other studies also show an increasing use of zero- and low-emission fuels over the next decades. For instance, IEA's 'Net Zero Road Map' (2023 update) projects an increase in the use of sustainable aviation fuels (SAF) at global level, with biofuels representing 10% and 33% of the energy consumed in 2030 and 2050, respectively, and synthetic hydrogen-based fuels representing 1% in 2030 and 37% in 2050. Similarly, both DNV's 'Energy Transition Outlook 2023' and ITF's 'Decarbonising Air Transport' (published in 2021) expect a large uptake of sustainable aviation fuels (biofuels and e-fuels) over the next decades, which will play a key role in decarbonising air transport (together with technological and operational measures to improve energy efficiency, which will play a smaller role).

2015, and 70% lower intensity in 2050 than in 2015) and lowest in the S3 scenario (37% lower intensity in 2040 than in 2015, and 74% lower intensity in 2050 than in 2015).

In LIFE, the total amount of energy consumed by the aviation sector increases over time less than in the core scenarios, mainly because of lower levels of air transport activity, as explained in Section 1.5.2. In LIFE, total energy consumption is 6% higher in 2040 and 0.5% higher in 2050 relative to 2015 (i.e., 11 percentage points less than in the main scenarios in 2040, and 16-17 pp less in 2050), as shown in Figure 75. However, the energy efficiency of air transport (expressed in toe/pkm) is very similar in all scenarios. Furthermore, the fuel mix in LIFE is similar to that of the S3 scenario (in relative terms), although showing a somewhat lower uptake of hydrogen.

Figure 75: EU energy consumption in aviation by fuel/energy carrier type



Note: Energy consumption including domestic and international (intra-EU and extra-EU) aviation.

Source: PRIMES.

1.5.5. CO2 emissions from transport

Direct CO2 emissions from the EU transport sector are projected to decrease dramatically between 2015 and 2050, especially after 2030. It should be noted that this occurs within a context of increased transport activity (see Section 1.5.2). Even so, emissions drop because of a sharp decline in fossil fuel consumption, which is mainly caused by a decrease in energy consumption in the transport sector (resulting mainly from electrification and measures to improve energy efficiency) combined with an increased use of zero- and low-emission energy carriers, i.e., electricity, hydrogen, liquid biofuels, biogas and e-fuels (see Section 1.5.3). As a result of the latter, the carbon intensity (expressed in tCO2/toe) of all the energy carriers employed in the transport sector taken together decreases by more than 90% between 2015 and 2050 in all scenarios.

As shown in Figure 76, in the S1, S2 and S3 scenarios, the total CO2 emissions from the EU transport sector (including international navigation and aviation) are projected to drop from almost 1000 MtCO2 in 2015 to 37-46 MtCO2 (depending on the scenario) in 2050, i.e., a 95-96% reduction. It should be noted that, in 2015, almost 74% of the transport-related CO2 emissions were caused by road transport; instead, roughly 90% of the emissions remaining in 2050 are projected to come from the aviation sector, particularly from the international aviation sector. In 2040, the total amount of transport-related emissions differs significantly between scenarios (see Figure 76 and Figure 77):

310 MtCO2 in the S1 scenario (i.e., a 69% reduction relative to 2015), 252 MtCO2 in the S2 scenario (-75% compared to 2015), and 219 MtCO2 in the S3 scenario (-78% compared to 2015). Relative to 1990, this means CO2 emissions reductions of 62% in S1, 69% in S2 and 73% in S3 by 2040. Emissions are lower in S2 compared to S1, and in S3 compared to S2, mainly because of a greater consumption of e-fuels, hydrogen and electricity taken together, which replace fossil fuels (see Figure 66).

In the S1, S2 and S3 scenarios, emissions from road and rail transport decrease by 77-86% and 62-78% in 2040 compared to 2015, respectively, and they are almost fully eliminated by 2050 (see Figure 76 and Figure 77). In 2040, both modes show the highest level of emissions in the S1 scenario, and the lowest level in the S3 scenario. These emissions reductions are driven mostly by large-scale electrification combined with a switch to zero- and low-emission fuels (i.e., advanced liquid biofuels, biogas and e-fuels) to power the remaining internal-combustion engine vehicles and rolling stock (see Sections 1.5.4.1 to 1.5.4.4). As shown in Figure 76 and Figure 77, direct emissions from the international navigation sector decrease by 68-81% in 2040 compared to 2015 and they are almost fully eliminated by 2050. The aviation sector (including both domestic and international air transport) is projected to reduce its CO2 emissions by 23-28% in 2040 and 65-72% in 2050 relative to 2015, thanks mainly to the uptake of SAF as a major emissions reduction driver. In 2040, both modes show the highest level of emissions in the S1 scenario and the lowest level in the S3 scenario. The emissions reductions in the maritime and air transport sectors are driven mainly by the uptake of zero- and low-emission fuels and the deployment of zero-emission airplanes and vessels, along with further improvements in energy efficiency (see Sections 1.5.4.6 and 1.5.4.7). If one analyses domestic and international transport emissions separately, domestic transport emissions decrease by 76-85% in 2040 compared to 2015 and they reach very low levels in 2050, whereas international transport emissions (including navigation and aviation) decrease by 47-56% in 2040 and by 84-87% in 2050 compared to 2015. However, as already mentioned above, in 2050, most emissions are caused by international air transport, while the international navigation sector is fully decarbonised.

In LIFE, which is designed to meet the same climate target in 2040 as the S3 scenario, transport-related CO2 emissions are in between those observed in S2 and S3 (although closer to S3) in 2040 (226 MtCO2) (132), and similar to those observed in the other scenarios in 2050 (35 MtCO2). This is driven by a combination of two factors: a) lower energy consumption compared to the S2 and S3 scenarios, which is caused by a different transport activity pattern including a higher modal shift to rail and to active modes; b) a fuel mix combining characteristics from S2 and S3 (see Sections 1.5.2 and 1.5.3).

In addition to the above, it should be noted that the transport sector also has significant non-CO2-related impacts on the climate. These effects are caused by emissions of non-CO2 greenhouse gases such as methane and nitrogen oxides, but also by emissions of black carbon from maritime transport, and various types of particles from air transport causing the formation of contrail cirrus. Methane and nitrous oxides emissions from the

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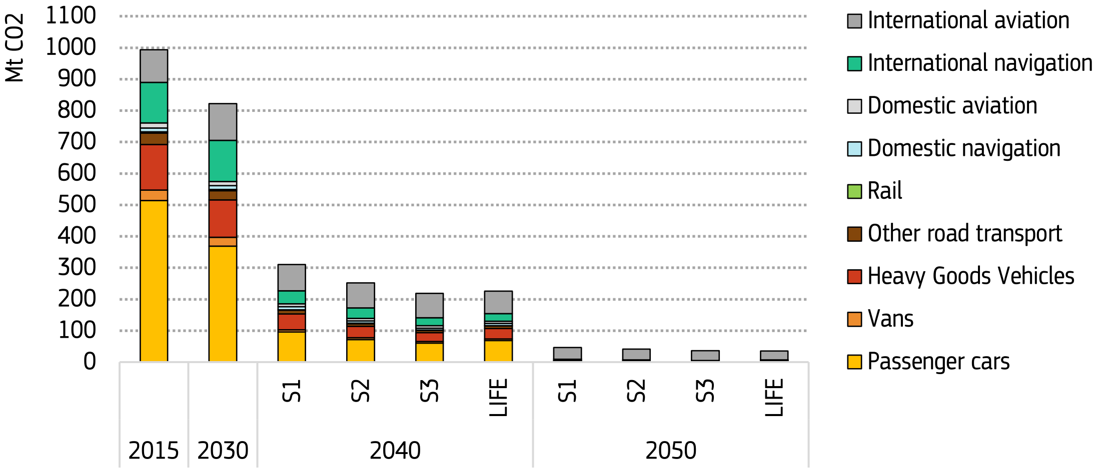
(132) Although S3 and LIFE are designed to meet the same climate target in 2040, transport-related CO2 emissions are higher in LIFE. Other sectors (e.g., agriculture) have lower GHG emissions in LIFE than in S3, which compensates for the higher transport-related CO2 emissions.

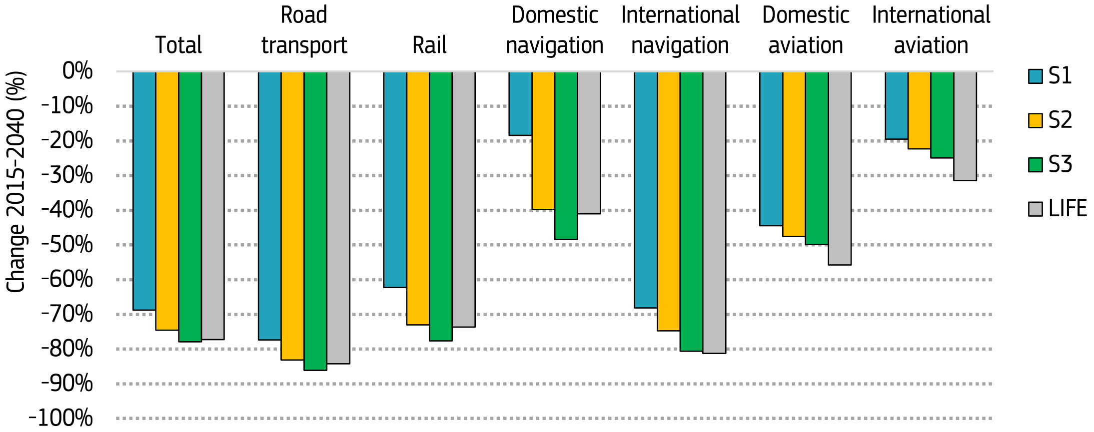
EU transport sector are presented in Section 1.6. Other non-CO2 effects are not quantified in this impact assessment, but they are discussed in Annex 12.

Figure 76: Direct CO2 emissions from the EU transport sector by mode



Source: PRIMES.

Figure 77: Change in EU transport direct CO2 emissions between 2015 and 2040 by mode



Source: PRIMES.

1.6. Non-CO2 GHG emissions in non-land-related sectors

1.6.1. Evolution of emissions without additional mitigation

For non-land-related sectors, the concept of “non-CO2 GHG emissions without additional mitigation” refers to the emissions trajectory resulting from applying a carbon value equal to zero to non-CO2 GHG emissions up to 2050. Thus, this emissions trajectory results solely from the combination of the following two types of drivers for emissions reductions: a) transformation of the energy system on its way to meet climate neutrality by 2050; and b) relevant existing and proposed legislation, particularly the Landfill Directive (133), the Waste Framework Directive (134), and the proposals for a regulation to reduce methane emissions in the energy sector (135), a revised Urban Wastewater Treatment Directive (136) and a revised F-gas regulation (137). In this impact assessment, the non-CO2 GHG emissions without additional mitigation in the non-land-related sectors are assumed to be the same in all scenarios. There is, however, significant mitigation potential beyond this level of emissions. This additional mitigation potential is discussed in Section 1.6.2.

The non-CO2 GHG emissions without additional mitigation corresponding to all non-land-related sectors taken together equal 116 MtCO2-eq in 2040, which represents a 65% reduction relative to 2015 levels. The degree of reduction varies across sectors (see Table 10), but all of them reduce their non-CO2 GHG emissions by more than 40% in 2040 compared to 2015. In the energy and transport sector, non-CO2 GHG emissions drop by 71% in 2040 compared to 2015. Heating and cooling is the sector showing the largest decline in emissions (97% reduction in 2040 relative to 2015, close to the maximum mitigation potential), mainly due to the impact of the proposal for a revised F-gas regulation. Finally, in industry and other sectors, emissions decrease by 50% over the same period.

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(133) Directive 1999/31/EC and Amending Directive (EU) 2018/850.

(134) Directive 2008/98/EC.

(135) COM(2021) 805 final.

(136) COM(2022) 541 final.

(137) COM(2022) 150 final.

Table 10: Non-CO2 GHG emissions without add. mitigation in non-land-related sectors

	NON-CO2 GREENHOUSE GAS EMISSIONS (MTCO2-EQ)*					CHANGE IN EMISSIONS (%)		
	2005	2015	2030	2040	2050	2015-30	2015-40	2015-50
Waste treatment**								
CH4	145	109	78	59	47	-29%	-46%	-57%
N2O	10	9.2	9.2	9.1	9.1	0%	-1%	-1%
Total (all gases)	155	118	87	68	56	-27%	-42%	-53%
Energy and transport								
CH4	110	86	38	20	14	-56%	-76%	-83%
N2O	24	23	18	11	8.1	-22%	-52%	-65%
Total (all gases)	135	109	56	31	23	-49%	-71%	-79%
Heating and cooling								
F-gases	43	76	21	2.6	0.7	-72%	-97%	-99%
Total (all gases)	43	76	21	2.6	0.7	-72%	-97%	-99%
Industry and other								
N2O	48	8.3	6.9	7.2	7.6	-16%	-13%	-8%
F-gases	28	18	8.9	6.1	6.8	-51%	-67%	-63%
Total (all gases)	76	27	16	13	14	-41%	-50%	-46%
Total								
CH4	255	196	116	80	61	-41%	-59%	-69%
N2O	83	41	34	27	25	-16%	-33%	-39%
F-gases	71	94	30	8.7	7.6	-68%	-91%	-92%
Total (all gases)	409	330	180	116	93	-46%	-65%	-72%

*Note: *Non-CO2 GHG emissions without additional mitigation, i.e., assuming a carbon value equal to zero. **The waste treatment sector includes solid waste and wastewater treatment.*

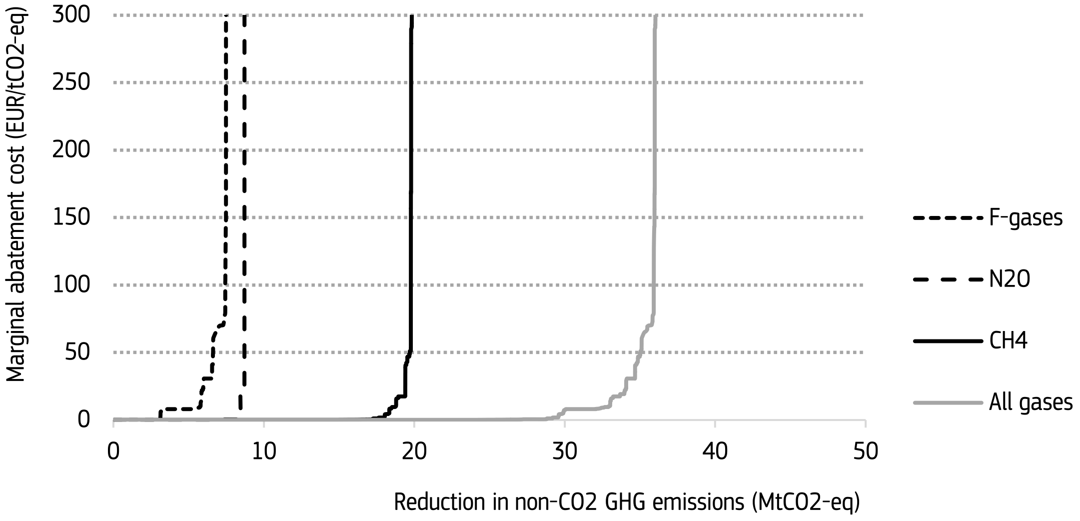
Source: GAINS.

1.6.2. Additional mitigation potential

Figure 78 and Figure 79 show the 2040 marginal abatement cost curves (MACC) corresponding to non-land-related sectors specified per gas and per sector, respectively. These curves indicate the marginal cost of the additional reductions in non-CO2 GHG emissions, which come on top of the "emissions without additional mitigation" described in Section 1.6.1. Similarly, Table 11 and Table 12 show the reductions in emissions achievable at various marginal abatement cost levels. Note that the marginal abatement cost curves corresponding to non-land-related sectors are assumed to be the same in all scenarios.

Table 11 and Table 12 show that, in the non-land-related sectors, there is significant additional mitigation potential: 41 MtCO2-eq in 2040, considering all sectors and gases. If fully achieved, this mitigation potential would reduce the EU's total non-land-related non-CO2 GHG emissions to 79 MtCO2-eq by 2040 (i.e., 76% less than in 2015). It is important to mention that 61% of this maximum mitigation potential (i.e., 25 MtCO2-eq) could be reached at a marginal cost close to zero. Note, however, that even in cases where marginal abatement costs are nearly zero, policy intervention is usually needed to overcome market barriers, lack of information and split incentives. The largest share of this near-zero-cost potential is found in the waste treatment sector. The remaining share of the maximum mitigation potential (39%) comes at a marginal cost significantly higher than zero. Nevertheless, 80% and 85% of the maximum mitigation potential (including all sectors and gases) may be reached at a marginal cost lower than 10 and 50 EUR/tCO2-eq, respectively, leaving only a small part of the maximum mitigation potential untapped (8 and 6 MtCO2-eq, respectively).

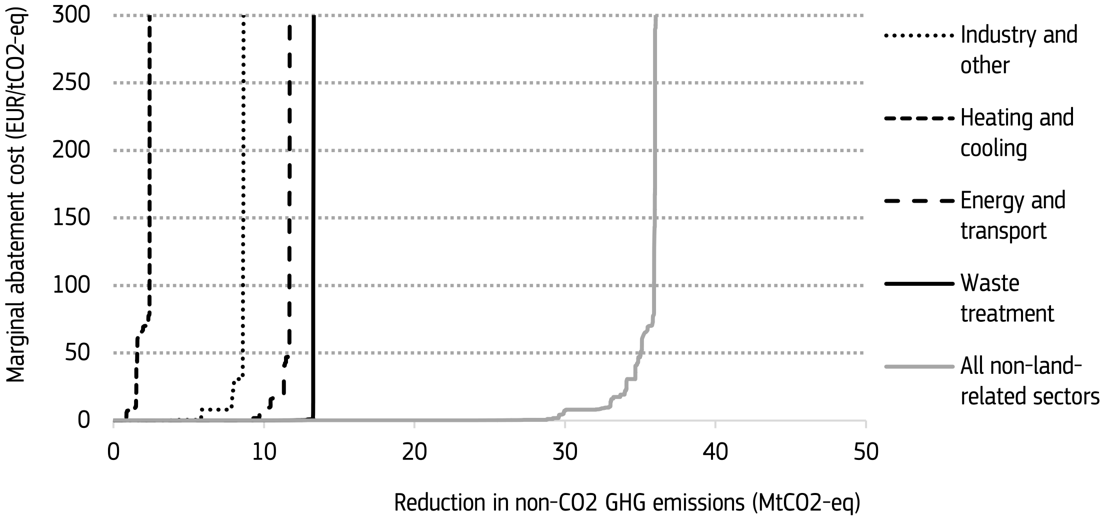
Figure 78: MACC across all non-land-related sectors in 2040 (per gas)



Note: MACC including all non-CO2 greenhouse gases, and MACCs per gas. Marginal abatement costs are expressed in constant EUR 2015.

Source: GAINS.

Figure 79: MACC across all non-CO2 greenhouse gases in 2040 (per sector)



Note: MACC including all non-land-related sectors, and MACCs per sector. Marginal abatement costs are expressed in constant EUR 2015.

Source: GAINS.

By analysing the additional mitigation potential across all non-land-related sectors separately for each gas, one can see that in all cases most of the maximum mitigation potential could be tapped at a low marginal cost. For instance, there exists potential to reduce methane emissions by as much as 23 MtCO2-eq below the “emissions without additional mitigation” in 2040 (see Table 11). Around 82% of this maximum mitigation potential could be tapped at a marginal abatement cost lower than 10 EUR/tCO2-eq, mainly in the waste treatment sector and the energy and transport sector. In the case of nitrous oxide, there exists potential to reduce emissions by as much as 10 MtCO2-eq below the "emissions without additional mitigation" in 2040, about half of which is to be found in the waste treatment sector, and the other half is to be found in industry and other sectors. Around 82% of the maximum mitigation potential for N2O emissions could be reached at a marginal abatement cost lower than 10 EUR/tCO2-eq. Finally, for fluorinated gases, the maximum additional mitigation potential is around 8 MtCO2-eq in 2040 (see Table 11), which is to be found mostly in heating and cooling, industry and other sectors. About 70% of this maximum mitigation potential could be reached at a marginal cost lower than 10 EUR/tCO2-eq and 80% may be tapped at a marginal cost lower than 50 EUR/tCO2-eq, leaving only a very small part of the maximum mitigation potential untapped (3 and 2 MtCO2-eq, respectively).

Table 11: Additional mitigation potentials of non-CO2 GHG emissions across all non-land-related sectors in 2040 (by gas)

	Marginal abatement cost for non-CO2 GHG emissions (EUR/tCO2-eq)**						
	0*	**0.1**	**10**	**50**	**100**	**300**	**Max**
Emissions mitigation in 2040 (MtCO2-eq)							
CH4	0	16	19	20	20	20	23
N2O	0	6.6	8.4	8.7	8.7	8.7	10
F-gas	0	2.7	5.8	6.7	7.5	7.5	8.3
Total	0	25	33	35	36	36	41
Share of maximum mitigation potential achieved in 2040 (%)							
CH4	0%	71%	82%	86%	87%	87%	100%
N2O	0%	64%	82%	85%	85%	85%	100%
F-gas	0%	33%	70%	80%	90%	90%	100%
Total	0%	61%	80%	85%	87%	87%	100%

*Note: *In this table, the non-CO2 GHG emissions at zero marginal abatement cost correspond to the emissions without additional mitigation in 2040. **Marginal abatement costs are expressed in constant EUR 2015.*

Source: GAINS.

By analysing the mitigation potential separately for each non-land-related sector, one can see that in almost all cases most of the maximum mitigation potential could be reached at a low marginal cost. In the **waste treatment** sector, there exists potential to reduce emissions by as much as 14 MtCO2-eq below the "emissions without additional mitigation" in 2040. Around 96% of this maximum mitigation potential could be tapped at a marginal abatement cost lower than 10 EUR/tCO2-eq (see Table 12), mainly through process optimisation and deployment of anaerobic digestion technology with biogas recovery. In the **energy and transport** sector, the maximum additional mitigation potential is 14 MtCO2-eq in 2040. About 73% of this mitigation potential could be achieved at a marginal cost lower than 10 EUR/tCO2-eq, and 82% could be tapped at a marginal cost below 50 EUR/tCO2-eq (in both cases, mostly through implementation of best available technology in bunker fuel use and leak detection and repair programs, and by flooding abandoned coal mines). Higher emission reductions could be achieved only at very high marginal costs, mainly by upgrading long-distance gas pipelines to minimum leakage rates, replacing steel gas distribution networks by PE/PVC networks, and additional leak detection and repair. Non-CO2 GHG emissions from the **heating and**

cooling sector are mostly F-gas emissions. In this sector, the "emissions without additional mitigation" are already very low in 2040 (less than 3 MtCO2-eq); however, there is enough additional mitigation potential in 2040 to almost eliminate these emissions fully (by using alternative agents). Around 57% of the maximum mitigation potential could be tapped at a marginal cost lower than 10 EUR/tCO2-eq, and 62% could be reached at a marginal cost below 50 EUR/tCO2-eq, leaving only a small part of the maximum mitigation potential untapped (around 1 MtCO2-eq in both cases). Finally, in **industry and other** sectors, the maximum additional mitigation potential is 11 MtCO2-eq in 2040. About 72% of this potential could be tapped at a marginal abatement cost lower than 10 EUR/tCO2-eq, while 79% may be reached at less than 50 EUR/tCO2-eq.

Table 12: Additional mitigation potentials of non-CO2 GHG emissions in 2040 (by non-land-related sector)

	Marginal abatement cost for non-CO2 GHG emissions (EUR/tCO2-eq)**						
	0*	**0.1**	**10**	**50**	**100**	**300**	**Max**
Emissions mitigation in 2040 (MtCO2-eq)							
Waste treatment***	0	12	13	13	13	13	14
Energy and transport	0	9	10	12	12	12	14
Heating and cooling	0	0.8	1.4	1.6	2.4	2.4	2.5
Industry and other	0	3.5	7.8	8.6	8.6	8.6	11
Total	0	25	33	35	36	36	41
Share of maximum mitigation potential achieved in 2040 (%)							
Waste treatment***	0%	85%	96%	96%	96%	96%	100%
Energy and transport	0%	65%	73%	82%	83%	83%	100%
Heating and cooling	0%	33%	57%	62%	94%	94%	100%
Industry and other	0%	32%	72%	79%	79%	79%	100%
Total	0%	61%	80%	85%	87%	87%	100%

*Note: *In this table, the non-CO2 GHG emissions at zero marginal abatement cost correspond to the emissions without additional mitigation in 2040. **Marginal abatement costs are expressed in constant EUR 2015. ***The waste treatment sector includes solid waste and wastewater treatment.*

Source: GAINS.

1.6.3. Emissions projections

As described in the previous section, the non-land-related sectors show relatively low-cost mitigation potentials, which translates into very close emission profiles across all scenarios except S1 (see Table 13). The S1 scenario assumes a carbon value equal to zero up to 2040. Therefore, in this scenario, the non-CO2 GHG emissions trajectory is the emissions trajectory without additional mitigation (see Section 1.6.1) until 2040. The level of non-CO2 GHG emissions in 2050 is the same across all scenarios (since the carbon value assumed is also the same).

The non-CO2 GHG emissions from the **waste management** sector in 2040 are projected to be 42% lower than in 2015 in S1, and 54% lower in the other scenarios. In 2050, emissions from the waste management sector are 73% lower than in 2015 in all scenarios. In 2040, in S2, S3 and LIFE, the additional mitigation is achieved mainly through the implementation of: a) source separation and anaerobic digestion with biogas recovery to treat solid waste; and b) 2-stage treatment (anaerobic with biogas recovery and then aerobic) combined with process optimisation to treat wastewater. In 2050, energy recovery technologies are used in addition to the above-mentioned ones in all scenarios.

The non-CO2 GHG emissions from the **energy and transport** sector go down to 31 MtCO2-eq in S1 and 24 MtCO2-eq in the other scenarios in 2040, which means a decrease by 71% and 78%, respectively, compared to 2015. In 2050, emissions are projected to be 83% lower than in 2015 in all scenarios. This mitigation is largely driven by the evolution of the energy system and the lower consumption of fossil fuels, complemented in S2, S2 and LIFE by implementation of technologies to improve bunker fuel use, leak detection and repair programs in gas networks, leakage control and gas recovery in crude oil and natural gas production sites, oxidation of ventilation air methane in coal mines, and flooding of abandoned coal mines.

Non-CO2 GHG emissions from the **heating and cooling** sector are projected to decrease to around 2.5 MtCO2-eq in S1 and to almost zero in the other scenarios in 2040, largely driven by the impact of the proposal for a revised F-gas regulation (reflected already in the S1 scenario, which assumes no additional mitigation). Emissions from this sector are almost fully eliminated by 2050 in all scenarios. Finally, the non-CO2 GHG emissions from **industry and other** sectors are projected to be around 13 MtCO2-eq in S1 and 5 MtCO2-eq in the other scenarios in 2040 (i.e., 50% and 82% less than in 2015, respectively). In 2050, non-CO2 GHG emissions from this sector remain at around 5 MtCO2-eq in all scenarios.

Table 13: Non-CO2 GHG emissions from the non-land-related sectors

	Non-CO2 greenhouse gas emissions (MtCO2-eq)					Change in emissions (%)		
	2005	2015	2040		2050	2015-40		2015-50
			S1	S2, S3 & LIFE	S1, S2, S3 & LIFE	S1	S2, S3 & LIFE	S1, S2, S3 & LIFE
Waste management*								
CH4	145	109	59	51	28	-46%	-53%	-74%
N2O	10	9.2	9.1	4.2	3.8	-1%	-54%	-59%
Total (all gases)	155	118	68	55	32	-42%	-54%	-73%
Energy and transport								
CH4	110	86	20	14	10	-76%	-84%	-88%
N2O	24	23	11	11	7.9	-52%	-53%	-66%
Total (all gases)	135	109	31	24	18	-71%	-78%	-83%
Heating and cooling								
F-gases	43	76	2.6	0.2	0.1	-97%	-100%	-100%
Total (all gases)	43	76	2.6	0.2	0.1	-97%	-100%	-100%
Industry and other								
N2O	48	8.3	7.2	3.7	4.0	-13%	-55%	-52%
F-gases	28	18	6.1	1.0	0.7	-67%	-94%	-96%
Total (all gases)	76	27	13	4.7	4.7	-50%	-82%	-82%
Total								
CH4	255	196	80	64	38	-59%	-67%	-80%
N2O	83	41	27	19	16	-33%	-54%	-61%
F-gases	71	94	8.7	1.2	0.8	-91%	-99%	-99%
Total (all gases)	409	330	116	84	55	-65%	-74%	-83%

*Note: *The waste management sector includes solid waste and wastewater treatment.*

Source: GAINS.

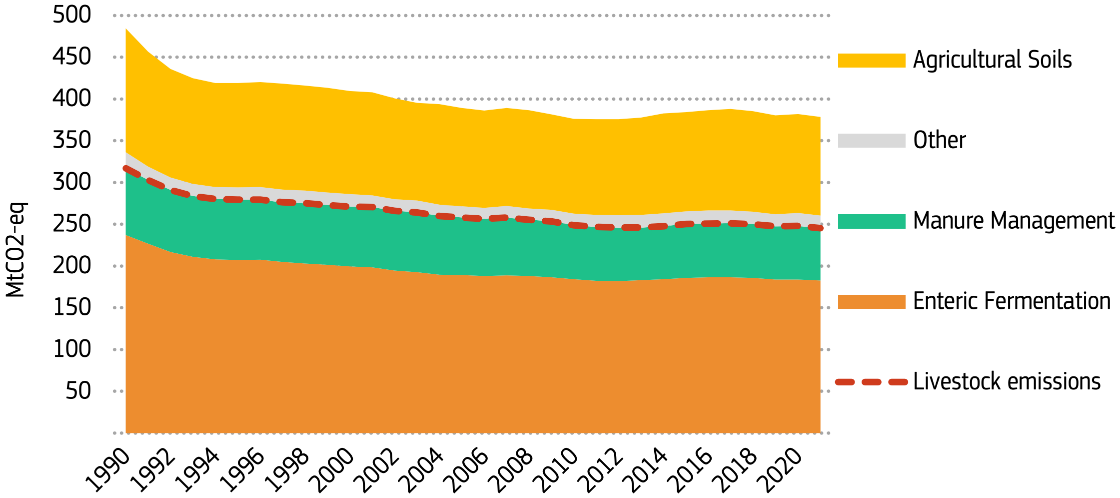
1.7. Agriculture

1.7.1. Introduction

Emissions in the agricultural sector declined since 1990 by 23% with an increase in outut efficicency (i.e., lower emissions per unit of output), but remained stable over the last 10 years (see Figure 80). This relative stability in emissions also applies to livestock emissions, which throughout the average 2019-2021 compared to 10 years ago only reduced emissions by around 1%. Since 1990, livestock emissions consistently make up around 65% of all emissions in the agriculture sector. Emissions from agricultural soil management increased in the last 10 years by about 4% (on a three-year average) and make up around 30% of all emissions in the agriculture sector.

Although agricultural GHG emissions changed very little at EU level in the past, the trend shows considerable variation between Member States, with some decreasing or increasing by about 20%, which highlights the dynamic of emissions from agriculture and the room for additional emission reduction in some Member States in relation to their specific emission profiles and sectorial context ([138]). It is important to note that the reduction of uncertainty in the GHG inventories in the agricultural sector, which does not fully capture the implementation of emission reduction practices at farm level, remains a significant challenge.

Figure 80: Emissions from Agriculture in the EU by sector



Note: Emissions based on UNFCCC categories. 'Livestock' depicts category 3.1 (3.A+3.B) 'enteric fermentation' 3.A, 'manure management' 3.B, 'agricultural soils' 3.D. 'Other' summarises emissions from 3.C Rice Cultivation, 3.F - Field Burning of Agricultural Residues, 3.G – Liming, 3.H - Urea Application, 3.I - Other Carbon-containing Fertilisers, 3.J - Other agriculture emissions.

Source: UNFCCC 2023.

Opinions on whether the land sector should do more to reduce GHG emissions were divided among stakeholders responding to the Public Consultation questionnaire. On a 5-point scale from 'can reduce little more' (1) to 'can reduce a lot more' (5), on average all respondents found that the land sector could do somewhat more to reduce emissions (Average: 3.96). But civil society organisations (Average: 4.59) and academic/research institutions (Average: 4.28) find that the land sector could contribute much more, while SME's, EU citizens and public authorities assessed the sector's potential for further reduction less positive (Average: 3.53 to 3.81). This divided assessment was also reflected in the question on which sector would achieve climate neutrality first. While about 22% of the respondents believed that the land sector will be the first one to achieve climate neutrality, 30% believed that it will be the last sector, a division presumably due to different expectations about the potential of nature-based removals and the potential to reduce agricultural emissions.

([138]) European Environment Agency, 'Agricultural emissions and projected emissions by EU Member State', https://www.eea.europa.eu/ds_resolveuid/KPQBZ3Y6T9 , 2022.

1.7.2. Activity

1.7.2.1.Mitigation options in the food system

Agricultural and forest land are the two primary users of land in the EU. A conversion of agricultural land has impacts on GHG emissions when forests or grasslands are converted into croplands and carbon stored in vegetation and soil is released into the atmosphere. However, current trends show a positive trend with a slow decline of cropland and a slow increase of forest land.

Implementing sustainable land management practices in agriculture, such as agroforestry, conservation agriculture practices, and proper land-use planning, can help minimise impacts of land use change and deforestation and thus preserving carbon stocks. Promoting carbon farming practices under the Common Agricultural Policy (CAP) and other EU and national programmes with financial incentives to farmers and foresters can enhance practices such as afforestation, reforestation, agroforestry, conservation agriculture practices and soil protection, appropriate peatland management, and sustainable and precision farming, which contribute to carbon removals with the potential to offset agricultural emissions. Throughout a combination of mandatory and voluntatry interventions, Member States planned significative support to farmers in the approved Common Agricultural Policy Strategic Planning Regulation, for the uptake of carbon farming practices, protection of carbon in soil and reduction of emissions.

Livestock production, particularly from ruminant animals like cows, sheep, and goats, is a significant contributor to GHG emissions in the EU's agriculture sector. Ruminant animals produce methane through enteric fermentation, a natural digestive process, responsible for roughly 38% of emissions in the agriculture sector. Additionally, the management of manure from livestock releases methane and nitrous oxide and is responsible for about 13% of emissions throughout the last 10 years (139). Implementing practices such as optimised fodder, feed additives, more favourable animal genetics (140), and improved herd management help reduce enteric fermentation and, consequently, methane emissions from the livestock. Anareobic digestion of manure and other biomass does not only mitigate emissions but also provides a new source of income for farmers (since it produces biogas, which can be recovered and used for energy production or other purposes) and can help to prevent excessive nutrient losses.

Nitrogen fertilisers are widely used in agriculture to enhance crop production. However, the excessive or inefficient application of nitrogen fertilisers leads to the release of N_2O into the atmosphere and losses of other nitrogen components to water and atmosphere. Utilisation of precision agriculture techniques (141), such as site-specific fertiliser management with variable rate distribution techniques, can help optimise fertiliser

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(139) UNFCCC inventory data 2023

(140) Wall, E., Simm, G., & Moran, D. (2010). Developing breeding schemes to assist mitigation of greenhouse gas emissions. Animal, 4(3), 366-376.

(141) for overview on precision agriculture technologies: Balafoutis, A.; Beck, B.; Fountas, S.; Vangeyte, J.; Wal, T.V.d.; Soto, I.; Gómez-Barbero, M.; Barnes, A.; Eory, V. Precision Agriculture Technologies Positively Contributing to GHG Emissions Mitigation, Farm Productivity and Economics. Sustainability 2017, 9, 1339.

application and minimise nitrogen losses, reducing N_2O emissions. Moreover, the use of N_2O stabilisers (142), inhibitors and nitrogen in more complex formulation (such as in organic fertilisers) can enhance fertiliser efficiency and reduce nitrogen losses, ultimately lowering nitrous oxide emissions. With regard to nutrients and the objective to reduce nutrient losses within the EU (143), implementing precision nutrient management and optimising the use of organic fertiliser improves the nutrient cycle and provides co-benefits for environmental protection.

It's worth noting that the effectiveness and feasibility of these mitigation options depends on local conditions, farm-scale factors, and policy support. Ongoing research and innovation play a crucial role in further developing and implementing these technologies to achieve sustainable agricultural practices with reduced emissions.

Importantly, action addressing primary agriculture is necessary to drive down emissions from the food system. But for the EU to achieve climate neutrality in 2050, the food system needs to take action along the entire value chain, which goes beyond primary agriculture and includes secondary agriculture (144), retail, and consumption (145). In other words, the adoption of certain practices and technologies can reduce GHG emissions from agriculture, but reducing food loss and food waste, dietary shifts away from animal protein and use of land resources for nature-based mitigation solutions is unavoidable to get to climate neutrality (146).

1.7.2.2.Sustainable Agriculture and bioeconomy

A living and functioning environment is vital for a functioning and resilient food system. Agriculture needs pollinators, healthy soils and functioning ecosystems. A more sustainable agricultural production will increase resilience and protect the food system in the long term. But sustainable agricultural practices may reduce agricultural intensity and agricultural output, which in turn may affect economic income in the sector. It is therefore important to ensure adequate support and discuss new business models, such as the provision of biogenic carbon as industrial feedstock and the remuneration of ecosystem services as additional income opportunities for European farmers (see Annex 9 for more details).

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(142) Panchasara, H.; Samrat, N.H.; Islam, N. Greenhouse Gas Emissions Trends and Mitigation Measures in Australian Agriculture Sector—A Review. Agriculture 2021, 11, 85.

(143) COM(2020) 381 final.

(144) Secondary agriculture is defined as processing and adding value to the basic agriculture commodities (O'Shea et al. Dietary fibre and phytochemical characteristics of fruit and vegetable by-products and their recent applications as novel ingredients in food products. Innov Food Sci Emerg Technol 2012, 16).

(145) Mc Kinsey & Company, 'The agricultural transition: Building a sustainable future', 2023.

(146) Ibid.

1.7.3. Evolution of emissions without additional mitigation measures

1.7.3.1.S1, S2 and S3 scenarios

In this impact assessment, the concept of “emissions without additional mitigation” in the agriculture sector refers to the emissions trajectory resulting from applying a carbon value equal to zero to non-CO2 GHG emissions up to 2050. Thus, this emissions trajectory results solely from the combination of two main types of drivers for emissions reductions: a) agriculture policy as reflected in the EU Agricultural Outlook 2022 (147); and b) relevant existing and proposed legislation, particularly the proposal for a revised Industrial Emissions Directive (148) (see Annex 11). The “emissions without additional mitigation” do not consider any other policies that would enable the implementation of extra practices and technologies.

In the S1, S2 and S3 scenarios, the GHG emissions without additional mitigation from the agriculture sector are 351 MtCO2-eq in 2040 and 347 MtCO2-eq in 2050 (including all greenhouse gases), which implies a 9% reduction by 2040 and a 10% reduction by 2050 relative to 2015 levels (see Table 14). It should be noted that, in all scenarios, there exists significant additional mitigation potential through different practices and technological solutions. This additional mitigation potential is discussed in Section 1.7.4.

Table 14: GHG emissions in agriculture without additional mitigation in S1, S2, S3

	Greenhouse gas emissions (MtCO2-eq)					Change in emissions (%)		
	2005	**2015**	**2030**	**2040**	**2050**	**2015-30**	**2015-40**	**2015-50**
Agriculture								
CH4	242	237	223	214	213	-6%	-10%	-10%
N2O	138	138	128	127	124	-7%	-8%	-10%
CO2	9	10	10	10	10	3%	3%	3%
Total (all gases)	390	385	361	351	347	-6%	-9%	-10%

Source: GAINS.

1.7.3.2.LIFE scenario

LIFE considers a more sustainable lifestyle guided by consumer climate-friendy choices and a more efficient use of the resources. Besides the impact of the existing policy framework, LIFE assumes changes in the food system in terms of dietary changes, food waste reduction and a gradual implementation by 2040 of the objectives of the Farm to Fork Strategy (149). This leads to changes in sectoral activity (notably in livestock of cattle and other animals as well as in use of manure and mineral fertilisers) compared to the main scenarios (S1, S2 and S3).

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(147) The Agricultural Outlook 2022 is assumed to reflect the Common Agricultural Policy at the time of publication in 2022.; European Commission, DG Agriculture and Rural Development, ‘EU agricultural outlook for markets, income and environment, 2022-2032’, Brussels, 2022.

(148) COM(2022) 156 final. Note that this impact assessment takes into account the changes made to the European Commission’s proposal during the co-decision process up to July 2023.

(149) COM(2020) 381 final.

As a result, assuming no deployment of additional mitigation practices and technologies, the GHG emissions from the agriculture sector are lower in LIFE than in the other scenarios (around 80 MtCO2-eq less, both in 2040 and 2050). More specifically, the level of emissions in LIFE is projected to be around 271 MtCO2-eq in 2040 and 269 MtCO2-eq in 2050 (i.e., 30% lower than in 2015 in both years), as shown in Table 15. Note that both CH4 and N2O emissions are lower than in scenarios S1, S2 and S3; for instance, in 2040, CH4 emissions are 48 MtCO2-eq (22%) lower, while N2O emissions are 32 MtCO2-eq (25%) lower.

Table 15: GHG emissions in the agriculture without additional mitigation in LIFE

	Greenhouse gas emissions (MtCO2-eq)			Change in emissions (%)		Difference compared to S1, S2 & S3 (MtCO2-eq)	
	2015	**2040**	**2050**	**2015-40**	**2015-50**	**2040**	**2050**
Agriculture							
CH4	237	166	167	-30%	-29%	-48	-46
N2O	138	95	92	-31%	-33%	-32	-32
CO2	10	10	10	3%	3%	0	0
Total (all gases)	385	271	269	-30%	-30%	-80	-78

Source: GAINS.

1.7.4. Mitigation potential for non-CO2 GHG emissions

The GAINS model provides marginal abatement cost (150) curves (MACC) for non-CO2 GHG emissions corresponding to the agriculture sector, specified per gas and per type of source, coming on top of the "emissions without additional mitigation" described in Section 1.7.3. Note that the S1, S2 and S3 scenarios are assumed to share the same MACCs, whereas LIFE has scenario-specific MACCs. Figure 81 shows the MACC applicable to the agriculture sector in 2040 in the different scenarios.

For the S1, S2 and S3 scenarios, the maximum abatement potential is estimated to be 83 MtCO2-eq in 2040, which would bring total non-CO2 GHG emissions down to 258 MtCO2-eq (i.e., a level 31% lower than in 2015). A bit more than 25% of this mitigation potential may be tapped at near-zero cost (151), mainly by introducing breeding through selection to enhance productivity, fertility and longevity, and farm-scale anaerobic digestion with biogas recovery, which reduce CH4 emissions. Almost 40% of the maximum mitigation potential could be reached at a marginal abatement cost lower than 20 EUR/tCO2-eq, mainly by using feeding additives that reduce CH4 emissions in addition to the near-zero-cost mitigation options. Finally, around 85% of the maximum mitigation potential can be achieved with a marginal cost lower than 140 EUR/tCO2-eq, mostly by scaling up the use of various mitigation options to reduce N2O emissions (such as nitrification inhibitors and variable rate technology) on top of the options mentioned above.

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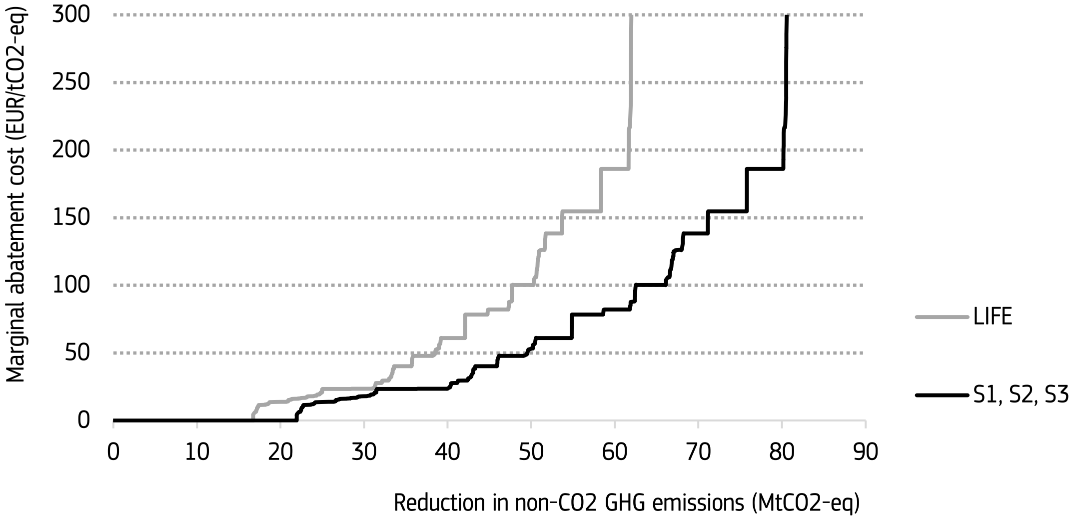
(150) Marginal abatement costs are defined using the *opportunity cost* approach.

(151) Note that even in cases where marginal abatement costs are nearly zero, policy intervention is often needed to overcome market barriers, lack of information and split incentives.

In LIFE, starting with lower emissions than in the S1, S2 and S3 scenarios, the additional mitigation potential for non-CO2 GHG emissions stemming from the deployment of extra mitigation practices and technologies is estimated to be still 64 MtCO2-eq in 2040. Fully reaching this potential would reduce total non-CO2 GHG emissions from the agriculture sector to 198 MtCO2-eq in that year, which implies a 47% reduction relative to 2015.

Figure 81: MACC of the agriculture sector in 2040 per scenario



Note: Marginal abatement costs are expressed in constant EUR 2015.

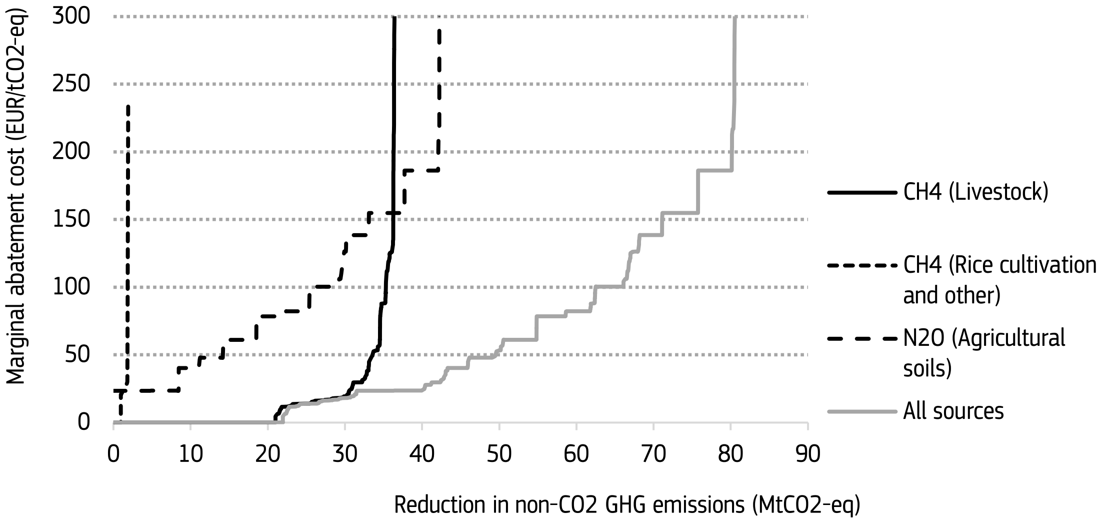
Source: GAINS.

By analysing the additional mitigation potential separately for each gas, one can see that most of the mitigation potential associated to CH4 emissions may be tapped at a relatively low marginal cost; instead, in the case of N2O emissions, higher marginal costs are observed (see Table 16 and Table 17).

For CH4, the abatement potential is mostly linked to mitigation options to reduce livestock emissions, with a small contribution from mitigation options to reduce emissions from rice cultivation and other activities (see Figure 82 and Figure 83). In 2040, the total maximum additional potential to reduce CH4 emissions is 38 MtCO2-eq in the three main scenarios (30 MtCO2-eq in LIFE, which starts from lower emissions). Around 57% of this potential would be accessible at near-zero marginal abatement cost (mainly through breeding through selection to enhance productivity, fertility and longevity, and farm-scale anaerobic digestion with biogas recovery), and 90% could be achieved at a marginal cost lower than 35 EUR/tCO2-eq (by including feeding additives).

For N2O, the abatement potential is entirely linked to mitigation practices and technologies to reduce emissions from agricultural soils, such as nitrification inhibitors and variable rate technology. In 2040, the maximum additional potential to reduce N2O emissions is 44 MtCO2-eq in the three main scenarios (34 MtCO2-eq in LIFE, starting from lower emissions). Around 32% of this potential could be reached at a marginal cost between 25 and 50 EUR/tCO2-eq, while 75% could be reached at a marginal cost below 140 EUR/tCO2-eq and 95% could be reached at a marginal cost below 190 EUR/tCO2-eq.

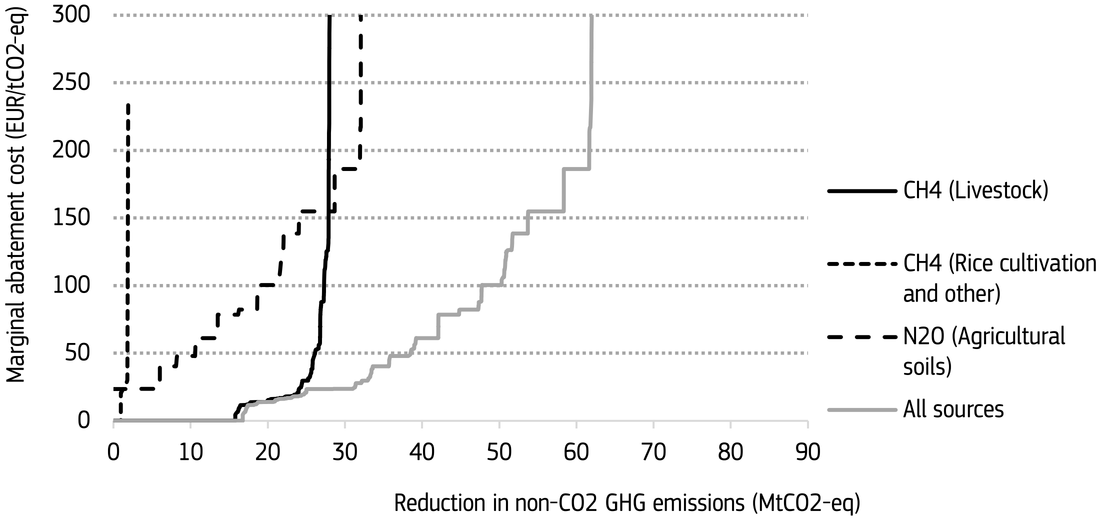
Figure 82: MACC of the agriculture sector in 2040 in S1, S2 and S3 (by gas and area of application)



Note: The MACCs include all non-CO2 greenhouse gases. Marginal abatement costs are expressed in constant EUR 2015.

Source: GAINS.

Figure 83: MACC of the agriculture sector in 2040 in LIFE (by gas and area of application)



Note: The MACCs include all non-CO2 greenhouse gases. Marginal abatement costs are expressed in constant EUR 2015.

Source: GAINS.

Table 16: Mitigation potential in the agriculture sector in S1, S2 and S3

	Marginal abatement cost for non-CO2 GHG emissions (EUR/tCO2-eq)**						
	0*	**0.1**	**10**	**50**	**100**	**300**	**Max**
Emissions mitigation in 2040 (MtCO2-eq)							
CH4 (Livestock)	0	21	22	34	35	36	37
CH4 (Rice cultivation and other)	0	1	1	2	2	2	2
N2O (Agricultural soils)	0	0	0	14	25	42	44
Total	0	22	23	50	62	81	83
Share of maximum mitigation potential achieved in 2040 (%)							
CH4 (Livestock)	0%	57%	59%	92%	97%	100%	100%
CH4 (Rice cultivation and other)	0%	50%	50%	94%	94%	100%	100%
N2O (Agricultural soils)	0%	0%	0%	32%	57%	95%	100%
Total	0%	27%	27%	60%	76%	97%	100%

*Note: *In this table, the non-CO2 GHG emissions at zero marginal abatement cost correspond to the emissions without additional mitigation in 2040. **Marginal abatement costs are expressed in constant EUR 2015.*

Source: GAINS.

Table 17: Mitigation potential in the agriculture sector in LIFE

	Marginal abatement cost for non-CO2 GHG emissions (EUR/tCO2-eq)						
	0*	**0.1**	**10**	**50**	**100**	**300**	**Max**
Emissions mitigation in 2040 (MtCO2-eq)							
CH4 (Livestock)	0	16	16	26	27	28	28
CH4 (Rice cultivation and other)	0	1	1	2	2	2	2
N2O (Agricultural soils)	0	0	0	11	19	32	34
Total	0	17	17	39	48	62	64
Share of maximum mitigation potential achieved in 2040 (%)							
CH4 (Livestock)	0%	56%	58%	93%	97%	100%	100%
CH4 (Rice cultivation and other)	0%	50%	50%	94%	94%	100%	100%
N2O (Agricultural soils)	0%	0%	0%	32%	56%	96%	100%
Total	0%	26%	27%	61%	75%	98%	100%

*Note: *In this table, the non-CO2 GHG emissions at zero marginal abatement cost correspond to the emissions without additional mitigation in 2040. Marginal abatement costs are expressed in constant EUR 2015.*

Source: GAINS.

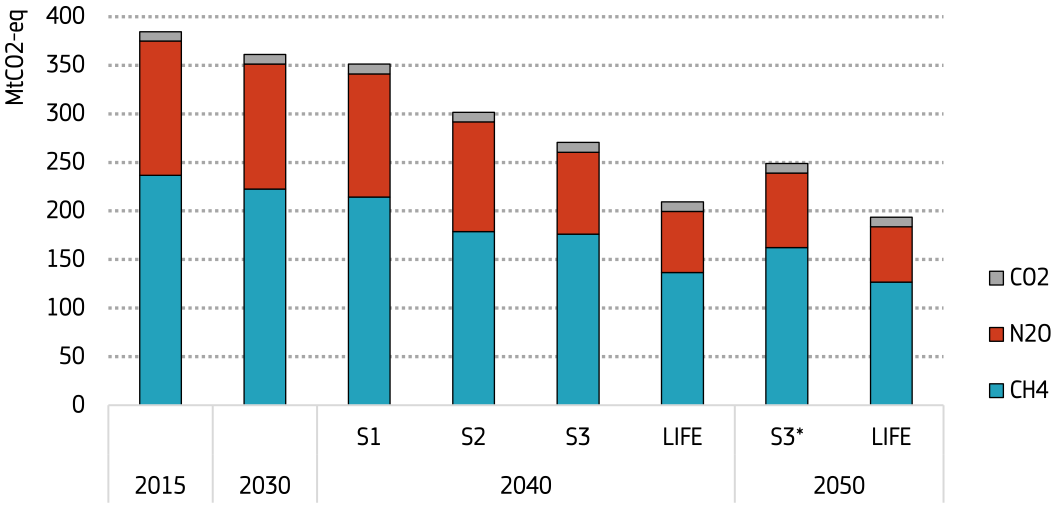
1.7.5. GHG emissions projections

This section presents the agriculture GHG emissions trajectory in each scenario.

Currently, almost all GHG emissions from agriculture that are not related to energy consumption (i.e., all category 3 of the UNFCCC inventory) are CH4 and N2O emissions (see Table 18 and Figure 84). CO2 emissions included in category 3 are very small and are assumed to remain constant at historical level (10 MtCO2). CO2 emissions from agriculture related to energy consumption (i.e., those included in category 1 of the UNFCCC inventory) are not analysed in this section, but in Section 1.1.3.

The S1 scenario assumes that no additional mitigation measures are deployed by 2040. In the S2 scenario, reductions take place, mostly through the deployment by 2040 of technologies reducing CH4 emissions (such as feeding additives, farm-scale anaerobic digestion with biogas recovery, and breeding through selection to enhance productivity, fertility and longevity), while technologies to reduce N2O emissions from agriculture are only partially deployed in 2040. S3 and LIFE assume the full deployment of all additional mitigation measures (including nitrification inhibitors, variable rate technology and restoring drained organic soils) by 2040, thus contributing to the overall net GHG reductions. In modelling terms, the extra mitigation to the baseline is realised through the application of a “carbon value” to GHG emissions applied to the sector (see Annex 6 and previous section on mitigation potential in the sector).

Figure 84: GHG emissions from agriculture by gas



*Note: *In the S1 and S2 scenarios, emissions in 2050 are equal to those in the S3 scenario. **CO2 emissions include only emissions in category 3 (“Agriculture").*

Source: GAINS.

The amount of GHG emissions (152) generated by the agriculture sector in 2040 is projected to be 351 MtCO2-eq in S1 (9% lower than in 2015), 302 MtCO2-eq in S2 (22% lower than in 2015), and 271 MtCO2-eq in S3 (30% lower than in 2015) (see Table 18). LIFE, which combines a different evolution of the food system and the application of technologies, shows a much lower level of emissions (209 MtCO2-eq, i.e., 46% lower than in 2015). In 2050, GHG emissions are projected to reach 249 MtCO2-eq (a 35% reduction relative to 2015) in the three main scenarios, and 194 MtCO2-eq in LIFE (a 50% decrease compared to 2015).

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(152) Including CO2, CH4 and N2O emissions in category 3 of the UNFCCC inventory.

Table 18: GHG emissions from the agriculture sector (by gas and type of source)

	Greenhouse gas emissions (MtCO2-eq)							
	2015	2030	2040				2050	
			S1	S2	S3	*LIFE*	S3*	*LIFE*
Disaggregated per gas								
CH4	237	223	214	179	176	*137*	162	*127*
N2O	138	128	127	113	85	*63*	77	*57*
CO2**	10	10	10	10	10	*10*	10	*10*
Total (all gases)	385	361	351	302	271	*209*	249	*194*
Disaggregated per type of source								
Livestock	244	230	221	188	185	*143*	171	*134*
Agricultural soils	127	118	116	102	74	*55*	66	*49*
Other	13	14	14	12	12	*12*	12	*12*
Total (all sources)	385	361	351	302	271	*209*	249	*194*

*Note: *In the S1 and S2 scenarios, emissions in 2050 are equal to those in the S3 scenario. **CO2 emissions include only emissions in category 3 ("Agriculture").*

Source: GAINS.

The analysis of emissions per type of source shows that, in 2040, GHG emissions caused by **livestock** (which are mostly CH4 emissions ([153])) are projected to be 221 MtCO2-eq (10% lower than in 2015) in the S1 scenario, 188 MtCO2-eq (23% lower than in 2015) in the S2 scenario, and 185 MtCO2-eq (24% lower than in 2015) in the S3 scenario (see Table 18 and Figure 85). In 2050, GHG emissions from livestock are 171 MtCO2-eq (i.e., 30% lower than in 2015) in these three scenarios. These emissions reductions (compared to 2015) are achieved mainly by implementing the following technologies: a) breeding through selection to enhance productivity, fertility and longevity; b) farm-scale anaerobic digestion with biogas recovery; and c) feed additives. Note that, in the S1 scenario, these technologies are only deployed after 2040.

In addition to the implementation of these technologies, LIFE assumes changes in sectoral activity compared to the other scenarios (notably, a decrease in livestock leading to a lower production of manure). As a result, GHG emissions caused by livestock decrease further: they are projected to be 143 MtCO2-eq in 2040 (i.e., 41% lower than in 2015) and 134 MtCO2-eq in 2050 (i.e., 45% lower than in 2015).

GHG emissions from **agricultural soils** (which are entirely N2O emissions ([154])) are projected to be 116 MtCO2-eq in S1 (8% lower than in 2015), 102 MtCO2-eq (19% lower than in 2015) in the S2 scenario, and 74 MtCO2-eq (42% lower than in 2015) in S3 in 2040 (see Table 18 and Figure 85). In 2050, emissions from agricultural soils are 66 MtCO2-eq (48% lower than in 2015) in these three scenarios. These emissions reductions (compared to 2015) are achieved mainly through the large-scale implementation of

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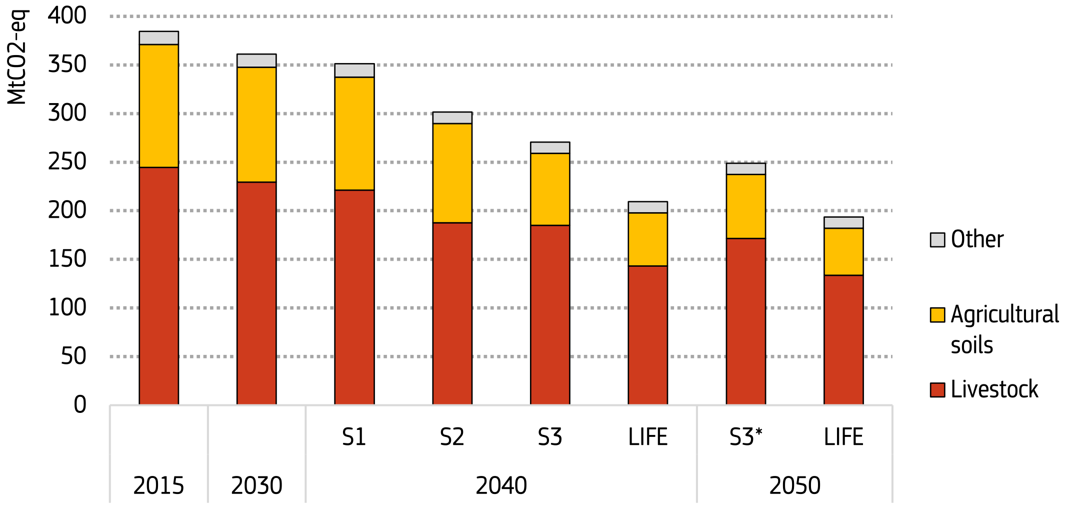
([153]) According to the UNFCCC inventory, around 93% of the GHG emissions from livestock in the EU in 2021 were CH4 emissions, whereas the remainder (7%) were N2O emissions.

([154]) According to the UNFCCC inventory, 100% of the GHG emissions from agricultural soils in the EU in 2021 were N2O emissions.

technologies to improve fertiliser application (notably, nitrification inhibitors and variable rate technology) and by restoring drained organic soils. The S1 scenario assumes that these technologies are only deployed after 2040 (see Annex 6).

In addition to the implementation of these technologies, LIFE assumes changes in sectoral activity compared to the other scenarios, with a decrease in the use of mineral fertilisers. Consequently, GHG emissions from agricultural soils decrease further: they are projected to be 55 MtCO2-eq in 2040 (57% lower than in 2015) and 49 MtCO2-eq in 2050 (62% lower than in 2015).

Figure 85: GHG emissions from agriculture by type of source



*Note: GHG emissions include CO2 (category 3), CH4 and N2O emissions. *In the S1 and S2 scenarios, emissions in 2050 are equal to those in the S3 scenario.*

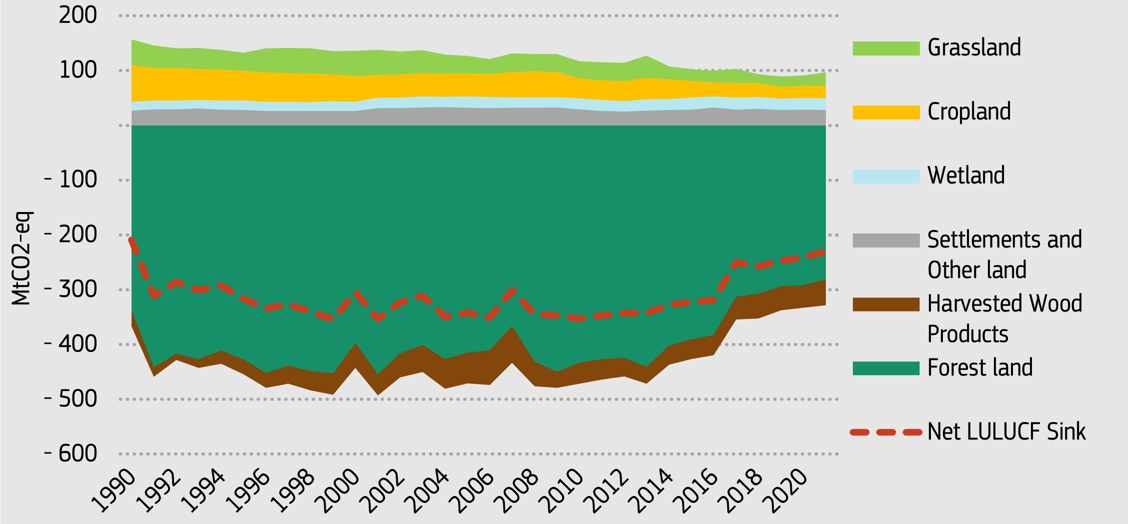
Source: GAINS.

1.8. LULUCF

1.8.1. Introduction

Figure 86 shows the evolution of the EU LULUCF net removals over 1990-2021. They have been on average about -325 $MtCO_2$-eq between 1990 and 2016, and declining since, down to -230 $MtCO_2$-eq in 2021.

Figure 86: Historical LULUCF emissions, removals and net carbon removals



Source: UNFCCC 2023

The LULUCF sector generates emissions from wetland, cropland, and grassland, settlements and other land (69 MtCO2-eq in 2021), which are counterbalanced with removals from forest land (-281 MtCO2) and through harvested wood products (-47 MtCO2).

The different categories show relatively stable development for settlements and other land as well as wetland with changes below 10% throughout the average 2019-2021 compared to 10 years before. Cropland emissions (-44%) and grassland emissions (-36%) decreased considerably and removals from harvested wood products increased at the same time (+26%). However, in absolute terms the change in these sectors plays a minor role with a total change of -38 MtCO2-eq. The changes in forest land are the decisive factor for the change in the net LULUCF net removal with a change of -34% in the last ten years of about -148 MtCO2-eq (average 2019-2021 compared to 10 years before). Ageing forests, increased wood harvest for material and energy purposes, as well as impacts of climate change and natural hazards are responsible for the variations of the carbon removals from forests (155) (156) (157).

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(155) JRC, 'Biomass production, supply, uses and flows in the European Union', *JRC Science for policy report*, 2023.

(156) ICOS ERIC, 'Forest carbon sinks under pressure' *Fluxes - The European Greenhouse Gas Bulletin Volume 2: Nature-based solutions for net zero.* ICOS ERIC, 2023. https://doi.org/10.18160/99JW-2D3S

(157) Ceccherini, G., Duveiller, G., Grassi, G. et al. Abrupt increase in harvested forest area over Europe after 2015. Nature 583, 72–77 (2020). https://doi.org/10.1038/s41586-020-2438-y

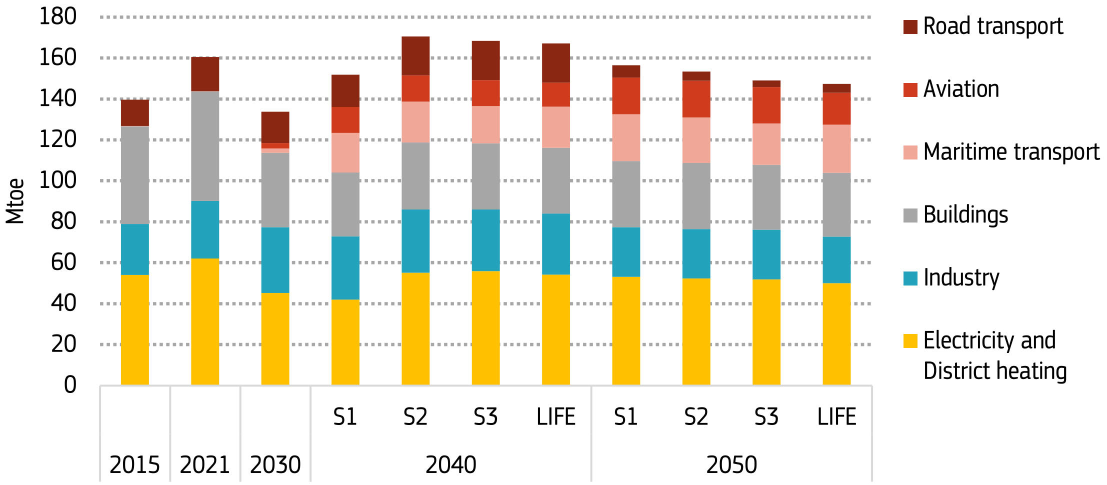
1.8.2. Activity

1.8.2.1.Bioenergy demand

The size of the LULUCF net removals is related to the use of biomass and particularly to the consumption of woody biomass. An important driver for the biomass demand is bioenergy, which made up 22% of the total biomass uses in 2015 ([158]). Furthermore, 49% of woody biomass went directly or indirectly into bioenergy in 2015 ([159]), underlining the strong relation of bioenergy and LULUCF net removals.

The modelling exercise shows final demand for bioenergy ([160]) in 2040 being only sightly higher than in 2021 in scenarios S2 and S3, and lower in scenario S1 (see Figure 87).

Figure 87: Final bioenergy demand by sector and scenario



Note: Graph includes consumption of waste for energy purposes. 'Industry' includes energy sector. 'Buildings' cover household buildings, services, and agriculture.

Source: 2015 and 2021 from Eurostat, projections from PRIMES

However, consumption shifts across sectors. Demand for (mostly solid) biomass for heating reduces strongly in buildings (by about 20 Mtoe, due to energy efficiency gains and electrification of the sector), as well as in electricity and district heating (notably in S1), compared to 2021. Conversely, the demand for (liquid) biofuels develops significantly in aviation and maritime in 2040 by respectively about 15 Mtoe and 20 Mtoe. After 2040, bioenergy demand decreases across all scenarios, which is driven

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([158]) JRC, 'Biomass production, supply, uses and flows in the European Union', *JRC Science for policy report,* 2023.

([159]) Camia, A., Giuntoli, J., Jonsson, K., Robert, N., Cazzaniga, N., Jasinevičius, G., Avitabile, V., Grassi, G., Barredo Cano, J.I. and Mubareka, S., The use of woody biomass for energy production in the EU, EUR 30548 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-27867-2, doi:10.2760/831621, JRC122719.

([160]) "Final" demand for bioenergy includes here bioenergy used in final energy consumption sectors (industry, transport, buildings, agriculture, services), in international aviation and maritime and as input to the electricity and district heating. It does not consider transformation process losses to produce biofuels, biogas or biomethane.

notably by reduced demand in road transport where it gets close to zero in a context of electrification of the vehicles fleet and, although to a lesser extent, in industry where it gets to levels observed in 2015.

Net imports of bioenergy (including solid biomass, waste, and liquid biofuels) are limited to 10-13 Mtoe in 2040 before reducing by 2050, against 9 Mtoe in 2021.

The evolution of bioenergy demand by 2040 towards an increasing role of second generation biofuels converts into higher domestic feedstock supply from lignocellulosic crops (both annual and perennial), while food crops decline. Bioenergy from agriculture residues is expected to also increase reflecting an improved mobilisation of their potential, including manure. S1 shows lower biomass supply needs than S2 and S3 by 2040, reflecting a lower recourse to bioenergy in electricity production and district heating. Woody biomass for bioenergy shows a limited increase to about 25 Mtoe for stemwood (161) and 20 Mtoe for forest residues in 2040, in a context of increasing use of secondary residues and used wood from consumers within the waste category. This has very important implications for the forest sink because primary woody biomass for bioenergy decreases the carbon pool and the LULUCF net removals. Therefore, an increasing use of secondary woody biomass from other uses (bark, secondary residues from material production, recovered post-consumer wood), which substitutes woody biomass coming directly from forests, has an alleviating effect on the LULUCF net removals. In 2040 wood plantations for energy use start to develop and stay stable in size in 2050, which also buffers the required harvest removals for energy use.

The total domestic feedstock for bioenergy and waste (including manure) peaks in 2040, ranging from about 210 Mtoe in S1 to just above 230 Mtoe in S2 and S3. By 2050 the feedstock supply decreases to a level ranging between 200 Mtoe (S3) and 215 Mtoe (S1). (162)

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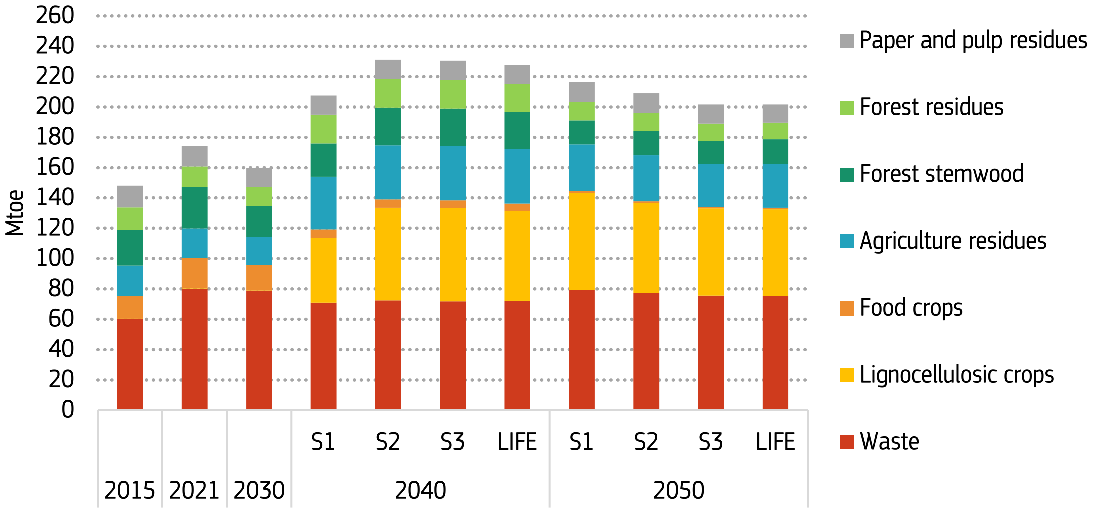
(161) Forest stemwood for bioenergy can be defined as fuelwood and usually consists of roundwood of quality that is in general not suitable for other purposes. It is harvested directly from forests.

(162) Future analyses may assume other supply levels of biomass to stay within the sustainability boundaries, in view of the on-going scientific debate.

Figure 88: Domestic supply of feedstock for bioenergy and waste



Note: 'Lignocellulosic crops' includes short rotation coppice and lignocellulosic grass. Manure is included in 'Waste'.

Source: PRIMES, GLOBIOM

As shown in section 1.1.2, scenario S3 requires more industrial carbon removals by 2040. This scenario may require higher biomass use for BECCS if the deployment of the other key identified option to generate industrial removals, DACCS, would remain limited in the coming 15 years. Section 1.8.4 below provides a sensitivity analysis on the impact of a higher need for biomass on the LULUCF net removals.

1.8.2.2. Bioeconomy demand

Beyond bioenergy, the role of bioeconomy at large will have impacts on the future LULUCF net removals. Notably, a change from short-term to long-term harvested wood products will increase the temporary carbon stock and lead to a temporary increase in the net removals. Hence, whether biomass from harvests is used for long-term harvested wood products such as furniture or woody elements in buildings or whether it is used for bioplastics, paper or single-use products is important as it has implications on the size of the temporary sink from harvested wood products. Annex 9 discusses the need for healthy nature and a sustainable bioeconomy in view of maintaining and enhancing the LULUCF net removals and other nature services.

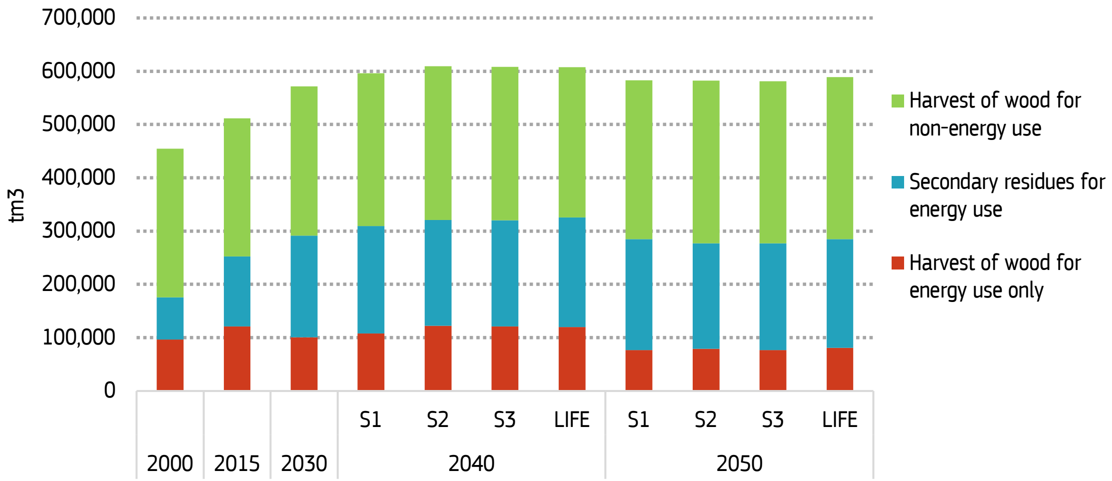
1.8.2.3. Harvest of wood and forest increment

The European forests play a decisive role for the EU LULUCF carbon net removals, as the share from forest land makes up nearly 90% of all carbon removals from the LULUCF sector (see Figure 86). The 'forest sink' depends on the gross annual increment of a forest, the natural mortality and fellings (harvest and logging residues) ([163]). Hence, the demand for woody biomass and the corresponding harvest and overall forest management has a direct impact on the forest sink.

([163]) Korosuo, A. et al., 'The role of forests in the EU climate policy: are we on the right track?', *Carbon Balance and Management*, 18, 15, 2023.

Figure 89 shows the evolution of wood harvest by 2050. Wood production increased significantly since the beginning of this century to satisfy the increasing demand for woody biomass (164). Compared to 2015, total harvest of wood is expected to be higher in 2040 (ranging from 17% in S1 to 19% in S3), and then decline by 2050. The increase is driven by harvest for elevating demand of biomass for material uses, combined with an improved exploitation of secondary residues used for energy purposes, while direct harvest for energy uses is expected to be similar to 2015 or slightly lower (for S1) in 2040 before declining by 2050.

Figure 89: Harvest of wood for energy and non-energy use



Note: "Secondary residues used for energy use" are forest residues that were initially harvested for material use (e.g., from the production of sawnwood) but then used for energy production.

Source: GLOBIOM

The gross annual increment of a forest is the second important factor that determines the forest carbon sink. As an important development, the productivity of the managed forests has peaked, given recent forest management strategies, and given the fact that the increase of the biomass stock in the EU has slowed down in recent years (165). The slower increase of growth productivity (i.e., the annual increment of the forests) is due to the age structure of the forests, which show a slower growing rate at higher ages. As shown in Figure 90, forest increment of managed forest is projected to reach its maximum around 2030 for S1 and around 2040 for S2 and S3 and will then slowly decline. The difference in forest increment between the scenarios in 2040 is caused by different carbon values to cover mitigation costs, which incentivize improved forest management and afforestation in S2 and S3 (see section 1.8.3). In 2050 S1, S2 and S3 use equal carbon values, resulting in the same forest increment. For LIFE the trend looks more optimistic, because a significant share of new land is used for afforestation, which leads to a greater forest increment compared to S2 and S3. In 2050 the discrepancy to the other scenarios becomes even bigger, because additionally afforested trees achieve high growth rates.

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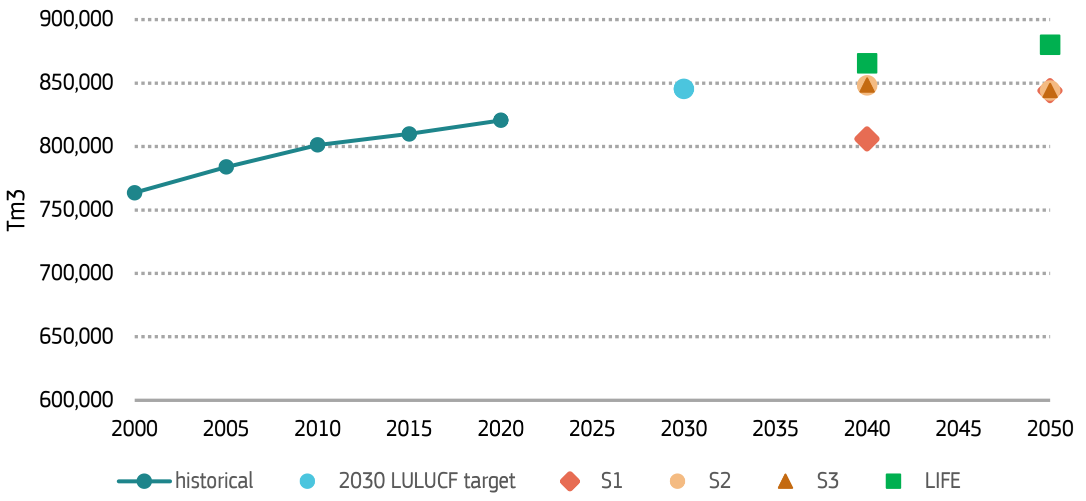
(164) JRC, 'Biomass production, supply, uses and flows in the European Union', *JRC Science for policy report,* 2023.

(165) JRC, 'Biomass production, supply, uses and flows in the European Union', *JRC Science for policy report,* 2023.

Figure 90: Total forest increment of managed forests per year and scenario in EU



Note: The graph depicts the forest increment projections per year for S1, S2, S3 and LIFE. The forest increment does not take natural disturbances or climate change and CO_2 fertilisation effects into account.

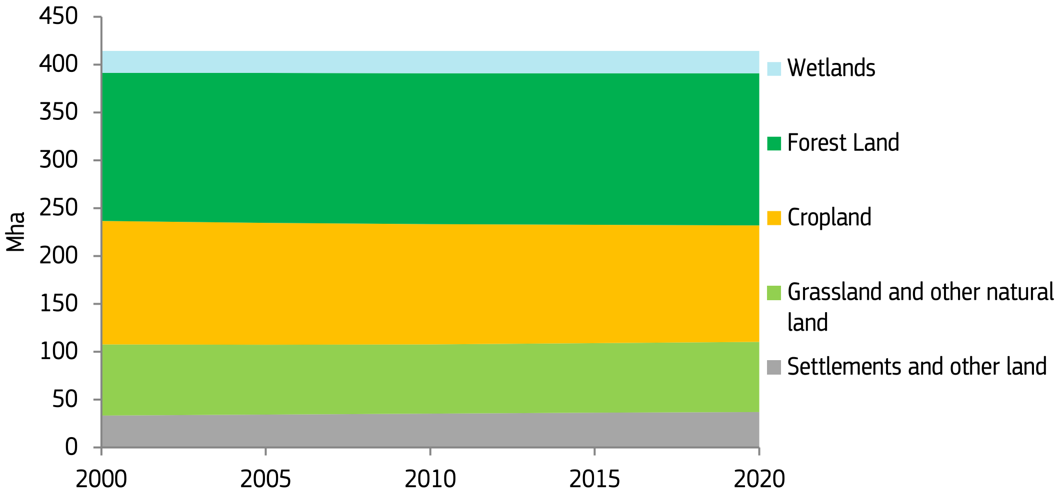
Source: GLOBIOM

1.8.2.4.Land use

The distribution of land for different uses impacts GHG emissions and carbon removals from land but is also influencing the functioning of habitats and ecosystems which play a vital role for biodiversity and climate. The use of land is under high competition in the EU to supply land for food, production of materials, bioenergy, housing and infrastructures, ecosystem services and other purposes. A change in land use for example by reducing the land for settlements or changing land used dedicated to fodder activities for carbon farming activities would reduce emissions or enhance carbon removals and thus have a positive impact on the net removals.

Figure 91 provides an overview of the historic evolution of the land use until 2020. Overall, the share of land use between different sectors appears very stable with a slow increase in managed forest land (+4 Mha) and land for settlements (+3 Mha) and a simultaneous decline of cropland (-7 Mha). The area for settlements has been steadily increasing until today, which is associated with additional emissions.

Figure 91: Evolution of land use in EU by category

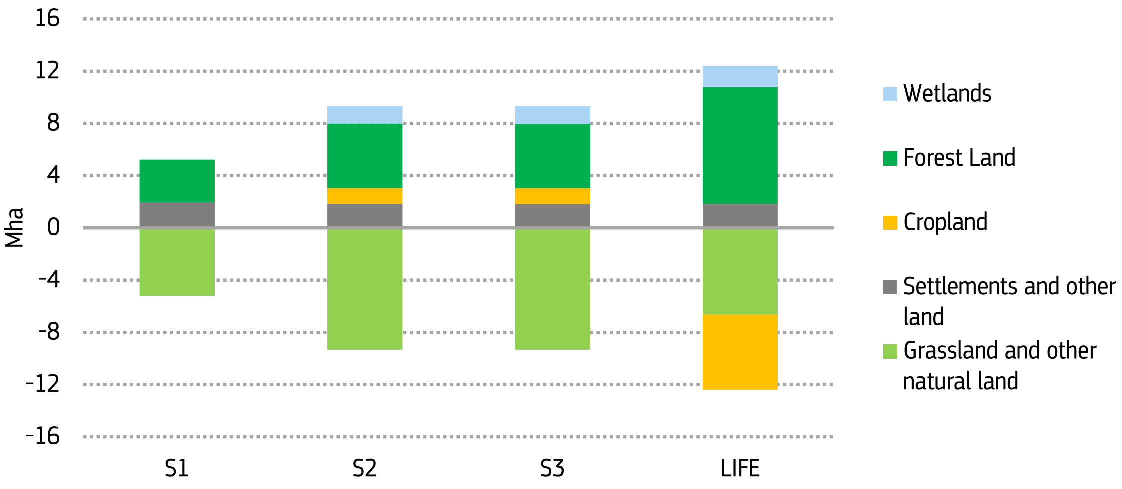


Note: Evolution of land use by land use category from 2000 until 2020.

Source: UNFCCC 2023, GLOBIOM

From 2020 onwards the different scenarios comprise different developments of land use (see Figure 92), although the absolute overall land use changes compared to today remain small in relative terms, which range from 5 Mha (S1) to 9 Mha in S2 and S3 and 12 Mha in LIFE, which corresponds to 1-3% of the total land.

Figure 92: Changes in land use between 2020 and 2040 by scenario



Source: GLOBIOM

Next to the assumed growing land take by settlements (+2 Mha), the land use changes in the scenarios are driven by actions to enhance the LULUCF net removals (166) and changes on energy demand in S2 and S3, which decrease grassland and other natural land

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(166) The scenarios assume a marginal mitigation cost covered for additional nature-based removals of EUR 50 for S2, S3, LIFE and no mitigation costs covered in S1. For details see Annex 6, section 3.2.

by 9.3 Mha in S2 and S3 and by 5.2 Mha in S1 ([167]). This shift translates for S2 and S3 into more land for forests (+4.9 Mha). Furthermore, additional nature-based removals to increase the LULUCF net removal are implemented through restoration of wetlands, which increase by 1.4 Mha in S2 and S3. Very limited land use changes occur in S1 due to no incentives for additional nature-based removals and lower demand for second generation lignocellulosic crops. In S2 and S3 about 1.2 Mha are converted into additional cropland by 2040, while in S1 no additional cropland is converted. The cropland in S2 and S3 increases by about 1% compared to 2020 and is still substantially smaller than the total cropland area during the period of 2000 and 2015.

Throughout the scenarios, financial incentives for nature-based removals have a higher impact on land-use change than a limited use of lignocellulosic crops for bioenergy. Even though from total cropland area, land for lignocellulosic crops requires 7 Mha in S1 and 10.6 Mha in S2 and S3, the overall land-use change impact from crops for biofuels on total cropland is with an increase in cropland of about 1% relatively small ([168]). This is because second-generation lignocellulosic crops replace in 2040 to a large extent cropland from first generation food crops. Lignocellulosic crops for second generation biofuels produce higher yields ([169]) and require less land for the same amount of bioenergy ([170]).

LIFE has significant effects for agricultural land used for livestock and fodder. Because less livestock and therefore less area for fodder is required, intensively managed grassland and cropland from fodder production are abandoned and converted into natural and set aside land partly covered with buffer stripes, hedges and other landscape elements, extensive grassland, and forests. The additional natural land vegetation is accounted in the grassland and other natural land category ([171]). In comparison to S2 and S3, the change in the food system in LIFE lead to additional forest land (afforestation;

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[167] 'Grassland and other natural land' consists of managed pasture land, unmanaged grassland and shrubland. The area of managed pasture land remains relatively stable within the category.

[168] In 2040 total cropland remains unchanged in S1 and increases by 1.2 Mha in S2 and S3, because around 80% of the required area for lignocellulosic crops comes from cropland currently used for first generation biofuels (7.5 Mha) or other cropland (1.9 Mha). The total potential for lignocellulosic crops is however limited. A higher use of biofuels for road transport, maritime transport and aviation than displayed in the scenarios would have a much bigger impact on land use change or food production, because no further areas from first generation lignocellulosic crops could be substituted.

[169] Muylle, H., Van Hulle, S., De Vliegher, A., Baert, J., Van Bockstaele, E., & Roldán-Ruiz, I., 'Yield and energy balance of annual and perennial lignocellulosic crops for bio-refinery use: a 4-year field experiment in Belgium', *European Journal of Agronomy*, 63, 62-70, 2015.

[170] Second-generation biofuel feedstocks often have a higher energy yield per unit of land and water compared to first-generation crops, which means that more energy can be obtained from the same amount of resources, making them more efficient in terms of land and water use. Moreover, these feedstocks are typically non-food feedstocks from energy crops which do not directly compete with food production and can also be produced on marginal lands; Antizar-Ladislao, B., & Turrion-Gomez, J. L. 'Second-generation biofuels and local bioenergy systems.' *Biofuels, Bioproducts and Biorefining: Innovation for a sustainable economy*, 2(5), 455-469, 2008.

[171] Additional land available from fodder production and for livestock is becoming either afforested land or abandoned land with buffer stripes, hedges or other natural vegetation. This abandoned land is attributed here to the UNFCCC grassland sector which also includes shrubland, hence including some woody vegetation. Some changes in LIFE occur within the grassland sector (from productive to unproductive grasslands) and are therefore not visible as change in the overview on land use changes.

+4.0 Mha), more high-diversity landscape features (172) which is natural land partly covered with buffer stripes, hedges, fallow land or other natural vegetation (+6.8 Mha) and rewetted organic soils (+0.3 Mha). LIFE produces land use changes which result in less cropland (-7 Mha) and more grassland (+2.7 Mha) compared to S2 and S3. Lignocellulosic crops require a total area of around 10.2 Mha in 2040. The increase in wetlands is possible, because less fodder production and less requirement for agricultural grassland reduce pressure on the food system and make land for rewetting of dried organic soils cheaper.

1.8.3. Options to increase the net LULUCF net removal

As discussed in previous section 1.1 technical and nature-based carbon removals are an essential part in each scenario to achieve net zero emissions in 2050. The share between technical and nature-based removals may vary depending on the development of prices for industrial carbon removal technologies, nature-based removal options and the saturation effect of the land sink. Hence, although nature-based removals are expected to make up the bigger share of carbon removals, it is not clear which options will be more cost efficient at a certain point in time.

Nature-based removal options in the LULUCF sector include interventions in forests (e.g., reduce deforestation and peatland degradation, afforestation, forest management, peatland restoration) and agricultural soils (e.g., soil organic carbon management, agroforestry) and have different mitigation potentials (173). The costs for different mitigation options are specified as a yearly price per ton CO_2-eq, which are required for the implementation of a certain option. Throughout the public consultation, respondents rated ‘afforestation, reforestation and forest restoration’ as the most relevant solution for limiting climate change (174) (Average: 4.44, on a 5-point scale form ‘very irrelevant’ (1) to ‘very relevant’ (5)), which illustrates the perceived prominent role of forests for climate action among both citizens and organisations. Though other nature-based removals such as peatland restoration (rewetting, revegetating, and paludiculture) (Average: 4.24) as well as Agroforestry and other soil management practices (Average 4.18) were rated second and third among the most relevant solutions for limiting climate change. Thus, nature-based removals in the LULUCF sector are clearly well known and seen as the most promising options throughout the portfolio of mitigation options.

For some nature-based removals to contribute to the long-term enhancement of the LULUCF net removals is a slow process – one that should start now to maximise the 2050 carbon removal potential. However, other options, such as rewetting of peat- and wetlands, quickly reduce emissions, when implemented. Therefore, the mitigation

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(172) Resulting from the goal to return at least 10% of agricultural area under high-diversity landscape features; see COM(2020) 380 final. A share of this natural land is formerly intensively managed grassland which stays within the grassland category.

(173) For an overview of nature-based removals see: Roe, S., Streck, C., Beach, R., Busch, J., Chapman, M., Daioglou, V., Deppermann, A., Doelman, J., Emmet-Booth, J., Engelmann, J., Fricko, O., Frischmann, C., Funk, J., Grassi, G., Griscom, B., Havlik, P., Hanssen, S., Humpenöder, F., Landholm, D., … Lawrence, D., ‘Land-based measures to mitigate climate change: Potential and feasibility by country.’ *Global Change Biology*, 27, 6025–6058, 2021.

(174) Among a range of possible offered options (e.g., Peatland restoration, Agroforestry, BECCS, Bioachar, DACCS, nuclear fusion, solar radiation modification)

potential of rewetting drained organic soils is substantial already in 2030. Forest and agriculture related options can also enhance the LULUCF net removal in the short term but most of their potential plays out in 2040 and 2050. As shown in Figure 93, improved forest management and afforestation, can provide a comparably large mitigation potential already by 2030 and largely to a relatively low price of 20 €/tCO_2-eq ([175]). Similarly, solutions for agricultural land unfold to a large extent as early as 2030, though mitigation costs are much more heterogeneous across the entire spectrum of mitigation options available in the agriculture sector and range from 5 to 150 €/tCO_2-eq. The potential of avoided deforestation is declining and will be almost exhausted after 2050.

Rewetting of drained organic soils makes up about 30% of the total potential for 50 €/tCO_2-eq or 100 €/tCO_2-eq. It provides a high mitigation potential ([176]) ([177]) but also requires substantial investment ([178]). It can be achieved by using appropriate forms of agriculture management such as paludiculture or by completely taking the land out of production. The elevation of water levels (i.e., 'rewetting') reduces emissions that stem from the organic material in these soils. Notably, a high share of today's drained peatlands is used for agricultural purposes, which hampers the peatlands from being rewetted. Thus, an important element for rewetting practices may be a compensation of farmers and landowners when switching to other forms of agriculture (e.g., paludiculture) or abandoning agricultural activity on these soils. Consequently, as shown in Figure 93, mitigation options for organic soils unfold their potential mainly at costs between 50 €/tCO_2-eq and 100 €/tCO_2-eq.

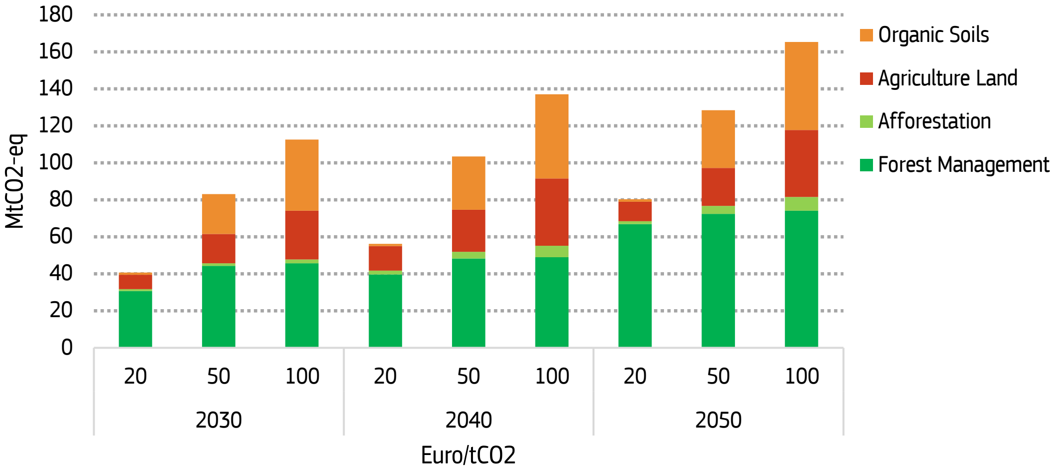
([175]) All mitigation costs to cover for nature-based removals in this section are expressed in EUR 2020 values.

([176]) CH4 emissions on rewetted lands decrease the sink potential of active rewetting activities. CH4 emissions have been included, to avoid an overly optimistic assumption of the potential. However, a high range of uncertainties still exist on CH4 emissions on rewetted lands and therefore the sequestration potential needs to be interpreted with caution.

([177]) Rewetting of drained peatlands overall reduces climate warming despite CH4 emissions. See for details: Günther, A., Barthelmes, A., Huth, V. et al. 'Prompt rewetting of drained peatlands reduces climate warming despite methane emissions', *Nature Communi*cations, 11, 1644, 2020.

([178]) New assumptions on active rewetting and corresponding prices for land acquisition, active rewetting and maintenance have been incorporated for this impact assessment.

Figure 93: Mitigation potentials in LULUCF at different mitigation costs



Note: Nature-based removals show mitigation (including sequestration) potential in $MtCO_2$ by different mitigation costs. Bars show the accumulated additional LULUCF net removal per year with the respective yearly cost. Costs expressed in EUR2020.

Source: GLOBIOM

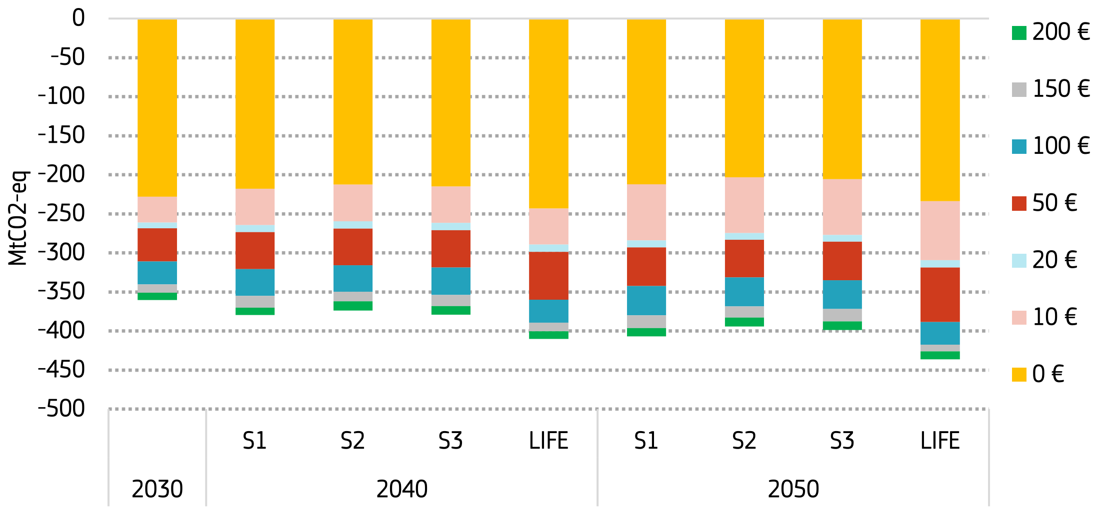
Importantly, many nature-based removals also provide co-benefits for biodiversity as it oftentimes involves a land-use change that can shelter diverse ecosystems and habitats (as in the case of wetlands or when land is converted into primary forest land).

The recently revised LULUCF Regulation sets out a target of -310 $MtCO_2$-eq of net removals ([179]) for the LULUCF sector in 2030 as well as corresponding targets for Member States. The modelling results (see Figure 94) indicate that most mitigation options to achieve this target, are available at low mitigation costs (0-20 €/tCO_2-eq), but some nature-based removals with mitigation costs between 40 and 50 €/tCO_2-eq ([180]) would be required. Implementing these nature-based removal options will also be beneficial beyond 2030 since substantial LULUCF net removals will be required to offset emissions from hard-to-abate sectors in 2040 and 2050.

([179]) See LULUCF regulation: Regulation (EU) 2018/841 (amended by Regulation 2023/839)

([180]) The Impact Assessment accompanying the proposal for a revised LULUCF Regulation indicated that the target of -310 $MtCO_2$-eq could be achieved at lower mitigation costs (5-10€/tCO_2-eq), but the starting point for those assumptions was the average LULUCF sink in 2016-2018 which was much larger than the current trend of the LULUCF sink. More importantly, updated mitigation costs have been taken into account in this impact assessment based on the latest scientific literature.

Figure 94: LULUCF net carbon removal potential for different mitigation costs



Note: Mitigation costs specify the price in Euro per tonne CO_2-eq removed by different nature-based removal options. The columns indicate the additional, marginal potential of nature-based mitigation available for the respective prices. Costs expressed in EUR2020.

Source: GLOBIOM

LIFE produces a consistently higher potential of carbon removals compared to S1, S2 and S3. This is because the agricultural area that is freed up in this scenario is expected to be used in part for carbon farming activities.

1.8.4. The LULUCF net removal

1.8.4.1.Analysis of the scenarios

The 2030 LULUCF target of -310 MtCO2-eq ([181]) is met by applying a carbon value of 50 €/tCO_2-eq ([182]). The exact size of the future level of LULUCF net removals bears many uncertainties, depending on the effect of future policy measures in the sector, potential additional nature-based carbon removals through certification schemes, climate change impacts, extreme events, biomass demands, resulting harvesting levels and other factors. A range for the LULUCF net removals is introduced in the analysis to illustrate this uncertainty for the period after 2030, by looking at three levels of net removals:

- A ‘lower level’, showing a lower boundary for the LULUCF net removals, which is technically implemented in the modelling by applying in the modelling a carbon value of 0 €/tCO_2-eq;
- A ‘central level’, showing the resulting net LULUCF removals when applying the carbon value of 50 €/tCO_2-eq necessary to meet the 2030 target;

([181])Regulation (EU) 2018/841 (amended by Regulation 2023/839)

([182]) In EUR 2020. The carbon value per tCO_2-eq are calculated as a yearly cost for mitigation. In the following only the marginal carbon values are specified, which means large shares of additional nature-based removals are available at lower costs (see previous section for details).

- An ‘upper level’, showing an upper boundary of the LULUCF net removals, which is technically implemented in the modelling by applying a carbon value of 200 €/tCO_2-eq (which translates into higher net removals than in the “central” level).

To calculate the overall net GHGs of the scenarios across the economy (see section 1.1), the “Central” level of net LULUCF removals is applied for all scenarios in 2040 and 2050, except for S1 in 2040, which applies the “Lower level”.

Figure 95 provides an overview of the LULUCF emissions and removals and the corresponding evolution of the central level as well as the range (i.e., lower and upper level) of the LULUCF net removals for the different scenarios. The difference across scenarios in terms of energy demand translate in differences into forest sink levels as well as different emission levels in cropland. Carbon stored in harvested wood products, and emissions from grassland, settlements and other land, as well as from drained wetlands remain fairly similar across scenarios.

S2, and S3 show very similar net removal levels in 2040 of about -320 MtCO_2-eq. S1 shows much smaller net removals in 2040 of about -220 MtCO_2-eq due to less nature-based removals from cropland, grassland, and forest land. Furthermore, S2 and S3 show higher removals from cropland due to more plantation of lignocellulosic crops in 2040 (183).

2050 illustrates a general increase in the net removals across all scenarios by roughly 15 MtCO_2-eq (S2, S3) to 120 MtCO_2-eq (S1), reaching -330 to -340 MtCO_2-eq. Despite this average increase by 2050, the range illustrates that the net removal depends considerably on the capacity of policies to safeguard the net removal to fall below the 2030 target or, conversely, to deliver a stronger contribution towards climate neutrality up of about -400 MtCO2-eq.

LIFE produces a higher LULUCF net removal, because agricultural land is converted into high-diversity landscape elements covered with buffer stripes, hedges and other landscape elements or provided for carbon farming activity (afforestation) which allows for a considerable increase in the forest sink (30 MtCO_2-eq) and decreases net emissions on agricultural land (15 MtCO_2-eq). The net effect for the LULUCF net removal in LIFE is approximately -45 MtCO_2-eq.

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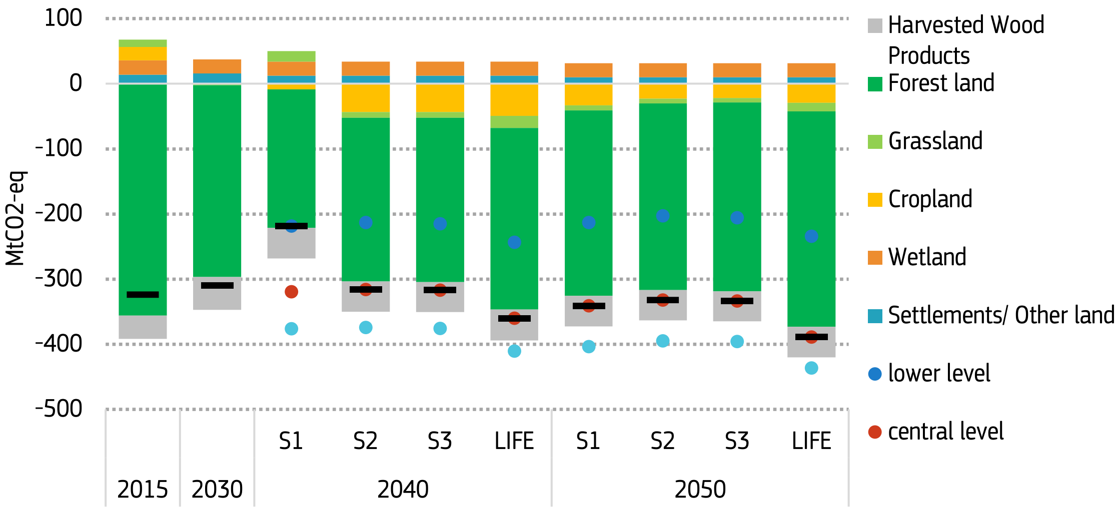
(183) Lignocellulosic crops create a singular short-term sink effect, when being planted the first time. This growing carbon stock is resulting in carbon removals in cropland starting by 2035 is fading out by 2050 when the carbon pool through these crops has been saturated and no additional carbon removal is achieved. This temporary sink is therefore not a reliable source for the LULUCF sink in the long term. S1 uses less lignocellulosic crops for biofuels compared to S2 and S3.

Figure 95: LULUCF net removal emissions and removals



Note: Emissions and removals include all GHG-emissions from the LULUCF sector and are reported in MtCO2-eq. For the calculation of LULUCF net removals of the scenarios in 2040, S1 considers the "lower level", while S2 and S3 the "central level". All scenarios consider the "central level" in 2050.

Source: UNFCCC 2023, GLOBIOM

The ESABCC analysis defines an environmental risk level of 400 $MtCO_2$ per year as a maximum net removals level by 2050 (184). All scenarios analysed in this impact assessment stay below this environmental risk level.

A complementary analysis scenario S2 was run with the JRC forest sector carbon model (FSCM) to crossvalidate the level of the forest sink and the temporary sink of harvested wood products (HWP), which are the main drivers of the LULUCF removals. The results show similar results across both models for these two major carbon removals categories (185) in the LULUCF sector throughout the period with somewhat higher projections of net removals with the FSCM for 2040: FSCM projects -334 $MtCO_2$-eq in 2030 (compared to -345 $MtCO_2$-eq in GLOBIOM model), -331 $MtCO_2$-eq in 2040 (compared to -298 $MtCO_2$-eq in GLOBIOM model) and -347 $MtCO_2$-eq in 2050 (compared to -333 $MtCO_2$-eq in GLOBIOM model).

1.8.4.2.Sensitivity of the LULUCF net removals to woody biomass use

The scenario S3 relies significantly more than S1 and S2 on industrial carbon removals from DACCS and on e-fuels, two novel technologies with uncertain deployment

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(184) This risk level was based on research by Pilli et al. (2022) who provide as a probable range of -100 to -400 $MtCO_2$-eq for the LULUCF net removals in 2050 taking future climate change impacts based on RCP 2.6 into account. Scenarios exceeding the upper bound of -400 $MtCO_2$-eq may rely on implausibly high LULUCF net removal levels.

(185) Carbon removals from Forest land and harvested wood products from both models are compared against each other in an aggregated form because neither of the two subcomponents deviated systematically from that aggregate. The numbers are missing emissions from other lands and do not show the total LULUCF net removal. The GLOBIOM model numbers derive from the central level LULUCF case with a carbon value of 50 €/tCO2, the JRC FSCM does not make these assumptions and assumes a market-driven process.

prospects, which could be substituted by biomass-based options (respectively BECCS and 2nd generation biofuels).

To assess the risks for LULUCF net removals from a higher uptake of biomass, a sensitivity analysis was produced with the GLOBIOM model based on the scenario S3 simulating a higher demand of 20 Mtoe of woody biomass, to showcase the worst possible impact on the LULUCF net removals. The increased demand of woody biomass results in a decrease of the LULUCF net removals by around 100 $MtCO_2$-eq in 2040, and around 65 $MtCO_2$-eq in 2050. However, if additional biomass would originate from other sources such as secondary residues, used wood products, lignocellulosic crops, or other waste, the impact on the sink would be much more limited. Still, the analysis shows that the mitigation obtained from a high use of bioenergy, associated to for instance BECCS, needs to be compared with the possible corresponding losses in the LULUCF net removals (186) (187), depending on the biomass type.

1.8.5. *Analysis of climate change impacts and CO2 fertilisation*

Increasing climate change and GHG emissions have the potential to affect the LULUCF sector, both in a negative (e.g., from lower rainfall, natural disturbances, extreme heat) and beneficial way (e.g., from CO_2 fertilisation, extended growing seasons) (188). What remains certain however is that the forest net removals are threatened by climate impacts and their future robustness is far from guaranteed. Hence, there exist large uncertainties on the future capacity of the LULUCF net removal due to the complex impacts of both human and natural drivers. Consequently, high uncertainties in current and future levels of nature-based carbon removals mean that it may not be precisely known if the LULUCF net removal is on track to match the required size in the scenarios (189). It is important to stress that water availability plays a crucial role for EU's forests. It appears that impact of climate change on forest productivity depends strongly on water availability (190) (191). While the impact of climate change on precipitation levels can be

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(186) Because the model assumes only sustainable harvest, yearly harvesting levels cannot exceed the yearly increment from growth. The higher bioenergy demand therefore leads to price feedbacks on biomass for materials, leading to a decline in material demands for harvested wood products.

(187) Merfort, L., et al., 'Bioenergy-induced land-use-change emissions with sectorally fragmented policies' Nature climate change, 2023

(188) It should be noted that the valence of an impact depends on different factors and therefore even natural disturbances may have long-term beneficial effects for the sink. Thus, the listed examples only illustrate the standard case.

(189) Smith, S. M., Geden, O., Nemet, G., Gidden, M., Lamb, W. F., Powis, C., Bellamy, R., Callaghan, M., Cowie, A., Cox, E., Fuss, S., Gasser, T., Grassi, G., Greene, J., Lück, S., Mohan, A., Müller-Hansen, F., Peters, G., Pratama, Y., Repke, T., Riahi, K., Schenuit, F., Steinhauser, J., Strefler, J., Valenzuela, J. M., and Minx, J. C. (2023). The State of Carbon Dioxide Removal - 1st Edition. Available at: https://www.stateofcdr.org

(190) Pastor, J., & Post, W. M. (1988). Response of northern forests to CO2-induced climate change. Nature, 334(6177), 55-58.

(191) Ruiz-Benito, P., Madrigal-Gonzalez, J., Ratcliffe, S., Coomes, D. A., Kändler, G., Lehtonen, A., ... & Zavala, M. A. (2014). Stand structure and recent climate change constrain stand basal area change in European forests: a comparison across boreal, temperate, and Mediterranean biomes. Ecosystems, 17, 1439-1454.

modelled, it is difficult to assess the full impact of climate change on regional water availability including groundwater levels because of high cascading uncertainties.

To assess these uncertainties, climate change impacts of different warming potentials were modelled in GLOBIOM, taking different drivers such as an increase of CO2, extended growing seasons, a higher frequency of natural disturbances and changing precipitation levels into account ([192]). Starting from the evolution of LULUCF net removals in absence of dedicated policies, two different representative concentration pathways for GHG concentrations (RCPs) 2.6 and 7.0 are used to illustrate the range of impacts through different levels of global warming ([193]), and four different climate models were used per RCP to estimate the range of possible outcomes ([194]). Furthermore, because the magnitude of the CO2 fertilisation effect on forest growth is still part of a scientific debate ([195]) ([196]), the eight trajectories are assessed both with and without persistent CO2-fertilisation. To illustrate the entire range of uncertainty, all 16 climate impact trajectories entail an additional soil related range due to uncertainty of the to heterotrophic respiration (i.e., soil, deadwood and litter decomposition rates), which vary by different degrees of climate change ([197]).

Even though climate change impacts vary on the different activities such as forest management, cropland management, grassland management, and harvested wood products the most severe impact is on forests and to a lesser extent on harvested wood products. The impact on forest depends on several factors such as the species used in forests, water availability in different regions, and CO_2 fertilisation.

Figure 96 shows a very wide range for the EU LULUCF net removal due to the effects of climate change. The range shows a deviation from the standard projection in 2040 by 68

([192]) As factors were considered climate change impacts (temperature, precipitation, vapor pressure deficit), increased in damage of wood due to natural disturbances (wind damage, fire, and instect damage) as well as CO2 fertilisation.

([193]) RCP 2.6 is associated with a best estimate long-term temperature increase until 2100 of 1.8°C, therefore assuming coordinated global action to keep climate change below 2.0°C. RCP 7.0 represents a medium-to-high end of range of emissions and associated global warming, associated to a baseline outcome rather than ambitious climate action on a global level and results in 3.6 °C long-term temperature increase until 2100.

([194]) UKESM1-0-LL - The UKESM1.0-N96ORCA1 climate model run by the Met Office Hadley Centre, UK; IPSL-CM6A-LR - The IPSL-CM6A-LR climate model run by the Institute Pierre Simon Laplace, France; GFDL-ESM4 - The GFDL-ESM4 climate model run by the National Oceanic and Atmospheric Administration, Geophysical Fluid Dynamics Laboratory, USA; MPI-ESM1-2-HR - The MPI-ESM1.2-HR climate model run by the Deutsches Klimarechenzentrum, Germany

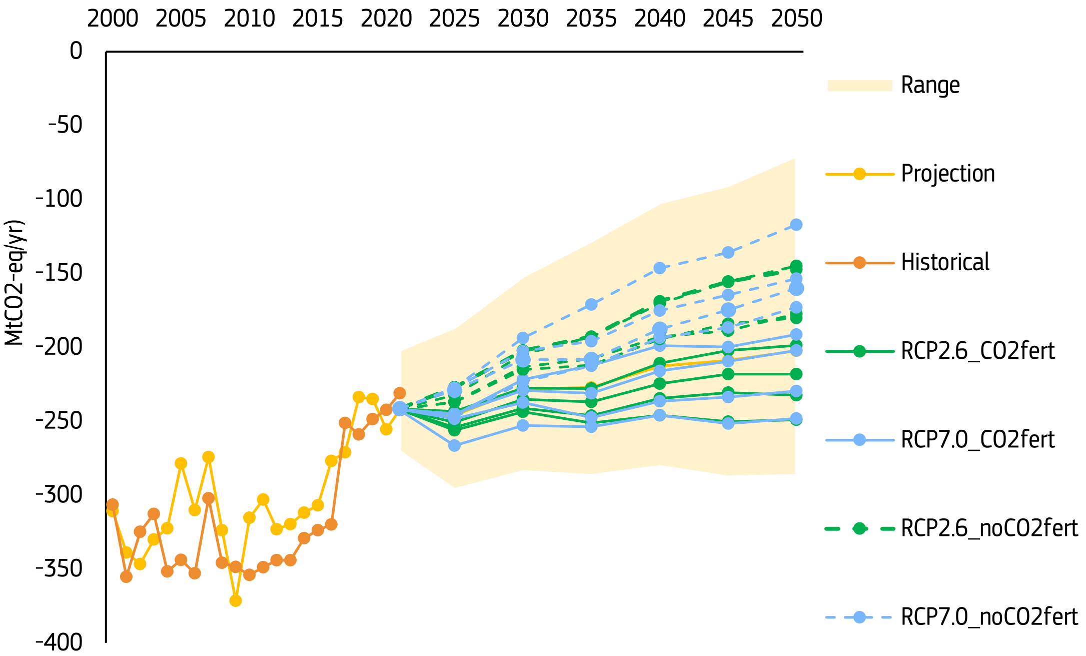
([195]) Jiang, M., Medlyn, B.E., Drake, J.E. et al., 'The fate of carbon in a mature forest under carbon dioxide enrichment', *Nature,* 580, 227–231, 2020.

([196]) Haverd, V., Smith, B., Canadell, J.G., Cuntz, M., Mikaloff-Fletcher, S., Farquhar, G., Woodgate, W., Briggs, P.R. and Trudinger, C.M., 'Higher than expected CO2 fertilization inferred from leaf to global observations', *Global Change Biology*, 26,4, 2390-2402, 2020.

([197]) The uncertainty is caused by changes in mortality and foliage/root turnover rates, as well as the influence of temperature and precipitation on the decomposition rates of these carbon pools. The different climate change trajectories entail different rates of carbon input to the soil (due to changes in forest dynamics) and different decomposition rates of deadwood, litter and soil carbon, resulting from changes in temperature and precipitation.

$MtCO_2$-eq to the upper bound (maximum net removals level) and 111 $MtCO_2$-eq to the lower bound (minimum net removals level). In 2050 the unsecurity increases further, resulting in a range with a deviation of 84 $MtCO_2$-eq to the upper bound and 133 $MtCO_2$-eq to the lower bound. Hence, depending on RCP, climate model and CO2 fertilisation, the analysis projects for 2050 a possible range of net removals between roughly -70 $MtCO_2$-eq and -290 $MtCO_2$-eq (in absence of additional LULUCF policies). The finding is corroborated by other analyses ([198]) and also roughly concurs with the identified range of -100 to -400 $MtCO_2$-eq for the LULUCF net removal by 2050, as mentioned by the ESABCC, when taking future impacts of climate change into account.

Figure 96: Estimated climate change impacts on LULUCF net removal in EU



Note: The graph displays a model-based projection of the development of the LULUCF net removal in absence of dedicated mitigation policies [lower level]. The historical trajectory shows the historical inventory data based on UNFCCC 2023. and the 'projection' shows the trajectory of the LULUCF net removal without considering the impact of climate change. The different 16 trajectories show RCP 2.6 vs. 7.0 (2) X different climate models (4) X CO2 fertilisation vs. no fertilisation (2). The range illustrates the uncertainty due to climate change impacts across all trajectories including uncertainty on carbon storage in soils.

Source: GLOBIOM, UNFCCC 2023

Taking a closer look at the individual climate scenarios, one can see the important role of CO2 fertilisation ([199]) and its potential impact on the EU-wide LULUCF net removals. When considering no effect from CO2 fertilisation, all scenarios show a decline in the LULUCF net removals. When including assumptions on effective CO2 fertilisation, the

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[198] For example: Pilli, R., 'The European Forest carbon budget under future climate conditions and current management practices', *Biogeosciences*, 19, 3263–3284, 2022.

[199] There is a high confidence among the scientific community of the existence of a positive effect of CO2 fertilisation and extended growing seasons on forests. However, uncertainty remains on the on the size of the effect, IPCC, Summary for Policymakers. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems, 2019.

scenarios show predominantly an increase in the LULUCF net removal in both RCPs. This is because the fertilization effects of increased atmospheric CO_2 lead on average to an increase in forest productivity in future climate scenarios. Considering regional variations in climate change effects, the highest gains occurred in the boreal zone, especially central Sweden and Finland, as well as montane areas in central Europe. Mediterranean forests displayed decreases in standing stocks compared to the reference climate, due to the increase in aridity in the region, with lower precipitation and higher temperatures. Hence, it should be noted that the CO2 fertilisation effect varies between tree species and regions.

1.8.6. Impacts from simulated extreme events on the LULUCF net removal

European forests are vulnerable to a variety of disturbances such as windstorms, forest fires, pest attacks, and water scarcity. Climate change is closely linked to these disturbances in Europe, making them more frequent and more severe (200). The hotter and drier conditions in the future due to climate change, the more drought and fire disturbances are expected to increase across Europe, especially in the Mediterranean areas (201). The last decades brought a variety of extreme events with 2022 showing the second largest wildfire burnt area on record in Europe with a total of 900 000 ha burnt across EU countries (202) and unprecedented droughts since 2018 leading to large outbreaks of bark beetles in Northern and Central Europe. Importantly, different regions within the EU are not expected to be affected similarly by the same type of disturbances. General hotspots of damage may be located in Scandinavia and mountain forests of Central Europe, which are particularly exposed to the impacts of winter storms, leading to higher risk of wind damage in forests (203). Modelling results also point to future damage hotspots in Portugal, Spain, southern France and Greece corresponding to regions with high wildfire activity in recent years. Annex 7 provides a more in-depth analysis on how disturbances affect different regions.

While climate change impacts including the increase of natural disturbances unfold their detrimental effects evenly in the mid- and long-term, extreme wheather events have an uneven and short-term impact on net removals from the LULUCF sector in general and on the forest sink in particular. In other words, these exceptional events add an additional layer of uncertainty on the evolution of forest stocks particularly for individual member states.

To illustrate the potential impacts for the LULUCF net removal, the year 2035 is simulated as a year with exceptional weather events resulting in a combination of fire, wind and biotic damages that occur across different regions across the EU (see Figure 97).

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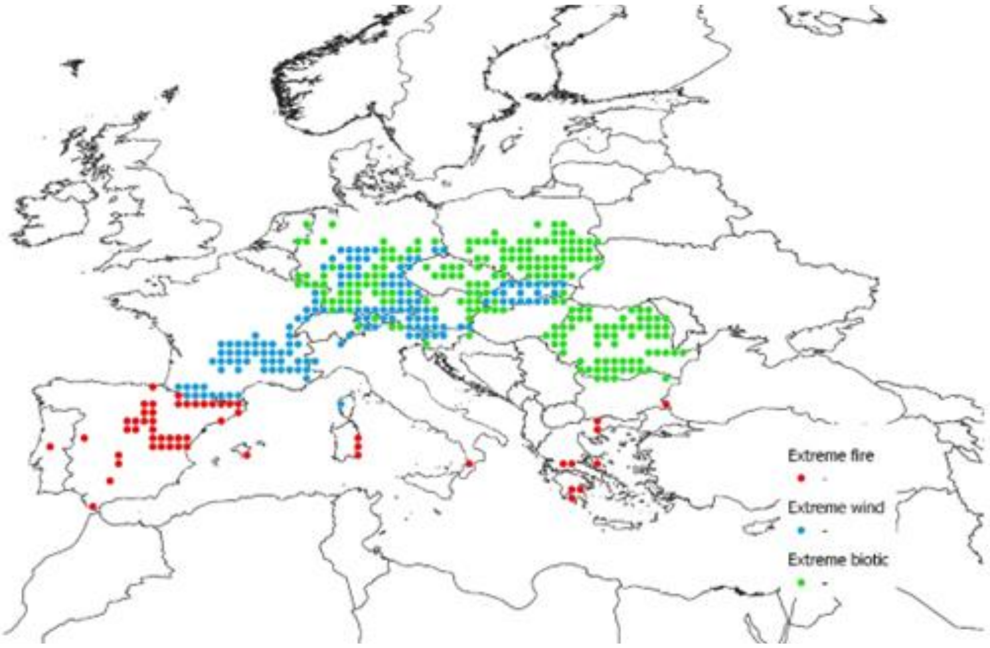
(200) Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., ... & Reyer, C. P., ‘Forest disturbances under climate change’, *Nature climate change*, 7(6), 395-402, 2017.

(201) Asensio, D., Zuccarini, P., Ogaya, R., Marañón-Jiménez, S., Sardans, J., & Peñuelas, J., ‘Simulated climate change and seasonal drought increase carbon and phosphorus demand in Mediterranean forest soils’, *Soil biology and biochemistryä*, 163, 108424, 2021.

(202) Copernicus Climate Change Service, ‘European State of the Climate Summary 2022’, 2022.

(203) corroborating with the results (Laurila et al. 2021)

Figure 97: Area coverage of simulated series of extreme events in 2035



Note: The graph shows the distribution of the different disturbance agents (extreme fire, extreme wind and extreme biotic disturbance) across the EU from the simulated extreme events.

Source: GLOBIOM

To model the damage on forests, historically the worst wind, fire, and biotic events over the period 1990-2020 for each disturbance agent were selected (204). The approximate damage from these events (205) is simulated to affect the most vulnerable forest stands across the EU (see Figure 97). In the simulation the Mediterranean region is strongly affected by extreme fires, while large parts of central Europe are affected by extreme wind and biotic events causing in total more than 300 000 000 m³ of forest damage. It is important to note, that the model assumes that salvage logging and replanting of the damaged trees occur the same year as the disturbance and that they predominantly affect more vulnerable older and larger trees, which are then salvage logged to the extent possible (206). Consequently, a partial compensation of the disturbance-induced forest loss through reduced harvesting rates is assumed. Thus, the simulation entails the assumption of an ideal environment for the recovery of the carbon pool and the LULUCF

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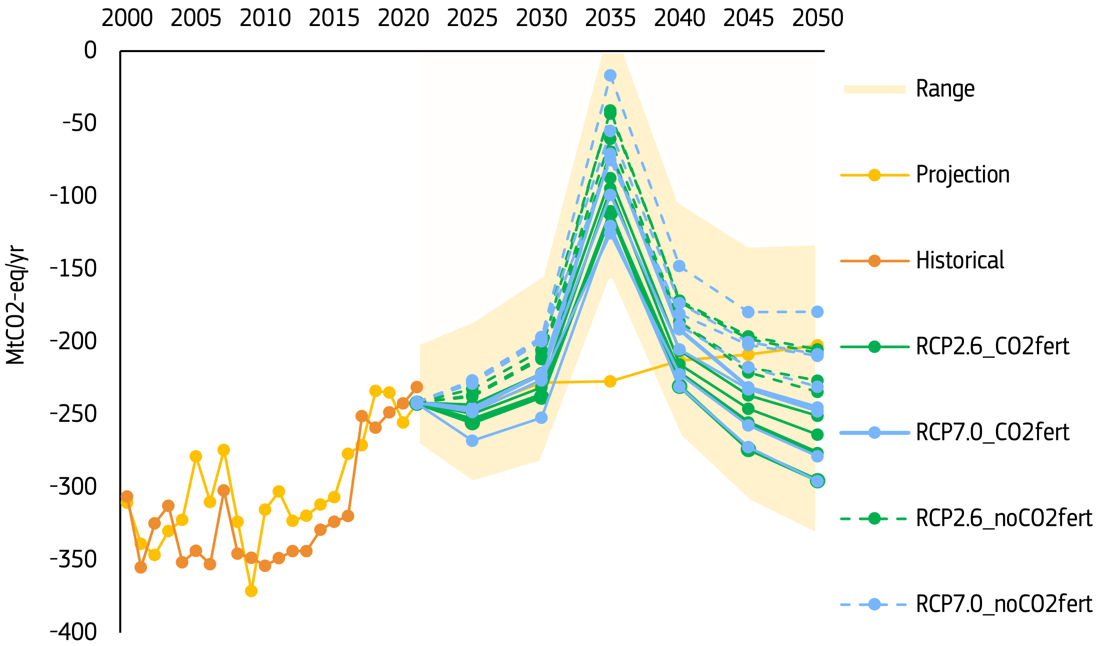
(204) Patacca, M., Lindner, M., Lucas-Borja, M. E., Cordonnier, T., Fidej, G., Gardiner, B., Hauf, Y., Jasinevičius, G., Labonne, S., Linkevičius, E., Mahnken, M., Milanovic, S., Nabuurs, G.-J., Nagel, T. A., Nikinmaa, L., Panyatov, M., Bercak, R., Seidl, R., Ostrogović Sever, M. Z. … Schelhaas, M.-J. 'Significant increase in natural disturbance impacts on European forests since 1950', *Global Change Biology*, 29, 1359–1376, 2023.

(205) In total, 333,066,346 m³ of forest are damaged in the simulation, wind damages 228,520,374 m³, biotic agents 77,828,111m³, and fire 26,717,862 m³ of forest wood.

(206) Disturbances usually damage older and larger trees, therefore, the extreme disturbance event eliminates a considerable amount of older trees, shifting the age structure of the damaged forest and enhancing forest regrowth. The model assumes that 86% of wood damaged by wind, 72% of wood damaged by biotic and 54% of wood damaged by fire, is harvested. The rest of the damaged wood is becoming deadwood and litter when disturbed by wind or biotic agents, while for wildfires about 10% of merchantable wood and 22% of litter and deadwood are burnt.

net removals. If these conditions are not met in a real event, the recovery of the LULUCF net removals might significantly impeded. The extreme events will cascade not only to the European forest carbon pool, but also to wood processing industry and markets, via changes in wood supply and market shocks (207).

Figure 98: Estimated climate change impacts and extreme events on LULUCF net removal



Note: The graph displays a model-based projection of the range of the LULUCF net removal under impacts from climate change and simulated extreme events. The 'historical' trajectory shows the inventory data based on UNFCCC 2023, the 'projection' shows the trajectory of the lower boundary of the LULUCF range (lower level net removal) without impacts from climate change and extreme events. The different 16 trajectories show RCP 2.6 vs. 7.0 (2) X different climate models (4) X CO2 fertilisation vs. no fertilisation (2). The range illustrates the range of uncertainty due to climate change impacts across all trajectories including uncertainty due to soil carbon removals. In 2035 a series of extreme events is simulated to illustrate its impact on the LULUCF net removal.

Source: GLOBIOM, UNFCCC 2023

In Figure 98 the impacts of a series of possible extreme events in one year for the LULUCF net removal are depicted through an uncertainty range that takes climate change impacts into account. The net removal level of the LULUCF sector drops to a range between -160 and +30 MtCO$_2$-eq at the time of the disturbance but recovers relatively quickly in the next 5 years (-105 to -265 MtCO$_2$-eq). Over the next 15 years the simulation provides a slightly higher range for the LULUCF net removals in 2050 (-130 to -330 MtCO$_2$-eq) than a scenario without extreme events (-70 to -285 MtCO$_2$-eq; see previous section), because of the enhanced forest regrowth of younger trees and under the assumption of immediate reforestation.

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(207) Gardiner, B., Schuck, A. R. T., Schelhaas, M. J., Orazio, C., Blennow, K., & Nicoll, B. (Eds.). 'Living with storm damage to forests', Vol. 3, pp. 129-p, Joensuu: European Forest Institute, 2013.

However, it should be noted that the modelling of such extreme events is at an early stage of development and assumptions on the severity of events, the share of wood that can be harvested after the event and replace otherwise planned harvests, the speed of forest recovery (i.e., cleaning and replanting), is critical for the outcome. For example, salvage logging preparation for replanting and afforestation may take several years due to lack of capacity, which will delay the forest recovery and consequently its capacity as a carbon removal. Furthermore, the range of uncertainty illustrates, that even when taking properly the development of the LULUCF net removal and climate change impacts into account, disturbances can disrupt the net carbon removal levels for years.

1.9. Environmental and health impacts

In addition to reducing GHG emissions, the different policy options directly or indirectly affect other environmental indicators.

Air quality is impacted in particular by the evolution of the energy and transport sector as well as the agricultural sector. Changes in the LULUCF and agricultural sector influence biodiversity and ecosystems, food security and the sustainable use of natural resources such as water.

1.9.1. Air quality

Clean air is essential to human health and sustaining the environment. Air quality has improved in the EU over the past three decades as a result of joint efforts by the EU and national, regional and local authorities in the Member States to reduce the adverse impacts of air pollution. However, nowadays, around 300 000 premature deaths per year and a significant number of diseases such as asthma, cardiovascular problems and lung cancer, among others, are still attributable to air pollution (and especially to particulate matter, nitrogen dioxide and ozone) (208). There is also increasing evidence that low air quality may be associated with changes in the nervous system, cognitive decrements, and dementia (209).

Air pollution remains the most frequent environmental cause of early death in the EU, and it disproportionally affects vulnerable groups such as children, elderly people and persons with pre-existing conditions, as well as socioeconomically disadvantaged groups (210). In addition, air pollution threatens the environment through acidification and eutrophication, causing damage to natural ecosystems and crops. Currently, eutrophication from deposition of nitrogen exceeds critical loads in two thirds of ecosystem areas across the EU, with significant impact on biodiversity (211). This has a direct impact on the health of ecosystems and can aggravate situations of nitrogen surplus via water pollution. Furthermore, high ground-level ozone concentrations negatively affect plant growth.

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(208) European Environment Agency (2021). Air Quality in Europe 2021.

(209) United States Environmental Protection Agency (2022). Supplement to the 2019 Integrated Science Assessment for Particulate Matter.

(210) European Environment Agency (2018). Unequal exposure and unequal impacts: social vulnerability to air pollution, noise and extreme temperatures in Europe.

(211) COM(2022) 673 final (The Third Clean Air Outlook).

Research to quantify the benefits of climate action associated with improved air quality highlights the significant magnitude of such co-benefits ([212]). In general, the economic, technological and societal transformations required to reduce GHG emissions in the EU have positive impacts on air quality because they lead to lower energy consumption and a shift to non-emitting renewable energy sources and to less polluting combustion fuels. Therefore, these developments lead to lower emissions of pollutants such as fine particulate matter with a diameter of 2.5 µm or less (PM2.5) and nitrogen oxides (NOx). In addition, climate action will contribute to mitigate the increasing negative effects that climate change itself has on air quality, due notably to heatwaves or wildfires ([213]).

The GAINS model has been used to produce projections of air pollutant emissions and their impacts on public health and ecosystems for the decarbonisation pathways analysed in this impact assessment ([214]). The combination of existing air pollution policies as well as ambitious climate policies result in strong reductions of air pollutants by 2040. As shown in Table 19, in scenarios S1, S2 and S3, primary PM2.5 emissions in the EU decrease by 62% by 2040 compared to 2015 levels. Moreover, primary SO2, NOx, NH3 and VOC emissions decrease by 77%, 71%, 16% and 29%, respectively, over the same period. Note, however, that the consumption of solid biomass, which still represents a large share of renewable energy consumption in Europe, emits large amount of particulate matter (PM2.5 and PM10), non-methane volatile organic compounds (NMVOCs) and polycyclic aromatic hydrocarbons (PAHs) ([215]). In 2021, in the EU, more than 60% of PM2.5 emissions were generated by the residential sector, showing the large share of domestic heating (and, particularly, bioenergy) in fine particulate matter emissions ([216]). Thanks to further electrification of heating needs and more energy efficient buildings, the consumption of solid biomass in the residential sector is much lower in 2040 than today in all analysed scenarios (see section 1.3.3 in this Annex). The small differences in particulate matter emissions between scenarios are mainly due to differences in solid biomass consumption.

Differences in air pollutant emissions between LIFE and the other scenarios stem from significant differences in agricultural activity levels (i.e., reduction in livestock numbers and fertiliser application in LIFE). The largest reduction is observed for NH3 emissions (from livestock, manure management and mineral fertiliser application), but there are also substantial reductions in NOx emissions (from the fertilisation of agricultural soils) and VOC emissions (from manure). More specifically, in LIFE, in 2040, NH3 emissions are 36% lower than in 2015 (i.e., the decrease is 20 percentage points higher than in the S1, S2 and S3 scenarios), NOx emissions are 74% lower than in 2015 (i.e., the decrease

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([212]) Vandyck, T. et al. (2018). Air quality co-benefits for human health and agriculture counterbalance costs to meet Paris Agreement pledges, *Nature Communications*, Vol. 9, No. 4939.

([213]) World Meteorological Organization (2023). WMO Air Quality and Climate Bulletin, No 3, September 2023.

([214]) Note that the methodology used in this impact assessment is similar to the one used in the Third Clean Air Outlook (COM(2022) 673).

([215]) European Environment Agency (2019). Renewable energy in Europe: key for climate objectives, but air pollution needs attention.

([216]) European Environment Agency. National air pollutant emissions data viewer 2005-2021 (online). [Retrieved in August 2023.]

is 3 pp higher than in the other scenarios) and VOC emissions are 33% lower than in 2015 (i.e., the decrease is 4 pp higher than in the other scenarios). A relatively small reduction in primary PM2.5 emissions is also observed, due to lower crushing of bedding material by livestock movements. The level of SO2 emissions is similar to that of the other scenarios, since agriculture activities do not emit much SO2.

Table 19 also shows the positive impact that reducing air pollutant emissions has on public health (217). In the S1, S2 and S3 scenarios, the number of premature deaths per year caused by PM2.5 and ozone exposure in the EU drops by 58% in 2040 compared to 2015. This means around 270 000 less premature deaths per year in total. Furthermore, the annual number of years of life lost due to PM2.5 and ozone (218) exposure decreases by 55% (i.e., around 3.3 million years of life lost per year less) between 2015 and 2040. In LIFE, the number of premature deaths per year goes down by 60% between 2015 and 2040 (which means 277 000 cases per year less), and the annual number of years of life lost decreases by 57% (i.e., 3.4 million years of life lost per year less) over the same period. This implies reductions in the annual number of premature deaths and years of life lost between 2015 and 2040 that are 2 percentage points greater than in the other scenarios.

The decrease in air pollutant emissions reduces the costs of air pollution control in the EU. Table 19 shows that in 2040 these costs are EUR 25-27 billion lower than in 2015 in the S1, S2, S3 scenarios, and EUR 27 billion lower than in 2015 in LIFE. There is a reduction in air pollution control costs for the agricultural sector in LIFE compared to the S2 scenario (EUR 1 billion less), since agricultural activity is lower. However, as the main part of the air pollution control costs are associated with sectors other than agriculture, the overall difference in control costs is relatively small.

Moreover, the reduction in mortality has been assessed economically using two methods: Value of Statistical Life (VSL) and Value of a Life Year (VOLY). In this impact assessment, the value of a statistical life is assumed to be EUR 4.36 million, and the value of a life year is assumed to be EUR 114 722 (219). As shown in Table 19, in the S1, S2 and S3 scenarios, in 2040, the premature mortality costs are EUR 1 046 to 1 051 billion lower compared to 2015 (i.e., a 61% reduction) if the VSL method is used, and EUR 380 to 382 billion lower compared to 2015 (i.e., a 56% reduction) if the VOLY method is used (220). In LIFE, the premature mortality costs are slightly lower because of the decrease in PM2.5 emissions: EUR 1 077 billion lower in 2040 compared to 2015 if

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(217) The analysis considers the direct effects of PM2.5 (full exposure range) and ozone on human health, together with the indirect effects of NOx as precursors of particulate matter and ozone. However, the direct effects of NO2 are not considered to avoid the risk of double counting, since there is conflicting scientific evidence on the extent to which the health impacts of PM2.5 and NO2 overlap.

(218) Like the Third Clean Air Outlook, this impact assessment assumes that on average one year of life is lost for each premature death caused by ozone exposure.

(219) In accordance with the premature mortality valuation methodology used in the Third Clean Air Outlook (COM(2022) 673). Note that in the Third Clean Air Outlook the value of a statistical life and the value of a life year are expressed in EUR 2015, whereas in this impact assessment these values are expressed in EUR 2023.

(220) As indicated in the Third Clean Air Outlook (Annex to the Final Report, p. 122), premature mortality caused by ozone exposure is considered only in the VOLY method, but not in the VSL method.

the VSL method is used, and EUR 394 billion lower in 2040 relative to 2015 if the VOLY method is used.

Table 19: Air pollution emissions, impacts on public health and costs

		2015*	2040		Change 2015-2040	
			S1, S2 & S3	*LIFE*	S1, S2 & S3	*LIFE*
Primary emissions	**Air pollutant emissions (kt)**					
	SO2	2316	525 to 529	*529*	-1787 to -1791 (-77.1% to -77.3%)	*-1787* *(-77.1%)*
	NOx	7392	2114 to 2140	*1913*	-5252 to -5277 (-71.1% to -71.4%)	*-5478* *(-74.1%)*
	PM2.5	1380	521 to 524	*517*	-857 to -859 (-62.1% to -62.2%)	*-863* *(-62.5%)*
	VOC	6362	4497 to 4503	*4259*	-1860 to -1865 (-29.2% to -29.3%)	*-2103* *(-33.1%)*
	NH3	3690	3086 to 3091	*2346*	-599 to -604 (-16.2% to -16.4%)	*-1345* *(-36.4%)*
Public health	**Premature mortality caused by PM2.5 exposure**					
	Expressed in 1000 cases/year	395	154 to 155	*148*	-240 to -241 (-60.7% to -61.0%)	*-247* *(-62.5%)*
	Expressed in million life years lost/year	5.91	2.61 to 2.63	*2.50*	-3.28 to -3.30 (-55.6% to -55.8%)	*-3.40* *(-57.6%)*
	Premature mortality caused by ozone exposure					
	Expressed in 1000 cases/year	71	42	*40*	-28 (-40.1% to -41.3%)	*-30* *(-42.8%)*
	Expressed in million life years lost/year	0.07	0.04	*0.04*	-0.03 (-40.1% to -41.3%)	*-0.03* *(-42.8%)*
Costs	**Economic costs (EUR 2023 billion/year)**					
	Air pollution control**	83	56 to 58	*56*	-25 to -27 (-30.3% to -32.6%)	*-27* *(-32.4%)*
	Premature mortality (VSL)***	1724	673 to 677	*646*	-1046 to -1051 (-60.7% to -61.0%)	*-1077* *(-62.5%)*
	Premature mortality (VOLY)****	686	304 to 306	*292*	-380 to -382 (-55.6% to -55.8%)	*-394* *(-57.4%)*

*Note: *Historical values for 2015 are slightly different than the ones reported in the Third Clean Air Outlook because of a different emission scope as well as recent updates in the emission factors assumed by the GAINS model. **Air pollution control costs are the costs associated with the measures/technologies employed in the control strategies of each scenario. ***In accordance with the valuation methodology used in the Third Clean Air Outlook, the value of a statistical life is assumed to be EUR 4.36 million (in EUR 2023), and the premature mortality costs estimated using the VSL method do not consider premature deaths caused by ozone exposure. ****In accordance with the valuation methodology used in the Third Clean Air Outlook, the value of a life year is assumed to be EUR 114 722 (in EUR 2023), and the premature mortality costs estimated using the VOLY method consider premature deaths caused by ozone exposure.*

Source: GAINS.

Note that not all air pollution costs have been included in the quantitative analysis presented in this section and shown in Table 19. Besides reducing premature mortality, improving air quality also reduces morbidity (impact of diseases) caused by air pollution (e.g., asthma). Consequently, improved air quality can reduce healthcare costs (due to avoided hospital admissions, lower need for medication, etc.), as well as trigger economic growth (by reducing employee absenteeism and increasing work productivity). Furthermore, improved air quality increases crop yields and reduces damage to materials and sensitive ecosystems. These co-benefits have not been quantified in this impact assessment. However, regarding the last point, Table 20 shows the total ecosystem area in the EU where acidification and eutrophication exceed critical loads harmful to these ecosystems. The total area where acidification exceeds critical loads decreases by around 126 000 km2 between 2015 and 2040 in the S1, S2 and S3 scenarios (which means an 80% reduction). The largest part of this reduction involves forest areas. Note that acidification is caused by atmospheric deposition of SO2, NOx and NH3. In addition, the total ecosystem area where eutrophication exceeds critical loads decreases by 272 000 to 274 000 km2 between 2015 and 2040 in these scenarios (23.5% reduction). The reduction in eutrophication effects is lower than the reduction in acidification effects (in relative terms) because the primary source of eutrophication is NH3 leakage from agricultural activities, and emissions of this air pollutant do not decrease as much as SO2 and NOx emissions, which are an important cause of acidification. In LIFE, the ecosystem area in the EU affected by severe acidification and/or eutrophication decreases more than in the other scenarios because of the lower NOx and NH3 emissions from agricultural activities: the total area where acidification and eutrophication exceed critical loads decreases by 88% (around 7 percentage points more than in the other scenarios) and 36% (around 13 pp more than in the other scenarios), respectively, between 2015 and 2040.

Table 20: Area affected by acidification and eutrophication per scenario

	2015	**2040**		**Change 2015-2040**	
		S1, S2 & S3	**LIFE**	**S1, S2 & S3**	**LIFE**
Acidification (1000 km2)	157	30.6 to 30.7	*19.3*	-126 (-80.4%)	*-137* *(-87.7%)*
Eutrophication (1000 km2)	1164	890 to 892	*742*	-272 to -274 (-23.4% to -23.5%)	*-422* *(-36.3%)*

Note: The table shows the affected ecosystem area within the EU (expressed in 1000 km2) where acidification or eutrophication exceed critical loads.

Source: GAINS.

1.9.2. Biodiversity and ecosystems

Climate change is expected to have significant influences on biodiversity including species-level reductions in range size and abundance (221) as it is one of the five main drivers of global biodiversity loss, with change of land and sea use, direct exploitation, pollution, and invasive alien species (222). For example, fire-prone areas are expected to expand across Europe due to climate change threatening not only carbon sinks but also biodiversity through habitat loss and fragmentation (223). At the same time, more biodiverse forests may deliver more ecosystem services necessary for climate mitigation and adaptation (224). In other words, making forest ecosystems more biodiverse can help

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(221) Warren, R., VanDerWal, J., Price, J. et al. Quantifying the benefit of early climate change mitigation in avoiding biodiversity loss. Nature Clim Change 3, 678–682 (2013)

(222) IPBES (2019) Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Zenodo. Available at: https://doi.org/10.5281/ZENODO.3831673.

(223) For more details on the complex interaction see IPCC AR6 WGII Chapter 13

to increase their resilience against forest fires. Forest management practices like monoculture plantations of fast-growing trees (eucalyptus, pines) are more prone to fires ([225]) than biodiverse forests such as primary or old-growth forests ([226]). However, the relationship goes both ways: an improved biodiversity and functioning ecosystems also positively impact both climate mitigation and adaptation ([227]).

On a general level, limiting the magnitude of climate change via GHG mitigation is necessary to preserve biodiversity and prevent further loss. More specifically, stringent GHG mitigation that includes nature-based mitigation efforts can deliver a net benefit to global biodiversity even if it comes at the cost of regional biodiversity loss in Europe. But, in view of these potential losses, policies in EU should be be carefully designed to conserve local biodiversity and to minimize the conversion of natural habitats ([228]). It is therefore important to focus on the many nature-based removals for carbon removals, which entail positive side-effects for biodiversity as they can provide new habitats and ecosystems and to consider biodiversity impacts from nature-based removals that can alter the habitat available for wildlife.

Modelling results showed that across all scenarios, overall species and habitats co-benefit from nature-based removals, which proved to be the main driver of change while at the same time providing additional carbon removals. Additional nature-based removals, applied in S2 and S3, delivered clear benefits for the suitable habitat of species and therefore biodiversity. The main factors for the improvement are afforestation, an increase in deadwood in forests and intensification coupled with longer rotation time of managed forests, and additional rewetting of peatlands. The impact of a second driver for biodiversity, the increased biomass demand from lignocellulosic crops and forestry, had a minor impact on biodiversity, resulting in statisticall non-significant differences between the scenarios.

On average the suitable habitat for European species increases by about 3% (S3) to 4% (S2) in 2040 compared to 2020. For S1 the average suitable habitat declined slightly by around 1% in 2040 compared to 2020 ([229]). The application of a carbon value to cover mitigation costs in the land sector of up to 50 €/tCO_2-eq in S2 and S3 results in small but positive biodiversity trends although it is worth noting the large variations around the

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([224]) Pukkala, T. 2016. Which type of forest management provides most ecosystem services? Forest Ecosystems 3:9; https://forestecosyst.springeropen.com/track/pdf/10.1186/s40663-016-0068-5

([225]) Barquín, J., L. Concostrina-Zubiri, I. Pérez-Silos, G. Hernández-Romero, A. Vélez-Martín, and J. M. Álvarez-Martínez. "Monoculture plantations fuel fires amid heat waves." Science 377, no. 6614 (2022): 1498-1498.

([226]) Barredo, J.I., Mansuy, N. and Mubareka, S.B., Primary and old-growth forests are more resilient to natural disturbances – Perspective on wildfires, European Commission, 2023, JRC133970.

([227]) Pörtner, H.-O. et al. (2021) Scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change. Zenodo. Available at: https://doi.org/10.5281/ZENODO.5031995

([228]) Ohashi, H., Hasegawa, T., Hirata, A. et al. Biodiversity can benefit from climate stabilization despite adverse side effects of land-based mitigation. Nat Commun 10, 5240 (2019)

([229]) Biodiversity impacts were calculated with GLOBIOM modelling framework. The biodiversity indicator provides the average suitable habitat change since 2020, by assessing the suitability of a habitat for each species. The indicator is based on a total set of 1033 species living across five land categories.

mean trend. In 2050, the average change in suitable habitat stays stable in S2 and S3 and returns to 2020 levels for S1.

In sum, the effects on biodiversity related to additional nature-based removals are positive but small. However, the results also confirm the need to align climate and environmental action in a co-beneficial way to obtain synergistic effects. Overall, on biodiversity and ecosystems, the effects on suitable habitats in Europe in S1 to S3 need to be complemented with the effects on acidification and eutrophication as shown in Table 20. The scenarios show a decline of affected area by 80% for acidification and 23.5% for eutrophication in 2040, which provides a significant positive impact for ecosystems.

LIFE evolves around a dietary change from consumers towards more healthy and sustainable food consumption, the implementation of the Farm to Fork Strategy, and food waste reduction (see Annex 6). Derived from the Farm to Fork Strategy and the Biodiversity Strategy for 2030, the scenario produced some relevant outputs (230) which have a beneficial impact on biodiversity as shown in Table 21.

Table 21: Overview of Farm to Fork objectives indicators in LIFE in 2040

	total	Change to 2020	Change to S1 - S3 in 2040
Nutrient surplus total [in 1000t]	5,504.794	-49%	-48%
Mineral fertilizer use	5,904	-41%	-44%
Chemical pesticide Use	7307	-39%	-50%
High-diversity landscape features (Set aside and fallow land) - Share of EU's agricultural land	14%		
Share of EU's agicultural land for organic agriculture	25%		

Source: CAPRI

Key factors in agriculture, such as the nutrient surplus, the amount of fertilizer and pesticides applied, and the intensity of farming practices impact ecosystems and biodiversity across different regions. Consequently, since LIFE has substantial impacts on agricultural land and farming practices (Table 21), the changes also affect ecosystems and biodiversity on these lands positively. Next to changes of farming practices, LIFE shows a decline in livestock from cattle and other animals, which also leads to a reduction in livestock density (Table 22). This reduction of livestock is due to the declining demand for meat and dairy products, the implementation of the objective to reduce nutrient losses by 50%, and to a limited extent to a reduction of food waste.

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(230) The exact steering towards the different objectives from the Farm to Fork and Biodiversity strategy, the dietary changes, as well as the targets for the food waste reduction in the modelling is technically difficult, which results in the overfullfillment of some targets and missing the threshold for others in the LIFE scenario.

Table 22: Overview of LIFE outputs related to biodiversity in 2040

	total	per ha	Change to S1 - S3
Beef meat activities [in 1000 LSU]	7,877		-49%
All Dairy [in 1000 LSU]	29,151		-18%
Pigs, poultry, sheep [in 1000 LSU]	42,875		-24%
All cattle activities [LSU/ha]		0.23	-29%
Other (non-cattle) animals [LSU/ha]		0.26	-26%

Note: LSU indicates livestock units, either as 'total' in 1000t or 'per ha' kg/ha.

Source: CAPRI

To assess biodiversity impacts on LIFE an indicator for biodiversity was necessary that can account for impacts on agricultural land. The biodiversity impacts of the LIFE setting uses the "BFP index" (Biodiversity-friendly farming practices), which assesses biodiversity friendly practices and reflects the likelihood to find agricultural areas with a high value for biodiversity and ecosystems in a region on NUTS 2 level (231). The total index is an area weighted average of the partial indices for arable crops, permanent crops, grassland and set aside / fallow land. In LIFE, this index increases by 14% compared to the three scenarios, reaching on EU level up to about 71%. The estimated improvement in biodiversity is mostly driven by three factors. Biodiversity on areas with arable crops improves by about 20% due to the nutrient surplus reduction on the fields (232), supplemented with reduced pesticide use. Areas with permanent crops benefit (38%), mainly due to the reduction of pesticides, while lower nutrient surpluses are a secondary driver here. Also managed grassland improves to a limited extent (3%), because the stocking intensity of livestock units decreases, resulting in a substantial increase of extensive use of grassland (see Table 23), while the pesticide reduction is less influential on grassland.

Table 23: Agricultural area change in 2040 by scenarios.

Area use [in 1000 ha]	S1 - S3	LIFE	Change
Utilized agricultural area	160,108	161,763	1%
Fodder activities	65,922	54,185	-18%
- of which: Gras and grazings intensive	23,872	5,174	-78%
- of which: Gras and grazings extensive	23,867	36,595	53%
Total set aside or rewetted land*	7,084	22,360	216%

**This includes fallow land set aside and rewetted cropland or grassland. The additional area is partly mobilized by displacing agricultural crops and partly by converting other "unproductive" land.*

Source: CAPRI

The third key driver for improved biodiversity friendliness would be the expansion of areas for landscape elements such as hedges, buffer strips etc. The share of this set aside

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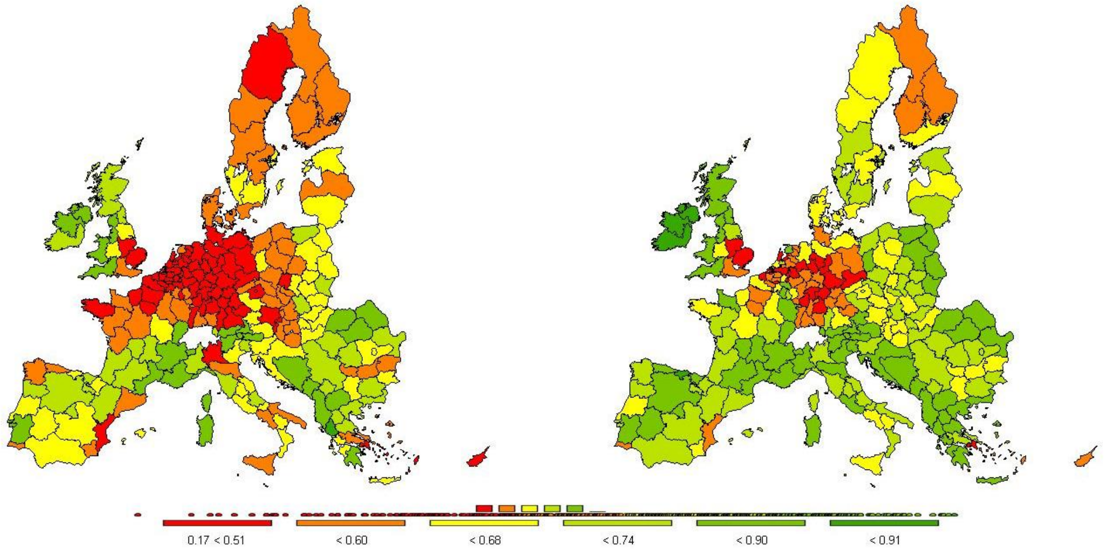
(231) Using the 'Biodiversity Friendly Practices' (BFP), a biodiversity indicator capturing the likelihood to find High Nature Value farmland in a region. Partial indices for different land use categories are weighted according to their proportion of the total utilized agricultural area.

(232) The nutrient reduction through the farm to fork strategy aims to reduce nutrient losses by 50%. The areas for arable crops make up almost 60% of the total farmland, therefore this partial index plays a significant role.

or fallow land would more than double to about 14.5 Mha in total. Figure 99 Shows the regional biodiversity impacts through LIFE, indicating that the improvements are evenly distributed across the EU, shifting particularly southern and eastern European regions into a much more favourable state for biodiversity.

Figure 99: Biodiversity impacts from LIFE by region.



Note: Results on the total BFP index in LIFE (right) against the default setting of the scenarios S1, S2 and S3 (left) in 2040 on NUTS 2 level. The Biodiversity Friendly Practices (BFP) indicator depicts the likelihood to find High Nature Value farmland in a certain NUTS 2 region. The indicator ranges from red (17%-51%) to dark green (<100%).

Source: CAPRI

1.9.3. Food security, animal welfare and health

The food system itself is not only contributing to climate change but is also highly exposed to climate change itself, which jeopardises food security (233). Foodborne diseases and an increase in extreme weather events are expected in the future under altered climatic conditions, such as draughts and heavy rainfall, impacting the food system and food safety. For Europe a combination of heats and droughts resulting from a 2°C to 3°C global warming level will lead to substantive agricultural production losses for most European areas which will not be offset by possible gains; an effect that will also affect the economic output from agriculture in the EU (234).

Food security and sustainable and healthy diets are strongly interlinked (235). A sustainable food system makes optimal use of natural resources. Dietary patterns with high meat consumption require more energy, water and land resources. One hectare of land may produce enough lamb or beef to feed one to two people, while the same hectare

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(233) IPCC AR6 SPM

(234) IPCC AR6 WG II, 13

(235) Capone, R., et al., ‘Food System Sustainability and Food Security: Connecting the Dots.’, *Journal of Food Security*, 2, 1, 13-22, 2014.

can produce rice or potatoes for 19 to 22 people per annum (236). Thus, because livestock farming demands extensive land use, a decrease of animal-based products in human diets would reduce demand for feed and make more land available for growing human food. Today, more than 50% of EU's use of cereals goes into animal feed (237). Reducing the demand of cereals for animal feed would contribute to strengthen strategic autonomy in the food sector and thereby enhance food security.

However, a closer look at the net production of agricultural products (see Table 24:) shows that LIFE with its shift towards healthier diets and a reduction of food waste not only decreases demand for food but also decreases livestock herds and agricultural area related to animal products (see Table 22; Table 23), but also net production of animal based and many other agricultural products. In part this is due to market adjustments due to declining demand but partly this is also reflecting the desired move to less intensive production systems with higher shares of organic agriculture, lower pesticide use, and nutrient surpluses and some additional agricultural area taken out of production in view of biodiversity targets. On a global perspective it is important to mention that only the combination of supply side measures through the Farm to Fork objectives, together with demand side measures (i.e., dietary shift and food waste reduction) result in a mutual decline of production and demand, which does not jeopardise global food security.

Table 24: Net production of agricultural outputs in 2040 by scenarios

Net production [in 1000 t]	S1, S2, S3	LIFE	Change
Feed energy input	704,146,368	563,934,976	-20%
Cereals	267,900	214,751	-20%
Vegetables and Permanent crops	126,013	122,510	-3%
Wheat	118,239	98,450	-17%
Meat	45,368	33,841	-25%
Other Animal products	168,985	151,862	-10%
Raw milk	161,303	145,473	-10%
Dairy products	64,444	57,295	-11%

Source: CAPRI

Compared to scenarios S1, S2 and S3, LIFE leads to a shift from intensive grazing to extensive grazing (Table 22) and to an overall reduction in livestock density per ha for cattle and dairy cows but also for pigs and poultry (238). This may also positively impact animal welfare and increase resilience against transboundary animal diseases in animal related food production (239).

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(236) Institution of Mechanical Engineers-UK, 'Global food, waste not, want not'. London. 2013. Available online at: global-food---waste-not-want-not.pdf (imeche.org)

(237) Based on the years 2020 to 2022; European Commission, DG Agriculture and Rural Development, 'EU agricultural outlook for markets, income and environment, 2022-2032', Brussels, 2022.

(238) In LIFE the overall animal density [lifestock units / ha] decrease by -27%; for all cattle activities by -29% and other animals -26%. See Table 22

(239) Sundström, J.F., Albihn, A., Boqvist, S. et al. ‚Future threats to agricultural food production posed by environmental degradation, climate change, and animal and plant diseases – a risk analysis in three economic and climate settings', *Food Security*, 6, 201–215, 2014.

LIFE incorporates significant health benefits for its citizens. For Europe, research finds a greater consumption of red meat, eggs and dairy products than recommended consumption levels of healthy reference diets ([240]) ([241]). Studies indicate that reducing meat consumption, while maintaining a broad and varied diet is beneficial for human health as it reduces the risk of cardiovascular diseases ([242]) ([243]), cancer ([244]), diabetis and obesity ([245]). This has also significant economic benefits on health costs. For example, adopting an energy-balanced, low-meat dietary pattern is associated with large reductions in premature mortality, both for a flexitarian (-19%) and a vegan (-22%) diet ([246]).

The reduction of meat consumption (i.e., shift to more plant-based diets) and fertiliser application in LIFE also generates significant co-benefits for air quality, since it reduces methane emissions, a short-lived climate forcer but also a precursor of ozone (247), and ammonia emissions. Hence, an increase in plant-based diets in the EU is improving human health both directly through more healthy diets and indirectly through cleaner air, which creates economic benefits from improved human health that would compensate some part of the economic losses in agricultural sector (248).

([240]) Willet et al., ‘Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems’, Lancet, 2019.

([241]) WHO/FAO (2003) Diet, nutrition and the prevention of chronic diseases: report of a joint WHO/FAO expert consultation. World Health Organization, Geneva.

([242]) Koch et al. (2023) Vegetarian or vegan diets and blood lipids: a meta-analysis of randomized trials. European Heart Journal

([243]) Westhoek, Henk, Jan Peter Lesschen, Trudy Rood, Susanne Wagner, Alessandra De Marco, Donal Murphy-Bokern, Adrian Leip, Hans van Grinsven, Mark A. Sutton, and Oene Oenema. ‘Food choices, health and environment: Effects of cutting Europe's meat and dairy intake.’ *Global Environmental Change*, 26, 196-205, 2014.

([244]) Chan, Doris SM, Rosa Lau, Dagfinn Aune, Rui Vieira, Darren C. Greenwood, Ellen Kampman, and Teresa Norat. "Red and processed meat and colorectal cancer incidence: meta-analysis of prospective studies." *PloS one* 6, no. 6 (2011): e20456.

([245]) Tukker et al. (2011) Environmental impacts of changes to healthier diets in Europe. Ecological Economics

([246]) Springmann et al. ‘Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail’, *Lancet Planet Health*, 2018.

([247]) COM(2022) 673 final

([248]) A shift to flexitarian diets could reduce ammonia emissions by 33% in the EU. Through avoided premature mortality rates, economic losses in the agricultural sector from dietary shifts could be mitigated by 39% in the EU in such a scenario. See Himics et al. ‘Co-benefits of a flexitarian diet for air quality and human health in Europe’, 2022

1.9.4. Raw materials

The demand for raw material is expected to grow considerably by 2050 ([249]), and this growth in raw materials use is likely to increase the pressure on the planet resources.

The material growth is expected to be driven only partially by the climate transition, with the rest is distributed among the electronic sector, the automotive and building sector and production of alloys for different applications. The share of the raw material increase attributed to climate actions depends strongly on the material. BNEF calculates that the share of manganese, and silver needed for clean energy use are responsible for less than 25% of the total demand increase by 2050 ([250]), while the IEA indicates that the share of nickel, cobalt and copper needed by the energy transition will represent per each of these materials less than 40% of total demand in 2040 ([251]). The IEA estimates that clean energy technologies and infrastructure account for 2-3% of cement and steel demand today, and this value will increase to only about 2% (for cement) and 7% (for steel) in 2050 ([252]).

Furthermore, climate policy, together with increase material efficiency, circular economy actions and possible sufficiency measures can create synergies to reduce the need of primary raw materials and pressure on planet resources to produce them ([253]).

The IEA estimates that most of the growth in the total global material demand associated to clean technologies and infrastructure in the NZE scenario will occur between 2021 and 2030, while after 2030, growth in demand is much more modest, despite the continuously increasing of the in-use stocks of these materials ([254]). This is attributed to several factors often associated to direct climate policy or related measures. Technology innovation accelerates quickly with economy of scale ([255]), leading for example to more energy-dense batteries (requiring lower material needs) in a world with higher share of electric vehicles, or faster development of innovative catalysts reducing the need for platinum group metals in electrolysers in a decarbonised energy system requiring hydrogen. Material substitution with low-carbon technologies can also play a role in limiting the increase in material demand the pressure on resources. In efforts to reduce demand for nickel, Tesla is producing Evs with a lithium iron phosphate (LFP) battery that contains no nickel and have suggested that a large share of the future EV battery market will contain iron-based cells rather than nickel based ([256]). Likewise, efforts to eliminate

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([249]) World Bank (2020), Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition.

([250]) BNEF (2023b), Transition Metals Outlook 2023.

([251]) As per the STEPS scenario of the IEA, described in The Role of Critical Minerals in Clean Energy Transitions, Revised Version in May 2022.

([252]) IEA (2023) Energy Technology Perspectives.

([253]) Desing et al., Resource pressure – A circular design method, Resources, Conservation and Recycling,

Volume 164, 2021, 105179, ISSN 0921-3449.

([254]) IEA (2023) Energy Technology Perspectives.

([255]) See for instance Moore's law and Swanson' law

([256]) [Tesla to use iron-based batteries in Semi electric trucks and affordable electric car | Reuters] lithium from batteries have seen battery manufacture CATL announce a sodium-ion EV battery ([257]). Material efficiency measure associated to less energy-intensive production methods reducing resource intensity of products, while providing the same service. Some metals have high potential for recycling in the future. Cobalt and copper are supplied almost completely by primary supply today but has the potential to have over 80% for cobalt and approximately 60% for copper being supplied from recycled metals in 2050 ([258]). Circularity actions, and more in general sufficiency-driven behavioural change can decrease primary demand of critical materials in favour of products with longer life, repair or products manufactured from secondary raw materials that stay longer in the market.

2. SOCIO-ECONOMIC IMPACTS

The options under consideration for the 2040 target in this impact assessment take the legally defined ambition for 2030 and 2050 as a given. The impact assessment for the 2030 Climate Target Plan ([259]) made a detailed analysis of the socio-economic impacts of the achievement of the net GHG reduction 55% target for 2030. It assessed these impacts in relation to a baseline defined by the Reference 2020 scenario, which reflects the first national energy and climate plans as submitted by Members States and the EU legislation prior to the adoption of the Fit-for-55 proposals. The impact assessment covered a wide range of issues, from the impacts on GDP and employment to sectoral transformations, competitiveness and distributional effects. Issues relating to impacts on households or competitiveness, among others, were further assessed in the impact assessments that accompanied the legislative proposals of the Fit-for-55 package.

Overall, the impact assessment for the 2030 Climate Target Plan concluded that the 55% objective was expected to have only limited impacts on broad macro-economic aggregates, including GDP and total employment. It nevertheless stressed that the impacts of the transition are projected to be significant in terms of sectoral output and employment, investment and relative prices. Transformations across sectors and within sectors, including as they related to skills needs, and in consumption patterns will be major and would need to be managed carefully in order to ensure a fair and orderly transition process that preserves the competitiveness of the EU economy and leaves no one behind. Similar conclusions were derived from the in-depth analysis in support of the EU long-term strategy, which underpinned the endorsement of the climate neutrality objective by the European Council in December 2019 and its subsequent adoption in the EU Climate law.

This impact assessment therefore does not seek to revisit the expected impacts of the 2030 targets or assess the economic pathways to climate neutrality in relation to a baseline that would significantly deviate from that objective. Instead, the macro-economic models use S2 as the point of comparison for the other scenarios. To some extent, deviations from the macro-economic benchmark are therefore less relevant for the

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([257])https://www.bloomberg.com/news/articles/2021-07-29/catl-debuts-sodium-ion-batteries-amid-raw-material-cost-spike#xj4y7vzkg

([258]) BNEF (2023). Transition material outlook.

([259]) SWD(2020) 176 final.

analysis than under previous impact assessments. An increased focus is therefore placed in the following sections on the transformation requirements over time across pathways to climate neutrality, with specific attention placed on investment needs, competitiveness, and social and regional impacts. The co-benefits of the transition are also assessed.

The model-based analysis is a technical exercise based on a number of assumptions that are shared across scenarios. Its results do not prejudge the future design of the post-2030 policy framework.

2.1. Macro-economic impacts (260)

2.1.1. GDP and employment

As indicated in previous impact assessments, the transition to climate neutrality is unlikely to be a major driver of GDP growth and employment levels in and of its own. The transition will nevertheless imply transformations in production and consumption patterns. These are assessed in more details in the sections below.

At aggregate level, the models consistently show that a higher level of mitigation in 2040 is associated with a somewhat larger negative impact on GDP, at least on a transitory fashion. With the highest level of climate ambition (S3) in 2040, GDP is projected to be at best unchanged and at worst 0.8% lower than under S2 (Table 25). A lower level of ambition by 2040 (S1) translates at best into a slightly higher level (+0.6%) of GDP. By 2050, however, GDP is projected to return broadly to the same level under all three scenarios. As projected by the JRC-GEM-E3, the impact of the transition on GDP is also somewhat more negative under a "global action" scenario (where the rest of the world implements policies aligned with the 1.5°C objective under the Paris agreement) than under a "fragmented action" scenario (where the rest of the world implements NDCs). This is driven by the fact that higher climate ambition in the rest of the world is associated with higher negative impacts on global GDP, which reduces external demand for EU producers.

The negative impact is therefore mainly a transition effect, with no lasting impact, and it remains small across models and scenarios. As total employment is mostly driven by trends in aggregate output, the impact of a higher level of ambition is also only marginally negative in 2040, before converging across scenarios by 2050.

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(260) The model-based analysis is a technical exercise based on a number of assumptions that are shared across scenarios. Its results do not prejudge the future design of the post-2030 policy framework.

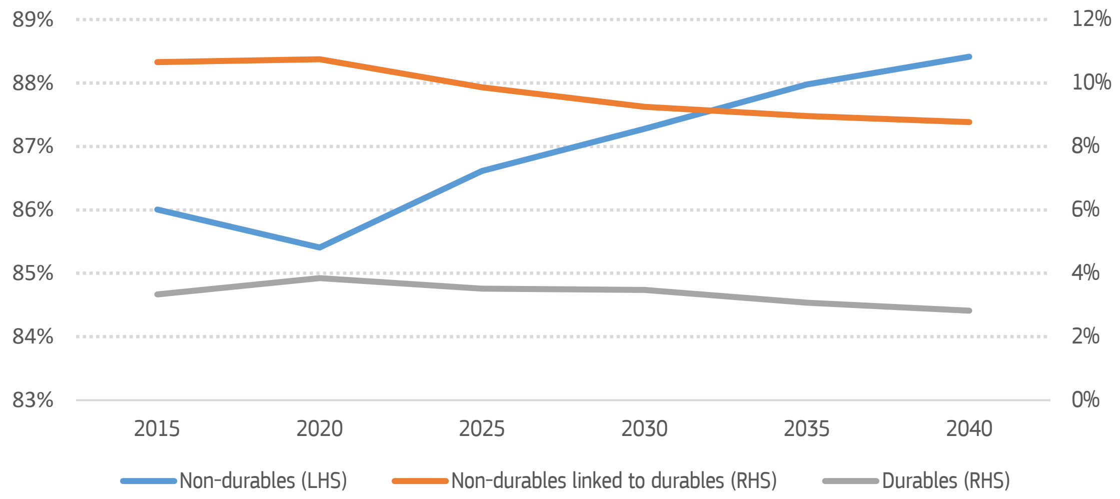
Table 25: Macro-economic impacts (% change compared to S2)

	S1 fragmented		**S1 global**		**S3 fragmented**		**S3 global**	
	2040	**2050**	**2040**	**2050**	**2040**	**2050**	**2040**	**2050**
JRC-GEM-E3								
GDP	0.5%	0.1%	0.6%	0.2%	-0.2%	-0.1%	-0.2%	-0.1%
Private consumption	0.7%	0.1%	1.8%	2.1%	-0.5%	-0.1%	-0.5%	-0.1%
Investment	-0.1%	0.3%	-0.5%	-0.5%	1.1%	-0.1%	1.1%	-0.1%
Exports	1.2%	0.1%	-0.1%	-2.6%	-0.8%	-0.1%	-0.7%	0.0%
Imports	0.3%	0.1%	1.6%	1.5%	0.1%	-0.1%	0.1%	0.1%
Employment	0.3%	0.1%	0.3%	0.1%	-0.1%	0.0%	-0.1%	-0.1%
E3ME								
GDP	0.00%	0.04%	0.01%	0.04%	0.04%	-0.02%	0.00%	-0.04%
Private consumption	0.3%	0.0%	0.4%	0.0%	-0.2%	0.0%	-0.3%	0.0%
Investment	-0.9%	0.1%	-0.9%	0.1%	0.7%	-0.2%	0.7%	-0.2%
Exports	-0.2%	0.0%	-0.2%	0.0%	0.1%	0.0%	0.1%	0.0%
Imports	-0.03%	0.02%	-0.03%	0.02%	0.02%	0.00%	0.01%	0.00%
Employment	0.03%	0.00%	0.03%	0.01%	-0.01%	0.00%	-0.02%	-0.01%
E-QUEST								
GDP	0.4%	-0.02%	n.a.	n.a.	-0.8%	0.01%	n.a.	n.a.
Private consumption	0.3%	0.03%	n.a.	n.a.	-0.5%	-0.01%	n.a.	n.a.
Investment	0.3%	0.03%	n.a.	n.a.	-0.5%	-0.03%	n.a.	n.a.
Employment	0.02%	0.00%	n.a.	n.a.	-0.03%	0.00%	n.a.	n.a.

Source: JRC-GEM-E3, E3ME and E-QUEST.

The macro-economic models also indicate that a higher level of ambition for GHG mitigation in 2040 is associated with a more significant shift in the composition of GDP from consumption towards investment, at least on a transitory basis. The negative impact on private consumption is nevertheless small across models and levels of ambition. Further, the JRC-GEM-E3 model projects that while private consumption is likely to be negatively impacted, the composition of consumption should also evolve, with a gradual decrease in the share of consumption of non-durables linked to the use of durable goods (i.e. mainly energy consumption) and a corresponding increase in the share of other non-durables (Figure 100). This shift in composition would be positive from a welfare perspective, as energy-related services would not be negatively affected by lower consumption of energy itself (e.g., a better insulated house provides the same – or likely better – level of comfort than a poorly insulated one, with lower energy consumption).

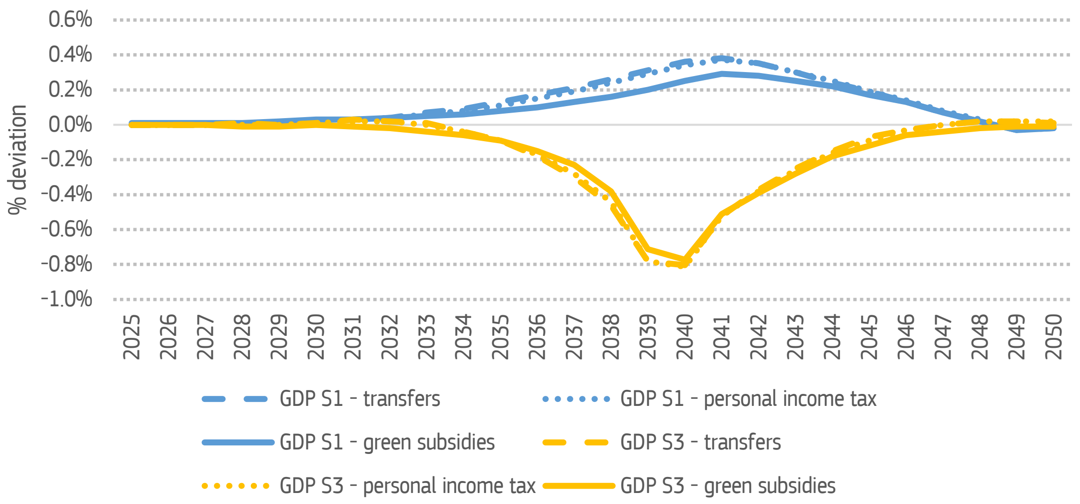
Figure 100: Composition of private consumption (% of total, S3)



Source: JRC-GEM-E3.

DG ECFIN's E-QUEST model shows that S3 generates some cumulative impacts in terms of output loss over the whole transition period (2025 to 2050) compared to S2, even if output levels converge by 2050 (Figure 101). In contrast, S1 generates very modest cumulative output gains compared to S2, with the GDP level converging across scenarios by 2050. Further, it indicates that using the economy-wide carbon revenues to subsidise green investment is more efficient in terms of output than lump sum transfers to households or the recycling of revenues to reduce personal income taxation on low-skilled workers. This is strictly an efficiency gains in terms of output, and it abstracts from distributional and equity considerations, which are discussed below.

Figure 101: Real GDP, deviation from S2



Source: E-QUEST.

2.1.2. *The impact of frictions in the economic transition*

Macro-economic models typically assume that frictions in the reallocation of capital and labour across sectors are limited. Capital is reallocated sectorally over time mostly via new investment and the depreciation of existing assets. In turn, the labour force is assumed to be mobile and responsive to evolving demand across sectors of the economy. While frictional unemployment is modelled and labour matching functions can operate more or less efficiently, workers are assumed to be in a position to take new jobs as they arise in any sector of the economy.

Such assumptions are simplifications used for modelling purposes, which are reasonable in particular when assessing impacts under a long-term perspective. However, the faster the transition, the more the simplifications diverge from the reality of the sectoral transformations. Model-based simulations were therefore used to provide an assessment of frictions in capital markets and investment decisions, and frictions in the reallocation of the labour force across sectors.

DG ECFIN's E-QUEST model is a dynamic stochastic general equilibrium model with fully forward-looking agents, which enables the assessment of the impacts of fully credible, partly credible or non-anticipated policies. While the main scenarios modelled in this impact assessment assume that the pathways under consideration are fully anticipated by economic agents (i.e., fully credible), a variant was used to assess the impact of potentially "erroneous" investment decisions on the economy, modelled via partial anticipations (or partly credible pathways). In essence, this aims to capture investment decisions that are not aligned at all times with the targeted GHG pathway. In this modelling variant, economic agents fail to recognise that additional policies (introduced as carbon values in the model) will be put in place to achieve the climate neutrality pathway and they base their expectations on the continuation of existing policies. Expectations are sequentially updated every five years to correct for erroneous predictions and align with the actual pathway, which is consistent with climate neutrality.

As economic agents do not act fully in accordance with the climate neutrality pathway, they miss the opportunity to take early action by increasing their investment in decarbonised technologies and the value of the capital invested in fossil fuel intensive technologies or sectors is negatively affected, i.e., the economy suffers from stranded assets. The other types of investment represented in the model are not affected (261), as they are not contingent upon the level of mitigation ambition. These investments represent the majority of aggregate investment in the model.

Such a sequential, 5-yearly adjustment of expectations leads to negative outcomes on all key macro-economic variables compared to the scenarios where expectations, and hence the investment decisions of economic agents, are aligned with the climate neutrality pathway. The sequential adjustment in investment on a 5-year basis leads to a type of "catching up" process in investment in decarbonised technologies. To illustrate the impact of this type of frictions, the sequential scenario was modelled based on the level of climate ambition of scenario 1, and impacts are measured in relation to S1 as a baseline. While all scenarios achieve the same level of ambition in 2050, the sequential scenario (S1.A) leads to a gradually larger loss of output over time, with GDP about 0.4 percentage point lower than under S1 in 2050. In contrast, the higher level of ambition under S2 entails only a transitional cost in terms of lower output compared to S1, with GDP marginally higher in 2050. Over the whole transition period, the sequential scenario therefore entails a significant cost in terms of lost output relative to the S2 (Figure 102).

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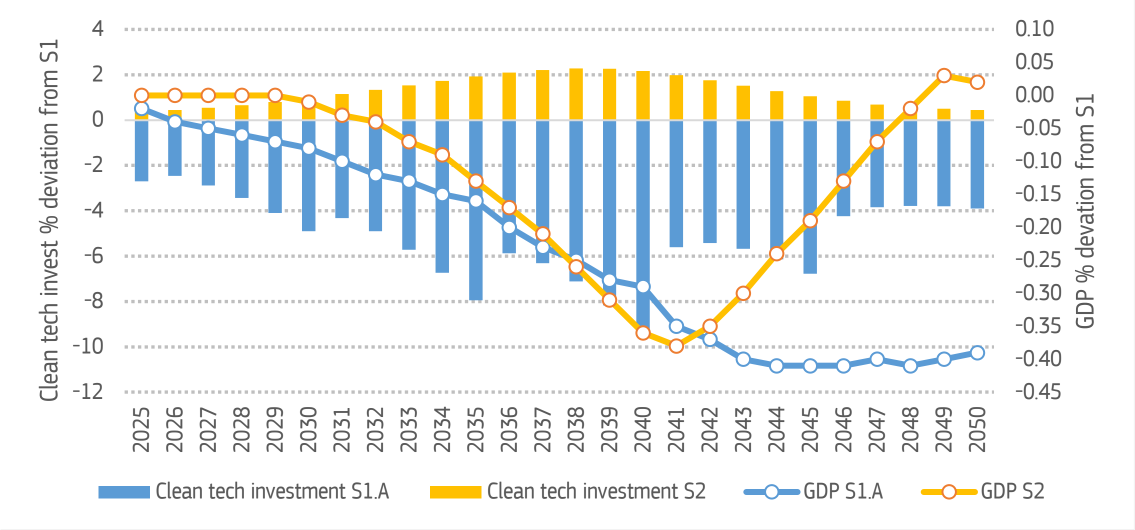
(261) E-QUEST includes a representation of 3 types of investment: (1) electricity intensive (clean technologies); (2) fuel-intensive technologies; and (3) all other types of investments.

Figure 102: Impact of frictions in investment decisions



Source: E-QUEST.

A recent analysis by the European Central Bank ([262]) also shows that an accelerated transition would provide significant benefits for firms, households and the financial system compared with a late-push scenario, which achieves the same level of ambition by a given year than under earlier action but postpones climate-related investment. Although the ECB's analysis is set with a 2030 horizon and is based on scenarios that are not aligned with those considered in this impact assessment, the conclusions concur with those above in that delaying action (or misreading policy signals and making errors in expectations as in the modelling exercise above) is costly. The ECB analysis concludes that credit risk would increase during the transition under all scenarios, but that it would be particularly so in case of a "late-push" configuration that would require very high levels of investment under a shorted period. They conclude that while early action would lead to greater costs for households and firms in the short-term, it would lower financial risks in the medium term because of a decrease in energy-related expenses and that the earlier the transition happens, the smaller the financial risks and potential costs in terms of policy support. Finally, they indicate that their analysis does not find financial stability concerns of the euro area, even if the transition would increase banks' expected losses and provisioning needs.

Cambridge Econometrics's E3ME model was further used to assess the potential impact of increased investment costs (captured in modelling terms as a lower return on investment) due to decisions that are not fully aligned with the transition and GHG mitigation requirements. Assets in selected sectors (mining, manufacturing, electricity supply, land transport and real estate) are assumed to generate lower returns or to operate for a shorter lifetime than projected under the investment decision, which means that investors incur an additional cost to either scrap and replace assets earlier than planned, or to refurbish them to extend their lifetime. The assumed increase in costs range from 1% in the real estate sector to about 4% in manufacturing and 3% in electricity supply. Higher investment costs driven by misaligned investment decisions lead to an increase in

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([262]) Occasional Paper Series N°328. The Road to Paris: stress testing the transition towards a net-zero economy. The energy transition through the lens of the second ECB economy-wide stress test.

consumer prices over the transition period as well as a negative impact on private consumption (-0.7%), investment (-0.2%) and GDP (-0.5%) by 2040, compared to the baseline without misallocations in investment decisions. Higher production costs also negatively impact total exports (-0.5%) and aggregate employment (-0.1%).

Cambridge Econometrics' E3ME model was also used to assess the impact of frictions and costs in the reallocation of the labour force across sectors of the economy. Transformations within sectors and across sectors constitute one of the main challenges of the transition to climate neutrality. Regardless of the scale of impacts on aggregate output, sectors will need to transform to adjust to the adoption of new production technologies and/or the production of new or different types of goods and services. On top of the capital investment needs that this will entail, the transformation will have significant impacts on the labour market, whether in terms of absolute and relative demand within and between sectors, occupations and skills requirements. It will also impact the investment needs in terms of labour force training, reskilling or upskilling.

Two types of effects were therefore modelled to assess potential macro-economic impacts. First, the risks and impacts related to the reallocation of the labour force across occupations and sectors is modelled by assuming that the economy faces retraining/reskilling costs that would not occur otherwise. It is assumed that on average 10% of the workforce receives training specifically to adapt to the climate and energy transition every year (up to 2050). The training costs are assumed to amount to EUR 10 000 per worker in mining and extraction (i.e., to transition them to other sectors as such jobs gradually disappear), EUR 1 500 per worker in manufacturing and agriculture, and EUR 500 in other sectors, where the skills implications of the green transition are likely to be much less significant (263). In addition, basic training at a cost of EUR 1 100 per annum for around 300 000 new workers in low carbon jobs is projected up to 2030 (264). It is further assumed that the costs are fully borne by the employers, which therefore translates into a small increase in labour costs.

Modelling results suggest that such training costs have negligible impacts at macro-economic levels. The larger training/re-skilling costs for workers in mining and extraction apply to a marginal segment of the labour force and even the skilling costs in manufacturing are relatively small in comparison to the total labour force and labour costs. While the model suggests a small increase in aggregate labour costs to employers, the negative impact on GDP or private consumption by 2040 amounts to less than 0.1 percentage point relative to the no-skilling costs baseline.

Higher assumptions regarding training/re-skilling costs amplify the impacts to some extent, though they remain limited. Using the same assumption as above on the training cost per worker in mining and extraction but doubling the percentage of the workforce receiving training to 20%, doubling the costs of training for workers in manufacturing (to EUR 3 000) and other sectors (to EUR 1 000), introducing a cost of training of EUR 5 000 per worker in construction and of EUR 10 000 per worker in energy intensive

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(263) These figures draw on European Economy Discussion Paper 176, December 2022: The Possible Implications of the Green Transition for the EU Labour Market.

(264) This assumptions builds on SWD(2023) 68 final and Employment and Social Developments in Europe 2023 (Box 2.4)

industries and increasing the number of new workers receiving training in low-carbon clean technology sectors to 568 000 generates a negative impact of about 0.25% and 0.35% of GDP in 2040 for GDP and private consumption, respectively. It is important to note, however, that these results do not simulate the potential impact of skills/qualified labour not being sufficiently available for the deployment of green technologies. The latter remains a critical factor in the transition process, and it is assumed here that investing in training ensures that skills are indeed available as needed.

Second, there is firm-level evidence that on-the-job training leads to productivity and wage gains ([265]). An economy-wide effort to train the work force in the context of the climate transition could therefore lead to productivity gains overall. The joint effect of such productivity gains and the small increase in labour costs due to training costs is assessed with the E3ME model by assuming that training positively impacts labour productivity of the affected labour force and that workers consequently benefit from a 1% increase in average wages from 2035, by when a full round of training is completed (assuming again that 10% of the labour force benefits from training each year). Higher wages feed into an increase of about 1.4% and 0.8% in private consumption and GDP, respectively, in 2040, with an associated small increase in consumer prices.

2.2. The investment agenda ([266])

2.2.1. Aggregate investment needs

The transition to climate neutrality requires that the EU's energy system be decarbonised rapidly and comprehensively. All policy options envisaged in this impact assessment imply an intensification in efforts to replace fossil fuels with renewable and carbon-free sources of energy, achieving significant energy savings and the deployment of innovative processes in industry. Existing capital assets (e.g., fossil-based power plants, heating and cooling systems or industrial processes) will be replaced with renewables, carbon-free or electricity-based assets, whose capital intensity may be larger than fossil-based assets. Therefore, the transformations of the energy system will require a general substitution of fossil fuels inputs with capital.

As the technologies to decarbonise the energy system are mostly identified, if in certain cases still in need of deployment at scale and at lower costs, the transition of the energy system is to a large extent an investment challenge, associated to questions on deployment capacity, including in terms of availability of raw materials and skilled labour force or acceptability. The impact assessments for the 2030 Climate Target Plan ([267]) and the legislative proposals under the Fit-for-55 package ([268]) already assessed the scale of the investment requirements up to 2030 and stressed the need for a significant increase in energy system investment compared to the decade 2011-2020. The

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([265]) See for example Konings J. and Vanormelingen S. The impact of training on productivity and wages: firm-level evidence.

([266]) The model-based analysis is a technical exercise based on a number of assumptions that are shared across scenarios. Its results do not prejudge the future design of the post-2030 policy framework.

([267]) SWD(2020) 176 final

([268]) See for example SWD(2021) 621 final

REPowerEU plan further identified additional investment needs in order to reduce the EU's dependence on Russian fossil fuels (269).

The scenarios assessed under this impact assessment generate differentiated requirements in terms of aggregate investment over the entire transition period from 2031 to 2050, as well as in terms of the sectoral composition of these investment requirements and their timing during the post-2030 period. What is most salient across all scenarios, however, are the commonalities and the need for a significant investment effort over a prolonged period, as carbon-intensive systems and processes are substituted with capital intensive, carbon-free solutions on the supply and demand side (Table 26). What this indicates as well is the necessity to ensure that the conditions be in place to facilitate this level of investment and avoid investment decisions that are not compatible with the transition, including in terms of the clarity of signals sent to investors and in terms of access to finance, for businesses and households alike.

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(269) SWD(2022) 230 final

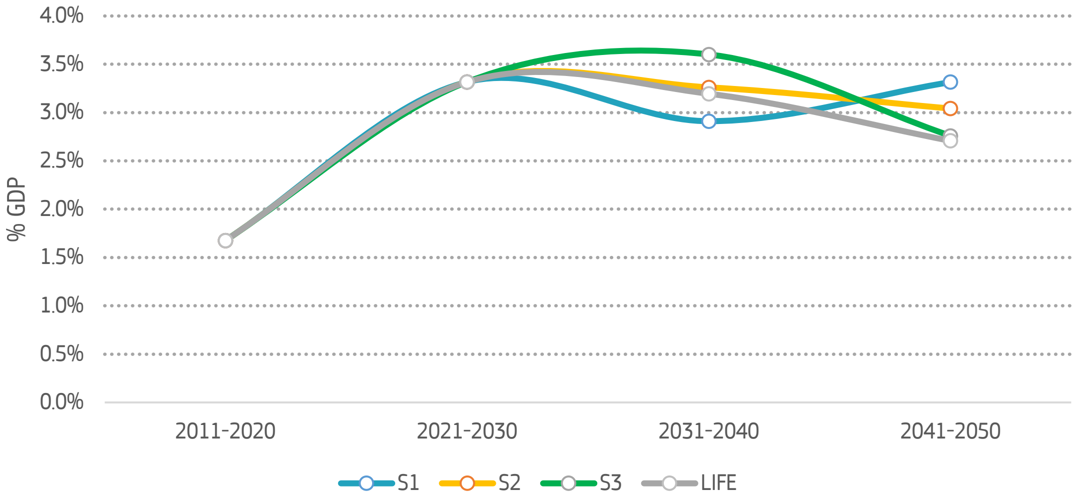
Table 26: Average annual energy system investment needs (billion EUR 2023)

	S1			S2			S3			LIFE		
EU27	**2031-2040**	**2041-2050**	**2031-2050**	**2031-2040**	**2041-2050**	**2031-2050**	**2031-2040**	**2041-2050**	**2031-2050**	**2031-2040**	**2041-2050**	**2031-2050**
Supply	236	377	306	289	328	308	341	281	311	282	268	275
Power grid	79	88	84	88	81	85	96	75	85	80	73	76
Power plants	97	187	142	128	157	142	151	133	142	123	128	125
Other	59	102	81	72	90	81	94	73	83	79	67	73
Demand excluding transport	332	377	354	355	357	356	372	338	355	349	339	344
Industry	38	31	35	46	24	35	48	22	35	40	19	30
Residential	225	250	237	237	242	239	248	230	239	236	234	235
Services	49	78	63	53	73	63	57	67	62	53	68	60
Agriculture	19	19	19	19	19	19	20	18	19	19	19	19
Transport	866	875	870	861	885	873	856	882	869	777	798	787
Total	1433	1629	1531	1505	1570	1537	1570	1501	1535	1407	1405	1406
Total excluding transport	567	754	661	644	685	664	713	619	666	631	607	619
Memo:												
Real GDP (period average)	19444	22369	20906	19444	22369	20906	19444	22369	20906	19444	22369	20906

Source: PRIMES.

Overall, the scenarios and associated pathways imply annual energy system investment needs (excluding transport) at or above 3% of GDP for the two decades from 2031 to 2050 (Figure 103). This amounts to an additional 1.5 to 2 percentage points of GDP compared to the average in 2011-2020. A higher level of ambition in 2040 is, as expected, associated with higher annual investment needs in 2031-2040 than lower levels of ambition in 2040, but also with comparatively lower investment requirements in 2041-2050 due to the early push on decarbonisation projects.

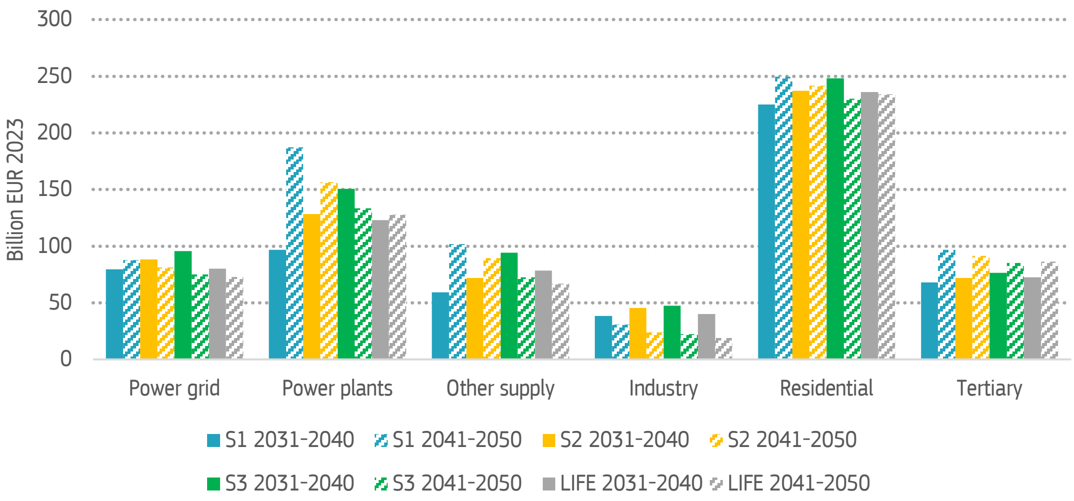
Figure 103: Average annual energy system investment needs, excluding transport



Source: PRIMES.

Cumulatively over the two decades (2031-2050), S3 implies a somewhat higher level of investment as well, partly because technologies need to be deployed faster, which reduces the gains from the projected decrease in the cost of decarbonisation technologies over time through learning-by-doing. S2 yields a smoother investment profile over the entire period 2031-2050 and avoids either anticipating or delaying investments. In turn, behavioural changes (LIFE), including in terms of mobility, consumption and energy use in the residential sector, enable a reduction in investment needs across the entire period (Figure 104). Excluding transport, average annual investment needs in 2031-2050 can be reduced by about EUR 47 billion (7%) compared to S3 over 2031-2050. The lowering of investment needs is evident across the board as reduced energy demand enables a reduction in average annual investment of about EUR 36 billion (12%) on the supply side in 2031-2050 while circularity enables a drop in annual investment needs of about EUR 5 billion (15%) in industry. As far as transport is concerned, lifestyle changes towards more active and public transport modes lead to a drop of around EUR 80 billion (9%) in annual investment needs in 2031-2050.

Figure 104: Average annual energy system investment needs by sector

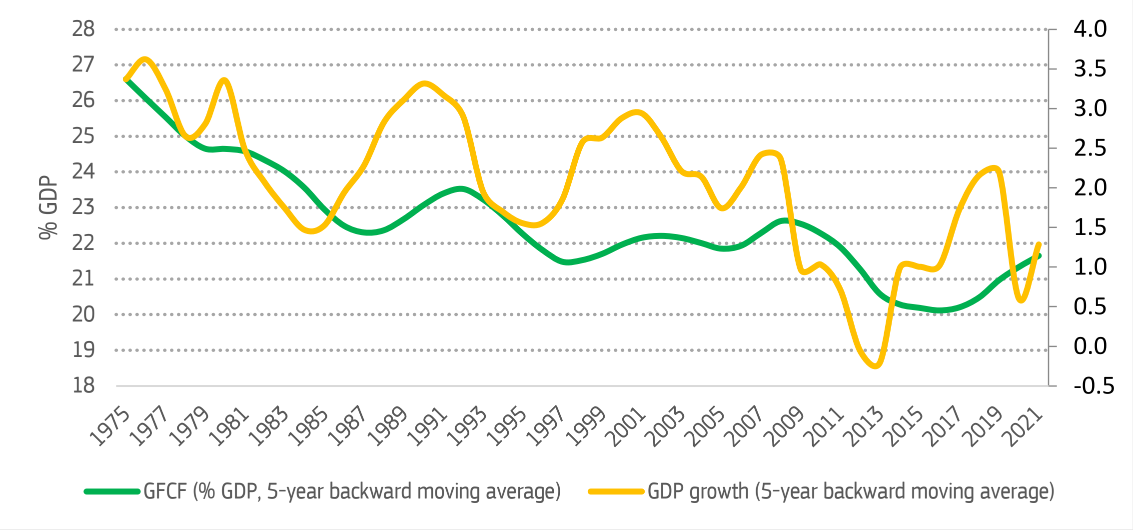


Source: PRIMES.

The projected increase in the investment to GDP ratio is significant, but not exceptional in historical terms. More mature economies typically have lower gross fixed capital formation (GFCF) to GDP ratios, as the need to invest in core infrastructure is lower than is less-developed economies. In the EU, the GFCF/GDP ratio was on a declining trend between the mid-1970s to the mid-1990s, before stabilising at around 21-22% (Figure 105). There has always been a fair bit of volatility in the ratio, however, with a marked low point in the mid-2010s followed by a return in more recent years towards the average of the first decade of the 2000s. Changes in the ratio of 1-2 percentage points of GDP within a relatively short period have not been uncommon in the past. The key difference in the current context is that an increase in the GFCF/GDP ratio would need to be sustained for an extended period, and that higher investment for decarbonisation purposes would need to be combined with higher investment on climate adaptation and higher investment to secure the EU’s ability to benefit from the growth and employment opportunities in green technologies and its strategic security, as discussed in section 2.2.7 ([270]). The latter would indeed require that the EU be in a position to manufacture a significant share of the green technologies necessary for the climate transition domestically.

([270]) SWD (2023) 68 final estimates investment needs for 2023-2030 associated with boosting EU manufacturing capacity for a part of strategic net-zero technologies, focusing on wind, solar photovoltaic, heat pumps, batteries and electrolysers, as part of the Net Zero Industry Act proposal.

Figure 105: Ratio of gross fixed capital formation to GDP and GDP growth (5-year backward moving average)



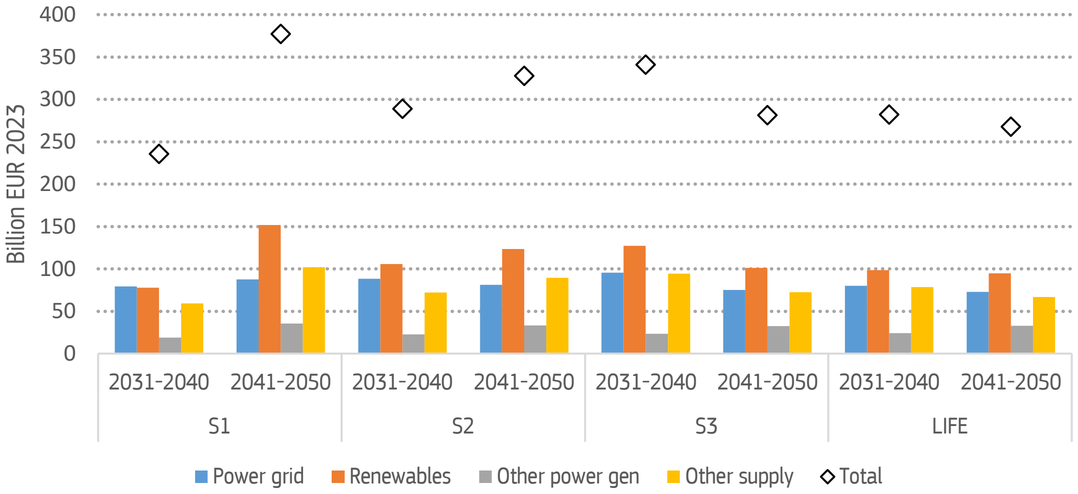
Source: World Bank.

2.2.2. *Supply-side investment needs*

The continued large-scale deployment of renewable and carbon-free sources of energy, in particular electricity, is a necessity across all scenarios and the shares of renewable electricity and energy reach very similar levels by 2050. However, the levels of primary and final energy demand vary somewhat across scenarios, and the speed at which renewable and carbon free energy sources are deployed differ, together with the composition of energy sources (section 1.2).

Over 2031-2050, average investment needs in power plants is projected at around EUR 140 billion per annum across scenarios (Table 26), more than 80% of which would be in renewables, mainly wind and solar. S3 entails a much faster deployment of renewable and other carbon-free power generation, with average annual investment of around EUR 135 billion in 2031-2040, while S1 entails a significant delay in such investments, with very high deployment levels in 2041-2050 (Figure 106). S2 entails a smoother investment profile overall, with lower investment needs in 2031-2040 compensated by higher investment needs in 2041-2050 compared to S3. In turn, LIFE enables a reduction of about EUR 17 billion (12%) in annual investment in power plants in 2031-2050 compared to S3. It also translates into a significant reduction in power grid investment needs of close to EUR 10 billion (10%) per annum.

Figure 106: Average annual investment in power supply



Source: PRIMES.

Given the similar high reliance on variable sources of renewable electricity, all scenarios require significant investment in electricity storage, starting this decade already and extending to 2050, at about EUR 8 billion annually in 2031-2050. Similarly, integrating a very high share of variable and geographically dispersed renewable electricity sources into the electricity network will require the upscaling and upgrading of the transmission and distribution networks. Average annual investment needs in the power grid are comparable across scenarios at about EUR 85 billion per annum, with an early push in investment under S3, a delayed deployment under S1, a more even profile under S2 and a reduction in investment needs under LIFE. Infrastructure investment in carbon storage is projected at around EUR 5 billion per annum on average in 2031-2050 and is similar across scenarios. The faster development of carbon capture and storage under S3 and S2 means that investment in carbon storage infrastructure is anticipated compared to S1, with average annual investment of EUR 9 billion in 2031-2040 under S3, compared to EUR 6 billion under S2 and EUR 1 billion under S1.

The bulk of investment needs on the supply side of the energy system will originate from power utilities and by the regulated operators of the transmission and distribution systems, many of which in the EU are fully or partly publicly owned corporations. Industrial companies also invest to some extent in their own (decarbonised) energy supply infrastructure, as illustrated by recent developments in investments in the generation of green hydrogen from electrolysis by large players in the steel industry. So far, the deployment of renewable electricity has mainly taken place with public support via a range of State aid schemes providing operating aid for generation ([271]). EU funding

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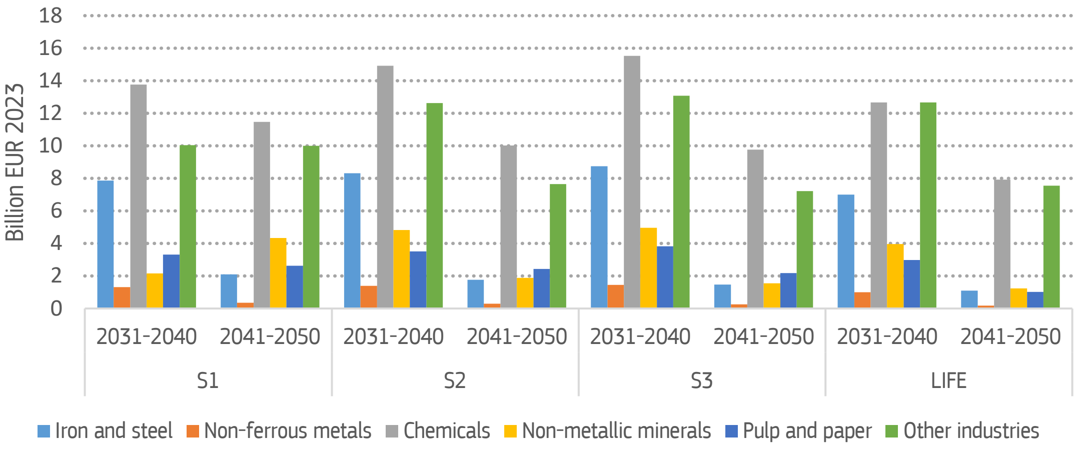
([271]) The Guidelines for Energy and Environmental Aid (EEAG) facilitated the provision of State aid for the deployment of renewable electricity and promoted the competitiveness of aid mechanisms by promoting competition auction mechanisms for the allocation of aid and requiring aid to be granted as a premium over market prices. The Guidelines on State aid for climate, environmental protection and energy (CEEAG), as adopted in 2022, further improved the framework for the allocation of aid for renewable electricity generation. Finally, the Temporary Crisis and Transition Framework further facilitates the granting of aid to accelerate the rollout of renewable energy and energy storage relevant for REPowerEU.

has also facilitated the deployment of renewables in the power sector, including via the Modernisation Fund. To some extent, households are also involved as investors on the supply side via the installation of rooftop solar panels and or/via energy communities, which have risen in importance in recent years. Investment costs for the deployment of renewable electricity have fallen sharply in the last decades, and renewable electricity is set to become cost-competitive on a market basis in a broad range of market situations encountered in Europe by 2030 ([272]). The need for public support should therefore decrease in future and it is expected that deployment should be increasingly driven under market conditions.

2.2.3. Demand-side investment needs, industry,services and agriculture

The shift towards electricity as the principal energy carrier on the demand side, the decarbonisation of industrial processes and improvements in energy efficiency will require significant investment over the coming decades. Investment needs to decarbonise industrial output will be most significant in energy-intensive industries, which tend to be dominated by large privately owned corporations. The estimated investment needs in iron and steel, non-ferrous metals, chemicals, non-metallic minerals and pulp and paper account for about 70% of investment needs in industry in 2031-2050 and the amounts vary little across scenarios (Figure 107). However, LIFE shows clear benefits from higher levels of circularity in industry, with investment needs reduced by 15% compared to S3 (Table 28). This is particularly noticeable in sectors where circularity offers most potential, including pulp and paper (-33%), non-ferrous metals (-31%), iron and steel (-21%) and chemicals (-19%).

Figure 107: Average annual energy system investment needs in industrial sectors



Source: PRIMES.

In the decade 2031-2040, annual energy-system investment needs in energy-intensive industries are projected at around EUR 28-34 billion in S1-S2-S3 (with a reduction of about EUR 7 billion under LIFE compared to S3). These estimates do not capture the full investment costs of new or refurbished production facilities, but only the part that relates

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[272] Sebastian Busch, Ruben Kasdorp, Derck Koolen, Arnaud Mercier, Magdalena Spooner: The Development of Renewable Energy in the Electricity Market. Directorate-General for Economic and Financial Affairs. Discussion Paper 187. June 2023.

to decarbonisation, e.g., the additional cost of a hydrogen-based steel plant relative to a baseline fossil-fuel based plant or investment in carbon capture. In turn, the investment needs related to hydrogen production are captured in supply-side investments (section 2.2.2). The estimates also do not capture possible investment in R&D itself. The faster deployment of industrial carbon capture under S3 and S2 means that investment is anticipated compared to S1, with average annual investment in carbon capture for industry as a whole of EUR 4 billion in 2031-2040 under S3 and S2, compared to less than EUR 1 billion under S1. On average over 2031-2050, however, industrial investment in carbon capture is almost the same across scenarios at about EUR 2 billion per annum.

Investment needs in other industrial sectors are more diffuse, both in terms of sectors concerned and in terms of size of enterprises. While there are no estimates of investment needs by size of enterprises, most SMEs active in manufacturing fall under these “other” sectors. SMEs active in manufacturing account for about 9% of total SMEs, and the vast majority are involved in non-energy intensive manufacturing activities (Table 27). While manufacturing-oriented SMEs account for a large share of total SME gross value added and employment in the economy with a share of 20%, the majority of that is again in SMEs involved in non-energy intensive manufacturing. SMEs are therefore most likely to decarbonise their production processes mainly via electrification and improvements in energy efficiency. The scenarios differ little in terms of investment needs for non-energy-intensive sectors in 2031-2050 at an average of around EUR 10 billion per annum, but S3 and S2 imply a fair degree of early push compared to S1.

Table 27: Indicators of SME activity by sector (2019)

	SME shares in the economy (% of total)		Sectoral split of SMEs (% of economy-wide SMEs)		
	Share in GVA	Share in employment	Number of companies	GVA	Employment
Fossil fuels	7.0%	6.6%	0.0%	0.1%	0.0%
Other mining and extraction	53.1%	59.2%	0.1%	0.3%	0.2%
Energy intensive industries	29.1%	34.4%	0.6%	2.9%	2.0%
Manuf. transport equipment (incl. parts and accessories)	7.9%	14.1%	0.1%	0.6%	0.6%
Manuf. electrical equipment and other machinery	32.0%	35.4%	0.5%	3.1%	2.0%
Other manufacturing	44.4%	65.0%	7.5%	14.3%	15.9%
Electricity, gas, steam and air conditioning supply	22.3%	29.0%	0.7%	1.4%	0.5%
Construction and architecture services	77.8%	89.1%	19.0%	16.4%	17.5%
Transport and storage	49.0%	43.6%	5.4%	5.2%	4.9%
Services	62.7%	69.5%	65.7%	54.3%	55.5%
Water, treatment and waste	46.7%	45.3%	0.3%	1.3%	0.9%
Total	52.9%	64.4%	100.0%	100.0%	100.0%
Memo:			Million	Billion EUR	Million people
All sectors above	52.9%	64.4%	23.1	3332	76.3
Agriculture	66.7%	95.6%	8.7	128	8.3

Source: Eurostat (273).

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(273) The data is calculated from the Structural Business Statistics (SBS), except for agriculture, which is not included in the dataset. For SBS sectors, the table is based on an aggregation of sectors by size class for special aggregates of activities (NACE 2). Fossil fuel sectors (B05, B06, C19); other mining and extraction activities (B07, B08, B09); energy intensive industries (C17, C20, C21, C23, C24);

Table 28: Average annual energy-related side investment needs in industry,services and agriculture (billion EUR 2023)

	S1			S2			S3			LIFE		
EU27	**2031-2040**	**2041-2050**	**2031-2050**	**2031-2040**	**2041-2050**	**2031-2050**	**2031-2040**	**2041-2050**	**2031-2050**	**2031-2040**	**2041-2050**	**2031-2050**
Industry	38	31	35	46	24	35	48	22	35	40	19	30
Iron and steel	8	2	5	8	2	5	9	1	5	7	1	4
Non-ferrous metals	1.3	0.4	0.8	1.4	0.3	0.8	1.4	0.2	0.8	1.0	0.2	0.6
Chemicals	14	11	13	15	10	12	16	10	13	13	8	10
Non-metallic minerals	2.1	4.3	3.2	4.8	1.9	3.3	4.9	1.5	3.2	4.0	1.2	2.6
Pulp and paper	3.3	2.6	3.0	3.5	2.4	3.0	3.8	2.2	3.0	3.0	1.0	2.0
Other	10	10	10	13	8	10	13	7	10	13	8	10
Services	49	78	63	53	73	63	57	67	62	53	68	60
Renovations	6	15	10	11	9	10	16	3	10	14	6	10
New constructions	3	3	3	3	3	3	3	3	3	3	3	3
Energy equipment	40	60	50	39	61	50	38	60	49	36	58	47
Heating	21	40	30	21	40	30	20	40	30	18	38	28
Cooling and others	6	7	7	6	7	6	6	7	6	6	7	6
Electrical appliances and lighting	13	13	13	13	13	13	13	13	13	13	13	13
Agriculture	19	19	19	19	19	19	20	18	19	19	19	19
Memo:												
Real GDP (period average)	19444	22369	20906	19444	22369	20906	19444	22369	20906	19444	22369	20906

Source: PRIMES.

It is also to be noted that the assessment of investments needs, including on the supply side, relate to the investment by the user/investor in asset, e.g., the investment costs related to the installation of windmills, solar panels, a hydrogen-based plant or a heat pump. While the installation costs of these technologies are fully accounted for, the assessment is silent on the sourcing of the equipment, which can be produced domestically or imported, without impact on the figures reported in these sections.

The sourcing of the technologies required for the decarbonisation of the economy, including manufacturing capacities, raw material supply chain and deployment of clean innovative processes, is nevertheless anything but neutral in terms of impacts on the economy, including GDP, investment, sectoral output and employment or skills needs and in terms of geo-strategic implications. The Commission recently conducted an evaluation of investment needs in key net-zero technologies for the period up to 2030 for key sectors in green technologies (274). It estimated that achieving a situation of no dependency on imports in wind, solar photovoltaic, heat pumps, batteries, and electrolysers would require a cumulative investment of about EUR 120 billion (in constant euros of 2022) until 2030. These investments, together with those to decarbonise the different industrial sector, typically require support and market creation to cover the capital and operational expenditure. Maintaining a strategic autonomy in key decarbonisation technologies post 2030 would further add to the economy’s overall investment needs. Section 2.2.7 elaborates on investment needs in key net-zero technologies for the period 2031-2040.

As for investments on the supply side, the bulk of investment in industry should originate from private investors. Member States have nevertheless actively supported the decarbonisation of industry in recent years via State aid mechanisms in favour of R&D&I or in favour of the deployment at scale of innovative, low-carbon processes (275). Similarly, EU funding has been established to support innovation for decarbonisation, including the Innovation Fund and the Horizon Europe programme.

While the deployment at scale of innovative production processes will be an important factor driving investment needs in industry on the path to climate neutrality, investment needs in tertiary sectors involve essentially the deployment of well-established technologies and a renovation drive. To the extent that investments in energy efficiency and the substitution of fossil fuels-based technologies with carbon-free ones generate a positive economic return over their lifetime, the potential barriers to deployment would therefore mainly relate to awareness, access to (long-term) finance at moderate costs and

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(274) SWD (2023) 68 final

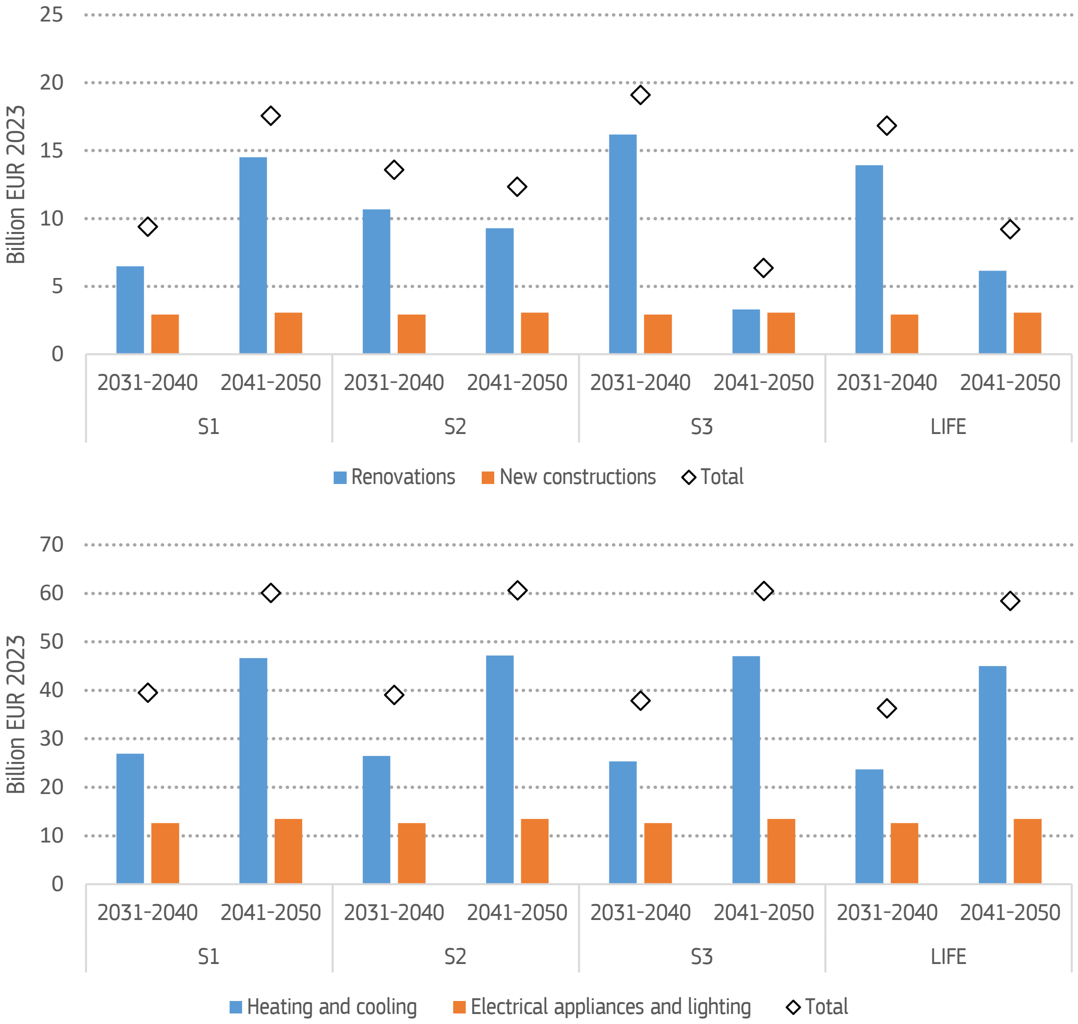
(275) For example, the Commission approved the granting of EUR 1 billion of State aid by Gemarny to Salzgitter to green its steel manufacturing processes, and over EUR 130 million of aid to BASF to replace natural gas-based hydrogen with renewable hydrogen at its chemical production facilities. Recently as well, the Commission approved two schemes notified by Slovakia, with a total budget of over EUR 1.1 billion from the RRF and the Modernisation Fund, aiming at reducing CO_2 emissions in industrial production processes as well as to implement energy efficiency measures in industrial installations. The measures supported under the schemes range from electrification projects to the installation of industrial waste heat recovery technologies. The projects will be selected through an open competitive bidding process and will be ranked on the basis of two criteria: (i) the lowest amount of aid requested per ton of CO_2 emissions avoided, and (ii) the highest contribution to the achievement of the CO_2 emission reduction objective.

access to skills, rather than a matter of innovation and new production processes. These potential barriers would likely be more significant for SMEs than for large players in the tertiary sectors.

The investment needs will also be much more diffuse among sectors and players than in industry, as they will involve a very wide range of services sectors, from retailers, hospitality or finance to energy-intensive data centres and encompass a wide mix of large, medium, small and even micro enterprises. SMEs are likely to account for a significant share of investment needs in the tertiary sector, given that a high proportion of them are active in services sectors and that they represent a large share of economy-wide gross valued added and employment. In 2019, SMEs accounted for about 63% of economy-wide gross value added and close to 70% of overall employment in services. Within SMEs, about 65% of companies are involved in the services sector (Table 27). Public sector investment will also be an important source of investment in the tertiary sector, given the scale of its buildings portfolio in central, regional and local administration, schools, hospitals or judiciary system.

On the buildings themselves, the main driver for investment will consist in the renovation of existing assets with the view to improve overall energy efficiency via insulation. The higher ambition in 2040 under S3 implies a significant early push in the renovation drive compared to S2 and S1, although cumulative investments over the full period 2031-2050 would be similar. Investment in new construction is projected to be relatively small in the three pathways, as the estimates capture only the additional investment in the building’s energy performance relative to a baseline, which already entails high energy performances given the existing stringent standards for new constructions at national and EU level (Figure 108).

Figure 108: Average annual energy system investment needs in services



Source: PRIMES.

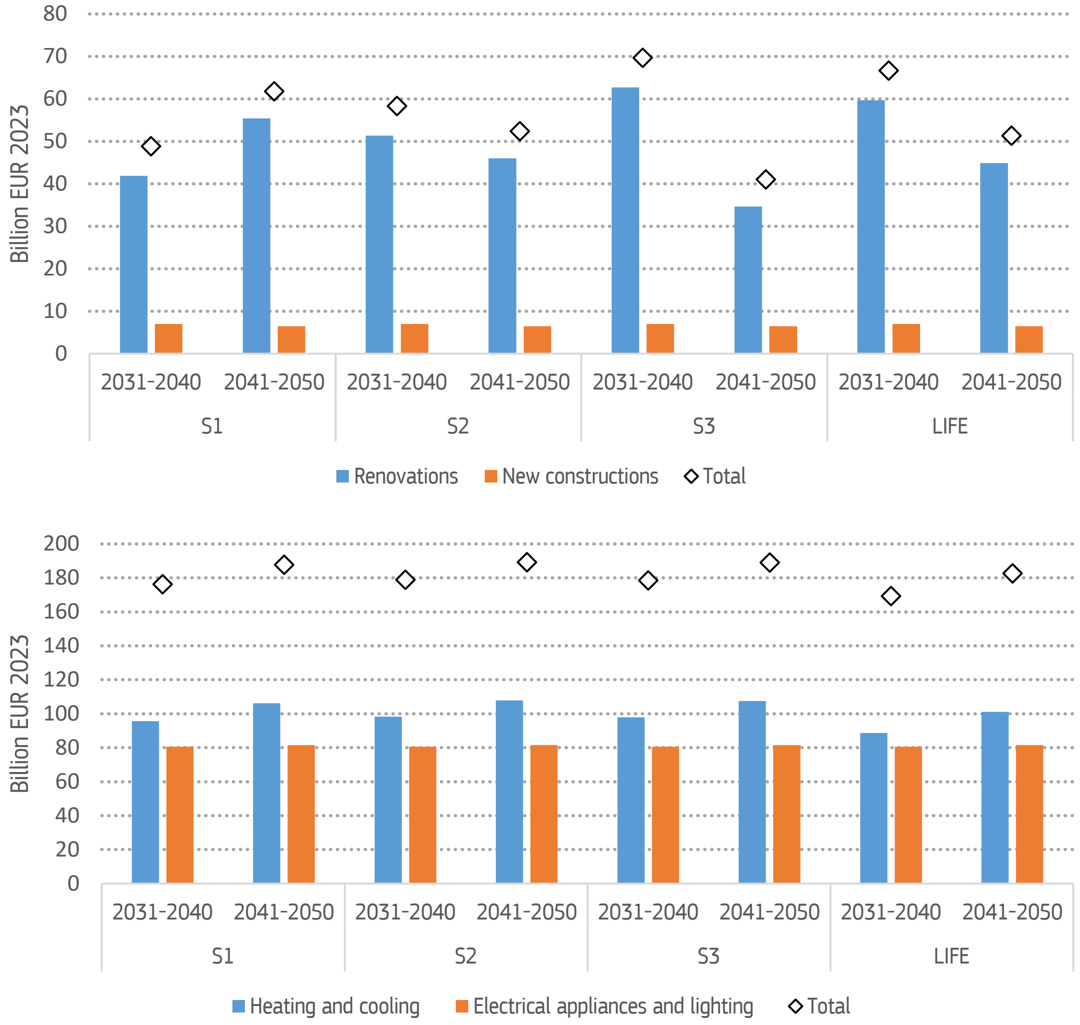
The bulk of the investment needs in tertiary sectors is projected to take place via the acquisition of energy equipment for heating, cooling, appliances and lighting. The full acquisition cost of such equipment is captured in the numbers as reported in Table 28, contrary to investments in on the building structure. The deployment of heat pumps is projected to start at a large scale during this decade already and to continue into the 2031-2050 period as the technology almost entirely replaces conventional technologies for heating. Investment in heat pumps in tertiary sectors is projected at around EUR 23 billion per annum in 2031-2050 under all main scenarios, with a comparable time profile. LIFE, however, enables a slightly lower investment level in tertiary sector heating and cooling systems.

2.2.4. Demand-side investment needs, households

Investments needs for the decarbonisation of the residential sector will be similar in nature to those in the tertiary sectors, focusing on improvements in the energy efficiency of buildings and the substitution of fossil fuels-based technologies for heating and cooling with carbon-free options. However, the scale of the residential building stock and current energy efficiency levels are such that investment needs will be a multiple of those in the tertiary sectors.

As in the tertiary sector, the higher level of ambition in 2040 under S3 would require an early push in renovation rates compared to S2 and S1. The latter would see higher renovation rates in 2041-2050, however, which means that average investment levels over the full period 2031-2050 would be very similar across scenarios, with differences mainly in terms of timing (Figure 109). On average in 2031-2050, renovation investment in the residential sector amounts to around EUR 50 billion per annum across scenarios (Table 29). This represents a significant increase compared to historical investment levels (2011-2020) in renovation and is about 5 times as much as the investment level required in renovation for tertiary sectors. As far as new constructions are concerned, the investment needs are relatively limited and do not vary across scenarios, as the estimates capture only the additional investment in the building's energy performance relative to a baseline.

Figure 109: Average annual energy system investment needs in residential sector



Source: PRIMES.

As in the tertiary sectors, the second big component of investment needs in the residential sector relates to heating and cooling equipment, and electrical appliances and lighting. The full acquisition cost of such equipment is again captured in these numbers (Table 29), which implies that households would incur a non-negligible share of such expenses under any circumstances. The estimated annual investment needs in 2031-2050 in energy equipment amount to around EUR 185 billion across scenarios, about twice the level in

2011-2020. The increase in energy equipment is most significant in heating and cooling systems (+240%) and less so in appliances and lighting (+56%).

The deployment of heat pumps is projected to start at a large scale in this decade and to continue in the following two decades. Average annual investment in heat pumps in 2031-2050 is projected at almost EUR 60 billion across scenarios and the timing of investment over the two decades is very similar, with slightly higher investment levels in 2041-2050 than in 2031-2040. The switch to heat pumps is a constant across the main scenarios, but the LIFE setting enables a reduction in investment in heating systems overall of about EUR 7 billion (10%) per annum in 2031-2050.

As for heating and cooling systems, investment needs for electrical appliances and lighting are estimated at full acquisition costs, which again implies that households would incur a significant share of such expenses under any circumstances. The estimated investment needs in appliances and lighting nevertheless represent about a third of estimated total investment needs in the residential sector, at around EUR 80 billion per annum in 2031-2050 across scenarios.

Investments in the residential sector will fall upon a range of players. While the costs of appliances will be borne mostly by households themselves, the situation is more contrasted for other types of investment needs. Homeowners will bear the full costs of improvements in energy efficiency and shifting to carbon-free heating and cooling systems. They will also reap the full benefits in terms of reduced utility bills and comfort levels.

In contrast, funding the necessary investment in energy efficiency and heating and cooling system for rented accommodation will fall upon a range of actors, from landlords owning a single asset to large property owners/developers and public housing entities. While access to affordable finance could be better for such players than for many home-owning households, the incentives to renovate and upgrade heating and cooling systems might not be as strong, as the benefits of lower utility bills and higher comfort levels arise to tenants. Finally, where distributed heating is well developed, households will also not directly face the need to provide up-front finance for investment, though the capital cost of modernising the centralised heating system will be reflected in their utility bills. Overall, the funding of investment needs in the residential sector will therefore involve a multiplicity of actors, who will need to be provided the appropriate incentives or financial support to act in accordance with the needs to decarbonise the sector.

Table 29: Average annual demand side investment, residential sector (billion EUR 2023)

	S1			S2			S3			LIFE		
EU27	**2031-2040**	**2041-2050**	**2031-2050**	**2031-2040**	**2041-2050**	**2031-2050**	**2031-2040**	**2041-2050**	**2031-2050**	**2031-2040**	**2041-2050**	**2031-2050**
Total	225	250	237	237	242	239	248	230	239	236	234	235
Renovations	42	55	49	51	46	49	63	35	49	60	45	52
New constructions	7	6	7	7	6	7	7	6	7	7	6	7
Energy equipment	176	188	182	179	189	184	179	189	184	169	183	176
Heating	66	74	70	68	75	72	67	75	71	59	69	64
Cooling and others	30	32	31	30	33	31	31	33	32	30	33	31
Electrical appliances and lighting	81	82	81	81	82	81	81	82	81	81	82	81
Memo:												
Real GDP (period average)	19444	22369	20906	19444	22369	20906	19444	22369	20906	19444	22369	20906

Source: PRIMES.

2.2.5. Demand-side investment needs, transport

Estimated average annual investment needs in transport in 2031-2050 are similar across the main scenarios at about EUR 870 billion ([276]). LIFE nevertheless enables a significant lowering of investment needs of about EUR 80 billion (9%) per annum in 2031-2050 compared to S3. While investment in public road transport and rail is 4% and 6% higher under the LIFE setting, the modal shift enables a decrease in the purchase of private cars of nearly EUR 70 billion (13%) per annum in 2031-2050. Similarly, changes in behavioural patterns under LIFE could reduce investment needs in aviation by about EUR 14 billion (23%) annually compared to S3 (Table 30).

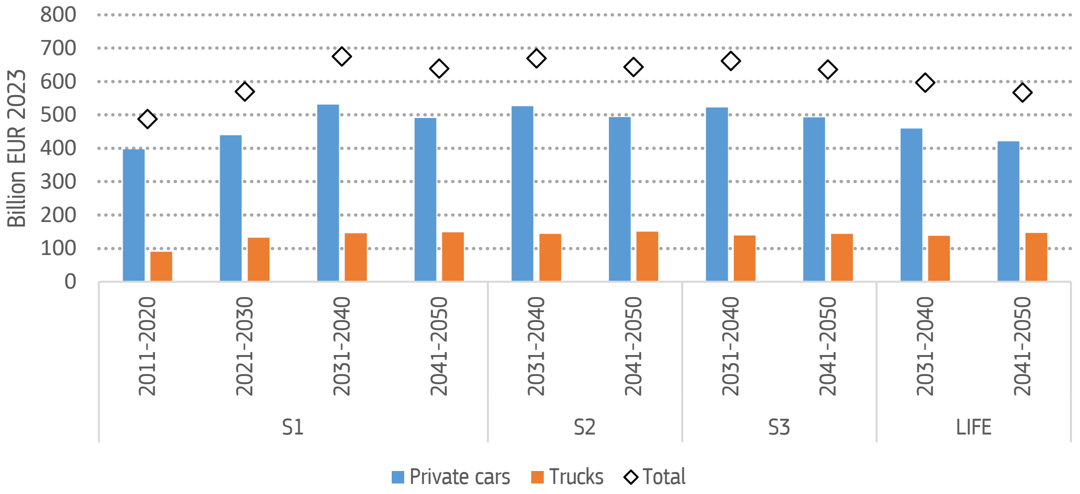
The acquisition of private cars represents the bulk of the investment needs in transport, accounting for around 60% of the total over 2031-2050. This is also the case in historical terms, as the share was 65% in 2011-2020. Average annual investment in the acquisition of private cars in 2031-2050 amounts to about EUR 510 billion across scenarios, which is almost 30% higher than on average in 2011-2020 (Figure 110).

This increase reflects two factors. An increase of around 18% in the number of new private cars purchased annually is projected between 2011-2020 and 2031-2050 under the three main scenarios. LIFE enables this increase to be limited to only 2%. As electric vehicles are deployed, it is also projected that the average purchasing cost of vehicles will increase during the transition. The increase is expected to take place mainly during 2031-2040, before tapering off in the last decade to 2050 as the cost of electric vehicles decreases. Over the entire 2031-2050 period, the average purchasing cost of vehicles is expected to be only around 10% higher than in 2011-2020. In addition, it must be noted that the maintenance and operating costs of electric vehicles, which will become dominant under all pathways, is significantly lower than internal combustion engine cars, which would generate net benefits to users, i.e., mainly households ([277]).

([276]) These figures represent the full acquisition cost of new vehicles, not only the incremental cost related to the decarbonisation of transport. In addition, it should be noted that investments in transport reflect here the expenditures on vehicles, rolling stock, aircraft and vessels plus recharging and refuelling infrastructure. They do not cover investments in infrastructure to support multimodal mobility and sustainable urban transport.

([277]) SWD(2021) 613 final.

Figure 110: Average annual investment needs in transport



Source: PRIMES.

While timely investment in recharging and refuelling infrastructure is critical for the transition to vehicles with zero tailpipe emissions, total investment in alternative fuelling infrastructure is relatively small from the perspective of overall investment needs. The needs are virtually the same across scenarios, with an average annual investment of around EUR 15 billion (1.7% of total investment needs in transport) in 2031-2050, and in terms of timing. The phasing in of zero tailpipe emission vehicles and the EU-wide ban on the sale of other types of light-duty vehicles as of 2035 implies a peak in annual investment in recharging and refuelling infrastructure of around EUR 20 billion in 2036-2040 before tapering off somewhat.

The second large component of investment in road transport relates to trucks, for which average annual investment is projected to increase by around 60% compared to the average in 2011-2020 (Table 30). Investment needs are broadly similar across scenarios. As far as public road transport is concerned the investment needs are relatively small and do not vary much across scenarios, with the exception of the LIFE setting and its associated modal shift towards public transport entails an increase in investment in the sector.

The 3 main scenarios differ little in terms of investment needs for rail, aviation and navigation. As a share of total transport annual average investments over 2031-2050, rail transport represents 5%, aviation represents 7%, and domestic navigation and international maritime transport represent 5-6% of the total. However, they do typically represent a significant increase relative to investment levels in 2011-2020. In contrast, S3 and S2 entail somewhat higher investment levels in international maritime transport than S1. As indicated above also, LIFE also implies a moderately higher level of investment in rail, and a decrease in average annual investment in aviation of EUR 14 billion (23%) in 2031-2050 compared to S3.

Table 30: Average annual demand side investment needs, transport (billion EUR 2023)

	S1			S2			S3			LIFE		
EU27	**2031-2040**	**2041-2050**	**2031-2050**	**2031-2040**	**2041-2050**	**2031-2050**	**2031-2040**	**2041-2050**	**2031-2050**	**2031-2040**	**2041-2050**	**2031-2050**
Total	866	875	870	861	885	873	856	882	869	777	798	787
Road	718	688	703	712	693	702	704	686	695	640	617	629
Public transport	24	29	26	23	30	27	24	30	27	25	31	28
Private cars	531	491	511	526	494	510	523	493	508	459	421	440
Two-wheelers	18	19	19	18	20	19	18	20	19	18	20	19
Trucks	145	149	147	143	150	147	139	144	142	137	147	142
Rail	41	51	46	42	51	47	43	52	47	46	54	50
Aviation	51	70	60	51	70	61	52	70	61	36	58	47
Domestic navigation	13	12	13	13	13	13	12	13	13	13	13	13
International maritime	26	41	33	27	42	35	31	47	39	27	42	35
Alternative fuel infrastructure	16	14	15	16	15	16	16	15	15	14	13	14
Memo:												
Real GDP (period average)	19444	22369	20906	19444	22369	20906	19444	22369	20906	19444	22369	20906

Source: PRIMES.

2.2.6. Sensitivity of investment needs to technology costs assumptions

Cost assumptions for the deployment of mitigation technologies are exogenous to the modelling exercise and constant across all scenarios. They are discussed in more details in annex 6, and summarised in Table 31 for a few technologies on the supply side and for heat pumps, based on averages in each case (average of sizes of installations for solar, wind and heat pumps and average of centralised and decentralised technology for hydrogen).

Over the past decades, the cost of solar, wind or heat pumps has decreased sharply as a result of technological progress and learning by doing fostered by the rising scale of deployment in the EU and globally. However, as demand for renewables and electrification – and the associated raw materials needed for the production of such technologies – is set to increase globally, the sector could potentially be subject to price shocks or sustained price pressures, depending on the capacity of global markets to respond to rising demand, on the ability of circular economy policies to create a resource base for “secondary” materials production in the EU and on the capacity of the EU to create a domestic value chain for primary materials.

Table 31: Technology investment costs assumptions (EUR 2015 per kW)

	2020	2030	2040	2050
Solar, residential	1399	1067	878	841
Solar, commercial	941	711	580	561
Solar, utility	511	394	322	284
Wind onshore	1347	1021	941	920
Wind offshore, shallow	2673	2067	1708	1619
Wind offshore, floating	5107	3212	2531	2478
Hydrogen, low temperature electrolysis – PEM	1586	833	683	529
Hydrogen, low temperature electrolysis – alkaline	1423	675	572	518
Hydrogen, high temperature electrolysis – SOEC (centralised)	2250	1050	792	580
Heat pumps, air to air *	468	551	445	424
Heat pumps, air to water *	1172	1243	1107	1068

*Note: * residential sector only.*

Source: PRIMES.

Understanding how investment needs could be affected by potential increases in technology costs is important. A sensitivity analysis on what a stylised price shock on the cost of renewable technologies would mean in the different scenarios is therefore presented in Table 32. It assumes that supply-side technologies are subject to a 20% increase in costs relative to the standard assumptions used across scenarios. Supply side technologies are most susceptible to be subject to price shocks as they rely on critical raw materials. The shock is tested for the 2031-2040 as it is more likely that demand could outpace supply for such technologies during that time, as the rest of the world also steps up investment to deploy renewables and as EU and worldwide manufacturing facilities take time to be established in response to the likely increase in global demand. It is simulated for solar, wind, new fuels and heat pumps, i.e., green technologies at the core of the Commission proposal on a Net Zero Industry Act that will be critical as enablers of the EU's decarbonisation objectives ([278]).

Given the scale of the investment needs, wind and heat pumps are the technologies that would be most susceptible to trigger an increase in energy system investment requirements. A 20% price shock on wind would add between EUR 9 billion (S1) to EUR 17 billion (S3) to annual investment needs in 2031-2040, while the same shock on heat pumps would add between EUR 11 billion (S3) to EUR 14 billion (S2) annually. A shock on all four technologies considered in this sensitivity analysis would increase annual energy system investment needs (excluding transport) in 2031-2040 by 5.5%, 6.1% and 6.3%, respectively under S1, S2 and S3. As expected, S3 is most affected as it anticipates investment in renewable technologies (Table 32).

It is important to note that the increase in total investment needs from such a shock nevertheless remains relatively small, with a cumulative impact of EUR 44 billion annually under S3, which is equivalent to 0.2% of average GDP over the period. Further, the impact on energy system costs should be smaller still, as capital costs represent only a share of total costs and as the shock would only affect new capacity installed during the period and not the entire capital stock. In this regard, a price shock on renewables technologies (or raw materials needed for their production) is therefore fundamentally different from a price shock on fossil fuels.

Table 32: Sensitivity of average annual energy system investment needs (excluding transport) to a price shock

	Deviation vs. default (bn EUR 2023)			**% change over default**		
EU27	**S1**	**S2**	**S3**	**S1**	**S2**	**S3**
Energy system invest. (default costs)	566	634	700			
Impact of 20 % cost increase vs. default::						
Solar	5	6	7	0.9%	1.0%	1.0%
Wind	9	14	17	1.7%	2.1%	2.4%
New fuels	3	5	9	0.6%	0.8%	1.2%
Heat pumps	13	14	11	2.4%	2.2%	1.6%
Cumulative increase on all of the above	31	38	44	5.5%	6.1%	6.3%

Source: PRIMES.

2.2.7. Investment needs for net-zero technology manufacturing capacity

The resilience of future energy systems will be measured notably by a secure access to the technologies that will power those systems: wind turbines, solar PV, electrolysers, batteries, heat pumps and others. In this context, the Net-Zero Industry Act is part of the actions announced in the Green Deal Industrial Plan of February 2023, aiming at simplifying the regulatory framework and improving the investment environment for the Union's manufacturing capacity of technologies that are key to meet the Union's climate neutrality goals and energy targets.

([278]) Given that there is very little difference across scenarios regarding the deployment of electric vehicles, no shock is simulated on the transport side.

Net-zero technologies are at the centre of strong geostrategic interests and at the core of the global technological race, as exemplified by the United States' Inflation Reduction Act and China's dominance in manufacturing of some cleantech. Fostering a competitive and resilient European net-zero industry can play a significant role in reducing high import dependence for key net-zero technologies, while guaranteeing affordable, reliable and sustainable clean energy to EU citizens and businesses.

This section estimates the investments needed to build an EU-based manufacturing capacity for five key net-zero technologies: wind, solar PV, batteries, heat pumps and electrolysers. The analysis focuses on the investment needs for the decade 2031-2040 (279).

Table 33: Manufacturing capacity and investment needs per technology (2031-2040)

Technology	Max annual technology deployment in 2030-2040	Installed EU manufacturing capacity in 2030	Market share of EU production	EU manufacturing capacity in 2040	New manufacturing capacity needed post-2030	Factory CAPEX (M€22/unit/year)	Manufacturing capacity investment needs (bn EUR)
Wind	62	33	85%	53	20	260	5.2
Solar PV	55	23	45%	25	2	340	0.7
Heat Pump	53	31	60%	32	1	333	0.5
Battery cell	729	549	90%	656	107	144	15.4
Electrolysers	49	25	100%	49	24	60	1.4
Total							**23.3**

Note: manufacturing capacity needed and investment needs per technology. Capacity is expressed in GWh/year for batteries and GW/year for the other technologies (GW of electricity for electrolysers, GWAC for solar PV)

Source: Commission own calculations based on PRIMES (280)

In a scenario where the EU achieves the market shares indicated in the Net-Zero Industry Act proposal(281), total investment needs reach a cumulative EUR 23 billion over 2031-2040. Two thirds of those investments are for battery manufacturing, one fifth to one quarter are for manufacturing of wind technologies, and electrolysers, solar PV and heat pumps represent each between 2 and 6% of the total. This level of investment needs takes into account that investments in manufacturing capacity already take place by 2030, so the EU has already a manufacturing base in place in 2030. Manufacturing investment needs would be lower in scenarios S1 and S2, as in 2040, net installed renewable power capacity is lower by 7% in S2 and by 16% in S1 compared with S3.

2.2.8. *Technical feasibility*

The cost-efficient decarbonisation relies on the deployment of net-zero technologies with varying but sufficient degree of maturity to be used on a large scale. The maturity of

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(279) Investment needs until 2030 have been assessed in the Commission Staff Working Document Investment needs assessment and funding availabilities to strengthen EU's Net-Zero technology manufacturing capacity (SWD(2023) 68 final.

(280) See Annex 8 of SWD(2023) 68 final.

(281) Objectives of global market shares of 85% for wind, 45% for solar PV, 60% for heat pumps, 90% for battery cells and 100% for electrolysers.

technologies is an important driver of the projected portfolio of net-zero technologies. In recent years, pressing innovation gaps have been addressed which resulted in significant improvements of the technology readiness. (282) For the bulk of net-zero technologies needed to reach the 2040 targets, the Technology Readiness Level (TRL) already amounts to at least 8 (out of 9) which means that they are in an advanced deployment stage. (283)

DAC is at the lower end of the deployment stage having a TRL of 7. Bioenergy with carbon capture and storage (BECCS) is the only technology that has a TRL of 5-6 ("Technology demonstrated in relevant environment") indicating that it is not fully established. However, there are already a variety of BECCS demonstration projects in Japan, Norway, Sweden and the United Kingdom.

Due to their relatively low maturity, DAC and BECCS come into play only between 2030 and 2040 allowing the technology to be further developed over the coming years. In 2040, DAC and BECCS is projected to capture 16 MtCO2 (S1) to 155 MtCO2 (S3) making up around 0.3% (S1) to 3.3% (S3) of 1990 total GHG emissions. The S3 scenario anticipates decarbonisation via DAC up to 2040.

2.2.9. Other related investment needs

The needs analysed above concern mainly the investment required to decarbonise the energy system, and to some extent the investment required to increase the domestic production of the clean technologies that will be essential to decarbonisation efforts. Beyond the energy system, additional climate-related investments will be necessary in the coming decades, in two main areas: LULUCF sectors and agriculture, and climate adaptation.

Investment in the land sector. The Bioeconomy Strategy Progress Report 2022 (284) finds that although at least EUR 2.7 billion of private investment have been unlocked to develop new technologies for sustainable and circular bio-based value chains more is needed to transfer knowledge into innovations due to the lack of financing. These investments are needed for example to tap the biomass potential, new biorefineries and plant lignocellulosic crops on EU cropland as feedstock for bioenergy.

The LULUCF sector plays already a very important role with its net removal, and it will become even more important in the future. Importantly investments into the sector are needed to maintain and enhance its capacity as a carbon sink, particularly considering the recent decline of the LULUCF net removals. Nature-based removals in the LULUCF and agricultural sector provide many options for implementation at large scale, but they require significant additional investments. Examples for such nature-based removals are afforestation and reforestation, peatland restoration activities, as well as the reduction of

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(282) IEA (2023). "Net Zero Roadmap. A Global Pathway to Keep the 1.5°C Goal in Reach"

(283) The TRL evaluation is based on the EU's Clean Energy Technology Observatory (CETO).

(284) European Commission, Directorate-General for Research and Innovation, European bioeconomy policy – Stocktaking and future developments – Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Publications Office of the European Union, 2022, https://data.europa.eu/doi/10.2777/997651

emissions from agricultural soil (e.g., through practices such as agroforestry or paludiculture). More generally, nature-based solutions currently receive only a small proportion of the existing financing on climate-mitigation, if one considers their potential ([285]). Globally, they can provide about one-third of the cost-effective climate mitigation needed until 2030 to stabilize warming to below 2°C ([286]). Notably, offsets on the voluntary market are of variable quality, which is why investments should be directed towards nature-based solutions that are ecologically sound, socially equitable and designed for the medium and long-term ([287]). According to GLOBIOM modelling, within the EU about 85% of available nature-based solutions with costs up to 200 €/tCO_2-eq are available for up to 100 €/tCO_2-eq in 2040 and about 65% for up to 50 €/tCO2-eq (see Annex 8).

Investments in adapatation. The European Climate Law requires the Union institutions and Member States to ensure continuous progress in enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change. As part of this, the Commission adopted a new EU strategy on adaptation to climate change in 2021 ([288]). The strategy sets out how the European Union can adapt to the unavoidable impacts of climate change and become climate resilient by 2050. It builds on four principal objectives: smarter adaptation, faster adaptation, more systemic adaptation and stepped-up international action on adaptation.

While the need for increased investment in climate adaptation and resilience is obvious, there is a big knowledge gap regarding the scale of the investment needs, in part because of methodological complexities. Existing estimates of adaptation investment needs at Member State level vary significantly depending on the methods used, the underlying assumptions (e.g., about the frequency and scale of hazards in future, or the time horizon chosen), the hazards taken into consideration, or the level of adaptation/resilience sought. The fact that the returns to investment are frequently reaped at the societal level rather than at the individual level and insufficient knowledge about adaptation investments also means that private agents do not sufficiently assess their own needs.

At EU level, there is currently no consolidated and coherent estimate of climate adaptation investment needs. The Commission is nevertheless addressing this knowledge gap via a number of initiatives, including the ongoing European Climate Risk Assessment ([289]) exercise and a tender ([290]) that will lead to a comprehensive assessment of adaptation investment needs at the EU level.

([285]) Girardin, C. A., Jenkins, S., Seddon, N., Allen, M., Lewis, S. L., Wheeler, C. E., ... & Malhi, Y. (2021). Nature-based solutions can help cool the planet—if we act now. Nature, 593(7858), 191-194.

([286]) Griscom, Bronson W., Justin Adams, Peter W. Ellis, Richard A. Houghton, Guy Lomax, Daniela A. Miteva, William H. Schlesinger et al. "Natural climate solutions." Proceedings of the National Academy of Sciences 114, no. 44 (2017): 11645-11650.

([287]) Girardin, C. A., Jenkins, S., Seddon, N., Allen, M., Lewis, S. L., Wheeler, C. E., ... & Malhi, Y. (2021). Nature-based solutions can help cool the planet—if we act now. Nature, 593(7858), 191-194.

([288]) COM(2021) 82 final and accompanying impact assessment SWD(2021) 25 final.

([289]) European Climate Risk Assessment.

([290]) CINEA/2023/OP/0013.

2.2.10. The role of the public sector and carbon pricing revenues

As pointed at above, direct public sector investment is likely to be important but contained to a relatively limited number of sectors. The key investment requirement on the public sector will relate to the renovation of buildings and the shift to decarbonised heating and cooling systems and transport modes across all levels of public administration and public services.

Indirectly, however, the public sector is likely to play a much more significant role in fostering the necessary levels of investment, as has been the case in the past. In past decades, public funding at the level of the EU and Member States has played a critical role in enabling the deployment of renewable electricity and the sharp reduction in the costs of solar, wind or other renewable sources of energy. Similarly, Member States have long provided support for the renovation of the residential housing stock. While such expenditures are accounted as current expenditure in government accounts, in essence they positive impact the capital stock of the economy as a whole.

Looking forward, public support will remain critical for the successful research, development and deployment at scale of the technologies that will underpin the necessary transformation of the EU economy. The need to ensure a fair transition will likely require continued targeted support from the public sector for the renovation of the residential building stock and the transition to carbon-free sources of heating and cooling. Similarly, support might be needed in transport in order to address concerns about transport poverty (section 2.4.1).

Similarly, direct public support will be essential for the decarbonisation of industry, the deployment of renewable hydrogen at scale and the development of carbon capture and storage/use. Finally, as evidenced recently with the adoption of the Inflation Reduction Act in the United States, the Temporary Crisis and Transition Framework for State aid in the EU, and the Commission proposal for the Net Zero Industry Act and Green Deal Industrial Plan, public support will be essential for the EU to build or strengthen its position in strategically and economically critical manufacturing sectors and their associated value chains, including wind and solar energy technologies, electrolysers and fuel cells, batteries and electricity storage, heat pumps and carbon capture and storage. It is necessary to collectively address those challenges and coordinate national measures to avoid any risk of distorting competition and fragmenting the single market.

The extent to which public finances could be affected by the transition itself and by the policy options reviewed in this impact assessment will depend on a multiplicity of factors, many of which will be determined at the level of Member States. On the revenue side, there should be a base erosion for environmental taxes as the EU progresses towards climate neutrality. In 2021, environmental taxes represented about 2.2% of GDP or 5.5% of total government revenue from taxes and social contributions (291), the bulk of which is linked to energy taxes linked to fossil fuels.

While no model-based assessment of direct and indirect public investment needs or impacts on total government revenues has been carried out, the pathways considered in

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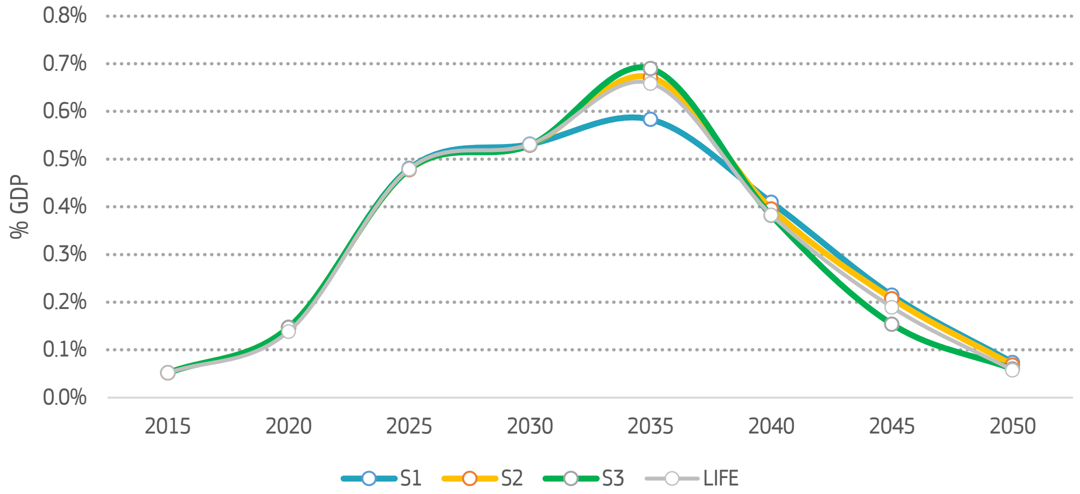
(291) Environmental tax statistics

this impact assessment provide an indication of the level of resources that the public sector could obtain from carbon pricing. While the use of these revenues will face competing demands, including to ensure a fair transition, they should be sizeable enough to also fund public support for investment.

Revenues from carbon pricing are very difficult to predict. While the emissions pathways for the sectors subject to the ETS (which will cover nearly the entire scope of domestic CO_2 emissions by 2030) are well defined in the scenarios, the price of ETS allowances is not a variable that the Commission predicts as such. The revenues from carbon pricing are nevertheless assessed on the basis of the carbon values that underpin the mitigation scenarios in the PRIMES model. These are not predictions of ETS carbon prices per se, but rather model-based carbon values necessary to achieve given levels of mitigation under the policy and techno-economic assumptions made in each scenario. Using such carbon values and based on the profile of CO_2 emissions over the transition period, carbon revenues are projected to peak around 2035. While carbon values are projected to increase beyond that time, the fall in CO_2 emissions will quickly erode the revenue base itself.

At their peak, revenues from carbon pricing could amount to close to 0.7% of GDP, which is significant in relation to the total energy investment needs for the transition to climate neutrality, and the contribution that may be required from the public sector (Figure 111). Between 2031 and 2050, total revenues from carbon pricing, based on the carbon values from the PRIMES model, would amount to about EUR 1 500 billion. This compares with cumulative energy system investment needs (excluding transport) of about EUR 13 100 billion, i.e., close to 11% of the total. Such projections are obviously very sensitive to assumptions regarding carbon values.

Figure 111: Carbon pricing payments



Source: PRIMES.

2.3. Competitiveness

2.3.1. Total energy system costs

Total energy system costs (292) include capital costs (for energy installations such as power plants and energy infrastructure, end-use equipment, appliances and energy related costs of transport), energy purchase costs (fuels, electricity and heat) and direct efficiency investment costs, the latter being also expenditures of capital nature. Capital costs (also for the equipment that is scrapped prematurely, *i.e.*, reflecting the costs of stranded assets) are expressed in annuity payments, calculated on the basis of sector-specific discount rates. For transport, only the additional capital costs for energy purposes (additional capital costs for improving energy efficiency or for using alternative fuels) are covered, but not other costs including the significant transport related infrastructure costs *e.g.*, related to rail to accommodate the increased rail capacity. Direct efficiency investment costs include additional costs for house insulation, double/triple glazing, control systems, energy management and for efficiency enhancing changes in production processes not accounted for under energy capital and fuel/electricity purchase costs. Unless specified, energy system costs do not include any disutility costs associated with changed behaviour, nor the cost related to the auctioning of allowances that leads to corresponding revenues that can be used in *e.g.*, in the social climate fund. Energy system costs are calculated *ex-post* after the model is solved (293).

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(292) The model-based analysis is a technical exercise based on a number of assumptions that are shared across scenarios. Its results do not prejudge the future design of the post-2030 policy framework.

(293) The calculated cost is influenced by the discount rate used. The discount rate of 10% is used to reflect in the perspective of the private investor faced with real world investment constraints. It is also applied ex-post to calculate system costs. The value of 10% is kept constant between modelling scenarios, to ensure comparability across scenarios. For planning investments, the model uses slightly different discount rates that are representative of investors' hurdles rates in the sector. A detailed explanation of this methodology is provided in the annex of the 2016 reference projection: https://ec.europa.eu/energy/data-analysis/energy-modelling/eu-reference-scenario-2016_en.

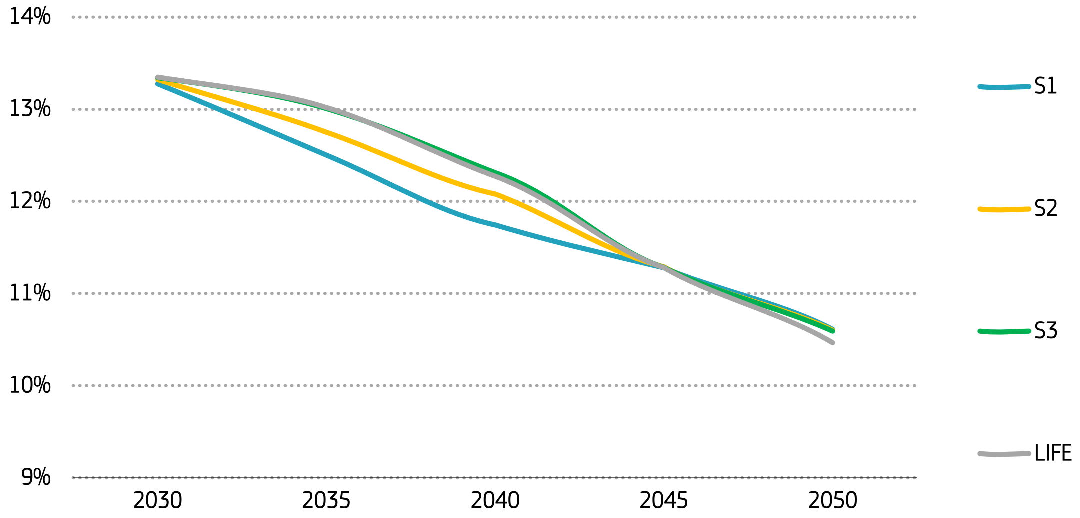
Table 34: Sectoral disaggregation of energy system costs (% difference vs. S2)

	2031-2040			2041-2050		
EU27	**S1 vs. S2**	**S3 vs. S2**	**LIFE vs. S3**	**S1 vs. S2**	**S3 vs. S2**	**LIFE vs. S3**
Total energy system costs	-2.1%	1.5%	-2.6%	-0.8%	0.1%	-4.6%
Industry	-3.4%	2.3%	-3.8%	-1.1%	0.6%	-8.7%
Tertiary	-0.5%	0.5%	-1.1%	0.2%	-0.3%	-2.7%
Residential	-1.4%	1.0%	-1.4%	-0.6%	0.2%	-2.0%
Transport	-3.1%	2.0%	-4.0%	-1.4%	-0.1%	-6.0%
Capital and direct efficiency investment costs	-1.8%	1.7%	-2.4%	-1.3%	1.2%	-3.4%
Industry	-3.2%	1.6%	-3.5%	-2.0%	0.8%	-8.1%
Tertiary	-2.1%	2.4%	-1.9%	-0.7%	1.0%	-1.9%
Residential	-1.9%	1.6%	-1.6%	-1.0%	0.9%	-0.4%
Transport	-1.1%	1.6%	-4.0%	-2.0%	2.0%	-7.5%
Energy purchases	-2.3%	1.3%	-2.7%	-0.4%	-0.7%	-5.5%
Industry	-3.4%	2.5%	-3.8%	-0.8%	0.5%	-8.9%
Tertiary	0.3%	-0.5%	-0.6%	0.8%	-1.0%	-3.1%
Residential	-0.7%	0.3%	-1.1%	0.0%	-0.8%	-4.3%
Transport	-3.9%	2.1%	-4.0%	-1.0%	-1.3%	-5.1%

Source: PRIMES.

Total energy system costs are relatively close across scenarios. In 2031-2040 they are 2.1% lower in the S1 scenario and 1.5% higher in S3 compared with the S2 scenario. In the residential sector, system costs are lower by 1.4% in S1 and higher by 1% in S3 compared with S2. While for the tertiary sector system costs are relatively similar across scenarios, they are 3.1% lower in S1 and 2% higher in S3 compared with S2 in 2031-2040. Capital costs and direct efficiency investment costs are increasing from S1 to S2 and S3 (-1.8% for S1 and +1.3% for S3 compared with S2 in 2031-2040), as higher ambition requires investments. For the tertiary sector, higher ambition and investments are also associated with lower energy purchases. This is illustrated by the fact that energy purchases are higher by 0.3% in S1 vs S2 and lower by 0.5% in S3 vs S1 for this sector in 2031-2040. For the following decade, the difference is even +0.8% and -1% respectively for S1 and S3 vs S2. As regards LIFE, energy system costs are lower than for the other scenarios in 2041-2050, as the increase in capital costs and direct efficiency investment costs is more than compensated by the 5.5% decrease in energy purchases compared with S3.

Figure 112: Total energy system costs as a percentage of GDP



Source: Commission based on the PRIMES model.

As a percentage of GDP, energy system costs decrease between 2030 and 2040 as GDP growth offsets the slight increase in system costs. As a result, the percentage of system costs over GDP decreases from 13.3% in 2030 to 11.7%-12.3% in 2040 and to 10.6% in 2050 for S1, S2 and S3 (10.4% for LIFE), as illustrated by Figure 112. In 2040, energy system costs represent a lower share of GDP in S1 (11.7%) than in S2 (12.1%) and S3 and LIFE (12.2-12.3%). Decreasing energy purchases are the main reason for the decrease in the share of energy system costs as a percentage of GDP.

Importantly, energy system modelling captures well the energy system costs but the costs associated with the transition are much broader and the challenge to address them much bigger. Rapid structural change will lead to the devaluation of equipment and other assets of several industries notably in fossil fuels extraction and processing. It will also force consumers to replace durable consumer goods and renovate houses more quickly. Workers with sector specific knowledge might lose part of their investment in training and education. These phenomena will have to be addressed by active labour market policies with greater demand on public expenditures.

2.3.2. Energy system costs and prices for industry

Table 35 shows energy costs for industry in relative terms compared to S1. Necessary implementation of low-carbon processes and energy efficiency improvements lead to stronger differentiation of capital-related costs across scenarios for energy-intensive industries in 2031-2040, with a difference of -3.4% for S1 and +1.7% for S3 compared with S2 (respectively -2.6% and +1.4% for non-energy intensive industries). Energy purchases increases across scenarios by 2040, with e-fuels driving the variation from S1 to S2 (-3.4% for S1 vs S2) and to S3 (+2.5% vs S2), in line with the level of decarbonisation and their role to substitute remaining fossil fuels. The part of the energy purchases that are linked to carbon revenues could also be channelled back toward industry through funding mechanisms encouraging the transition.

Table 35: Energy system costs for industry (% difference vs. S2)

	2031-2040			2041-2050		
EU27	**S1 vs. S2**	**S3 vs. S2**	**LIFE vs. S3**	**S1 vs. S2**	**S3 vs. S2**	**LIFE vs. S3**
Total energy system costs	-3.4%	2.3%	-3.8%	-1.1%	0.6%	-8.7%
Energy intensive industries	-4.4%	2.9%	-5.0%	-1.3%	0.3%	-11.5%
Non-energy intensive industries	-1.1%	0.9%	-0.9%	-0.3%	1.3%	-1.7%
Capital and direct efficiency investment costs	-3.2%	1.6%	-3.5%	-2.0%	0.8%	-8.1%
Energy intensive industries	-3.4%	1.7%	-4.5%	-1.8%	0.4%	-10.3%
Non-energy intensive industries	-2.6%	1.4%	-0.6%	-2.3%	1.9%	-1.9%
Energy purchases	-3.4%	2.5%	-3.8%	-0.8%	0.5%	-8.9%
Energy intensive industries	-4.7%	3.3%	-5.1%	-1.2%	0.3%	-11.9%
Non-energy intensive industries	-0.8%	0.8%	-1.0%	0.3%	1.1%	-1.7%

Note: Energy purchases include carbon revenues.

Source: PRIMES.

Table 36 shows the evolution of the average electricity prices for industry in 2040 and 2050. They remain fairly stable on the long run and are similar across all scenarios, reflecting the evolution of the electricity production system costs that evolve towards lower operating costs and higher capital-related costs. Low-carbon capacities substitute CO_2-emitting assets progressively driving the system to a more capital-based structure less exposed to fossil fuels prices.

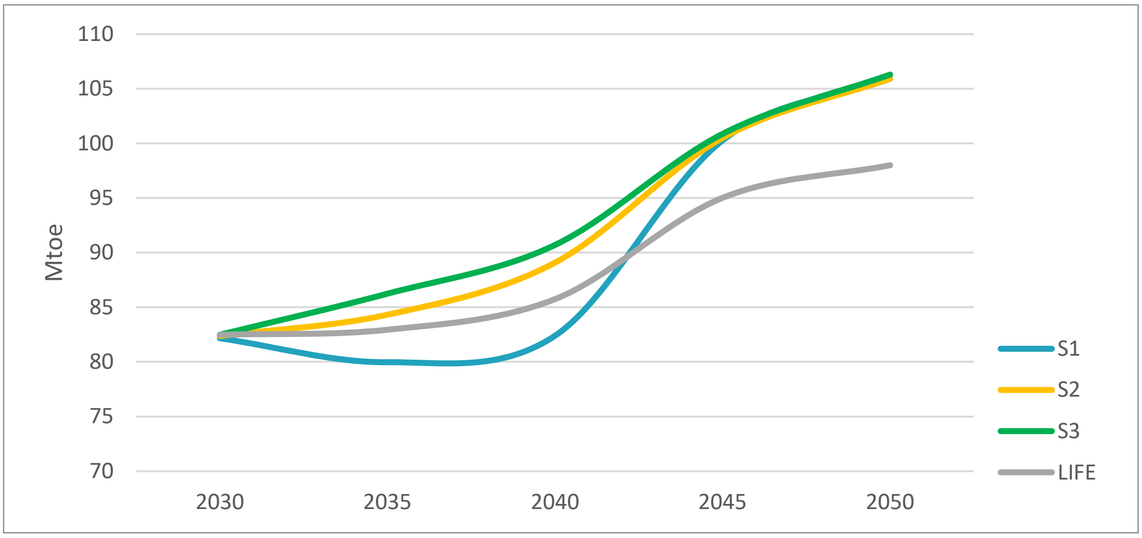
Table 36: Average final price of electricity for industry

EUR23/MWh	2030	2040	2050
	S1, S2, S3, LIFE	**S1, S2, S3, LIFE**	**(S2)**
Industry	133	130-131	131

Note: The electricity prices shown here reflects the evolution of the average electricity production costs to supply industry (i.e., considering their load profile) as well as the taxes applied to the sector.

Source: PRIMES.

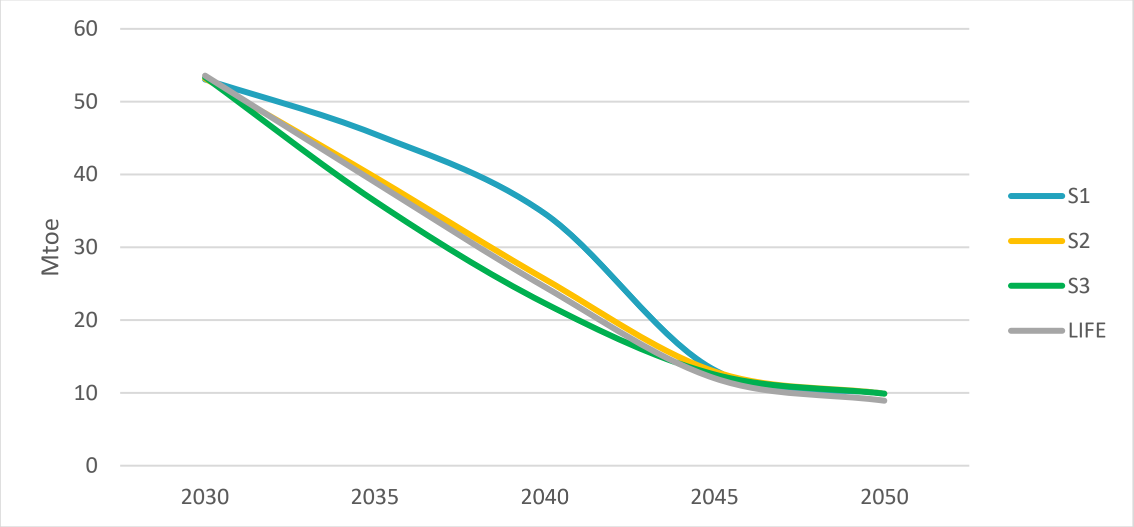
Figure 113: Consumption of electricity by industry



Source: PRIMES.

Figure 113 Shows also that electrification is delayed in the scenario S1 and has to accelerate significantly in 2040-2045 to catch up with the needed level by 2050. In scenario S1, the necessary increase of almost 20 Mtoe of electricity consumption by industry in only 5 years between 2040 and 2045 will put the system under pressure and will make it vulnerable to any possible delay in the deployment of some technologies such as renewables or storage.

Figure 114: Consumption of gas by industry



Source: PRIMES.

Figure 114 Shows that the increase in electricity consumption is concomitant with a swift decrease of gas consumption in industry. This is possible thanks to the investments made by industry in energy equipment, both in energy efficiency and in switching from fossil fuels to electricity. The phase-out of gas is slower in S1 compared with the other scenarios due to the lower investments made in energy equipment but catches up with the other scenarios by 2045. In all scenarios, gas consumption is reduced to around 10 Mtoe for all EU industry in 2050.

2.3.3. Energy system costs and prices for services

For services, total energy system costs are 0.5% lower in S1 and 0.5% higher respectively in S1 and S3 vs S2 for the decade 2031-2040 (Table 34). On the contrary, for the following decade 2041-2050, energy system costs are slightly higher in S1 (+0.2%) and lower in S3 (-0.3%) compared with S2. This illustrates that more ambitious scenarios lead to lower system costs for services. LIFE shows even lower cost, 2.7% less than in the S3 scenario in 2041-2050.

Increases in the capital-related cost in 2031-2040 are mostly related to investments to renovate buildings, with stronger energy efficiency related renovation effort in S3 (up to 2.4% more) than in S2, and which results in lower energy purchases expenses. Indeed, energy purchases are 0.5% lower in S3 compared with S2 in 2031-2040.

Table 37 shows the evolution of the average electricity prices for services in 2040 and 2050, which follow a similar trend as the prices for industry, remaining fairly stable on the long run and similar across all scenarios.

Table 37: Average final price of electricity for services

EUR23/MWh	2030	2040	2050
	S1, S2, S3, LIFE	S1, S2, S3, LIFE	(S2)
Services	255	249	255

Note: The electricity prices shown here reflects the evolution of the average electricity production costs to supply the services sector (i.e., considering its load profile) as well as the taxes applied to the sector.

Source: PRIMES.

2.3.4. Energy system costs and prices for transport

For transport too, total energy system costs are lower in S1 and higher in S3 compared to S2, respectively 3-3.1% and +2% for the decade 2031-2040 (see Table 34). LIFE leads to even lower system costs in 2041-2050, 6% lower than S3 in 2041-2050.

For LIFE, an increase in car occupancy due to higher use of shared mobility, as well as a stronger modal shift from passanger cars to public transport and rail explain the lower capital related costs in both decades in S2 and S3 compared with S1. Higher capital-related costs in S3 in 2031-2040 translate in lower energy purchases for this scenario in the following decade (-1.3% in S3 vs S2).

Table 38 shows the evolution of prices of electricity and gasoline for private transport in 2040 and 2050, which remaining stable on the long run.

Table 38: Energy prices for private transport in S2

EUR23/MWh	2030	2040	2050
Electricity*	226	222	225
Gasoline	215	279	280

*Note: *Average final price of electricity. The electricity prices shown here reflects the evolution of the average electricity production costs to supply the sector of private transport (i.e., considering its load profile) as well as the taxes applied to the sector.*

Source: PRIMES.

2.3.5. Costs related to mitigation of GHG emissions in the LULUCF sector and non-CO2 GHG emissions

2.3.5.1.Sectoral mitigation costs

Table 39 provides an overview of the average annual costs in the LULUCF sector and for non-CO2 emissions in the different scenarios. The costs are related to the implementation of abatement technologies or nature-based removal solutions. The technical available potential for nature-based removals and mitigation measures differs between the two decades, leading to varying annual costs across decades, as the entire potential up to the respective maximum carbon value is implemented.

Table 39: Costs related to GHG emissions mitigation in LULUCF and non-CO2

Average annual costs [EUR 2023 billion/year]	**2031-2040**			**2041-2050**			**2031-2050**		
	S1	**S2**	**S3**	**S1**	**S2**	**S3**	**S1**	**S2**	**S3**
Mitigation of LULUCF GHG emissions	1.1	2.5	2.5	1.6	2.8	2.8	1.3	2.7	2.7
Mitigation of non-CO2 GHG emissions	0.0	0.7	3.4	3.9	4.1	5.0	2.0	2.4	4.2
- of which in the agriculture sector	0.0	0.4	3.2	3.8	3.9	4.8	1.9	2.2	4.0

Note: All costs are expressed in EUR2023.

Source: GLOBIOM, GAINS.

S1 does not assume specific LULUCF and non-CO2 policies in 2040, showing smaller mitigation costs for the 2031-2040 period. Both sectors have to contribute to meeting climate neutrality in 2050 also in that scenario, which entails some mitigation action and associated costs in the last decade 2041-2050.

For LULUCF, additional nature-based removals such as improved forest management, afforestation or rewetting are applied in S2 and S3 by 2040. The associated average annual cost in these scenarios amount to EUR 2.5 billion in 2031-2040 and EUR 2.8 billion in 2041-2050.

The average annual costs associated to mitigation of non-CO2 emissions over the 2031-2040 period are around EUR 0.7 billion per year in S2 and around EUR 3.4 billion per year in S3. Over the 2041-2050 period, the average annual costs are higher than in the previous decade: EUR 3.9 billion in S1, EUR 4.1 billion in S2, and EUR 5 billion in S3. Most of the annual mitigation costs take place in the agriculture sector, which represents the bulk of the unabated non-CO2 GHG emissions after 2030. The mitigation costs of the sector are reflected in the macro-economic analysis presented in section 2.3.6.

2.3.5.2.The LIFE variant

The LIFE variant shows limited impacts on the agricultural sector. An analysis with the CAPRI model shows a decrease in 2040 by -5.4% (294) of the total revenues, most pronounced in meat production (-12% to -20%), while other activities such as vegetables and permanent crops benefit (+12%).

The LIFE variant demonstrates that freed up land from fodder production could be used for additional forest management land, which may counterbalance the overall decrease with additional income opportunities for example through other agricultural products, carbon farming, payment for ecosystem services (PES), and other activities.

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(294) Consumer prices for products from organic agriculture are conservatively assumed to be similar to conventional agricultural products. However lower outputs of products or higher quality of products may lead to higher producer prices, partly buffering the losses. Also, consumers' budgetary savings for food, which result from changing diets, which may be reinvested into food products with higher quality are not considered.

2.3.6. Sectoral output and international trade

As highlighted in section 2.4.3, the impacts of the climate and energy transition and the 2040 target need to be assessed while bearing in mind a general context that is affected by a multiplicity of factors, including the increased share of services in mature EU economies, digitalisation, the projected gradual decline in the EU population and the falling share of the EU in global GDP. Abstracting from such changes, the level of ambition in 2040 does nevertheless impact sectoral output in somewhat contrasted manners.

As expected, a higher level of ambition is associated with a bigger decline in the output of fossil fuel industries by 2040. Output under S3 is about 6% lower compared to S2 in 2040 (fragmented action scenario), which already entails a sharp drop in the sector's activity relative to current levels (Table 40). The sector's output is higher under S1 than S2, but only temporarily as the levels converge by 2050. The output of energy intensive industries is also projected to be affected by a higher level of ambition. The impact under S3 is small at -0.2% (relative to S2) in 2040 and 2050 under the fragmented action scenario. The lower level of ambition under S1 only generates a small positive impact of +1.4% in 2040 and +0.2% in 2050, relative to S2 (fragmented action). It must be noted also that the output of energy intensive industries is projected to continue growing across all scenarios in future decades. The growth rate between 2015 and 2040 is projected to range between 25.5% and 27.6%.

It must be noted also that under the global action scenario, the output of energy intensive industries is higher than under the lower ambition S1 scenario both for S2 and S3, with S3 yielding only a marginally lower output level than S2. This is driven by the early adoption of decarbonised technologies in EU industry relative to the rest of the world, which increases its competitiveness in a setting where the rest of the world also needs to invest in low-carbon processes. In addition, the decarbonisation of production processes in energy-intensive industries and the associated fall in fossil fuel inputs are susceptible to shelter EU industry from potential shocks on fossil fuel prices. They would indeed be impacted by such shocks to a lower extent than competitors elsewhere and less advanced in their decarbonisation process.

Table 40: Sectoral output, deviation vs. S2 (%)

	S1 fragmented		S1 global		S3 fragmented		S3 global	
	2040	2050	2040	2050	2040	2050	2040	2050
Fossil fuel industries	10.2%	-0.3%	15.0%	6.4%	-5.6%	-0.7%	-5.2%	-1.0%
Energy intensive industries	1.4%	0.2%	-0.3%	-2.3%	-0.2%	-0.2%	-0.2%	-0.3%
Transport equipment	0.7%	0.2%	0.6%	-0.5%	-0.5%	-0.1%	-0.4%	-0.1%
Other equipment goods	0.5%	0.2%	-1.3%	-4.9%	0.2%	-0.1%	0.3%	-0.1%
Consumer goods industries	0.7%	0.1%	-0.8%	-3.6%	-0.6%	0.0%	-0.8%	-0.1%
Transport	2.0%	0.1%	1.0%	-3.1%	-1.0%	-0.2%	-1.1%	-0.1%
Construction	0.0%	0.2%	0.0%	0.3%	0.5%	-0.1%	0.6%	-0.1%
Market services	0.5%	0.1%	1.1%	1.5%	-0.2%	0.0%	-0.2%	0.0%
Non-market services	0.2%	0.0%	0.4%	0.3%	-0.2%	0.0%	-0.2%	0.0%
Agriculture	2.0%	0.1%	1.0%	-3.1%	-1.0%	-0.2%	-1.1%	-0.1%
Forestry	-10.9%	-1.0%	-13.1%	-6.8%	-0.5%	-2.2%	-1.4%	-2.3%
Memo:								
GDP	0.5%	0.1%	0.6%	0.2%	-0.2%	-0.1%	-0.2%	-0.1%

Source: JRC-GEM-E3.

Other sectors that are likely to be affected by a higher level of ambition include transport (road, maritime and air), equipment goods and consumer goods industries, which would be impacted by the overall decline in GDP and private consumption. Under a global action setting, these sectors could actually be better off with a higher level of climate ambition as global demand for equipment goods linked to decarbonisation increases and as the EU gains competitiveness and export market shares, thereby also driving up transport activity (S2 and S3 both have a higher level of output under a global action setting than S1 in 2050, with S3 only marginally lower than S2). Agriculture is mildly affected by higher levels of ambition, with output only 2% higher under S1 than under S3 in 2040, and 1% lower under S3 than under S2. In contrast, output in the forestry sector in 2040 is significantly higher under the higher ambition scenarios than under S1 as a result of the increased demand for biomass. By 2050, the differences are much less significant as biomass uses tend to converge across scenarios.

In terms of output shares, it is assumed that the past trend towards a more services-oriented economy continues in the coming decades. Output in key industrial sectors, including energy intensive industries, is projected to grow significantly between 2015 and 2040 or 2050, and the growth rates across sectors is affected by the level of climate ambition for 2040 only to a very limited extent, with output levels in 2040 and 2050 broadly unchanged across the three scenarios (Table 41).

Table 41: Sectoral output, % change vs. 2015

	S1			S2		S3	
	2030	**2040**	**2050**	**2040**	**2050**	**2040**	**2050**
Fossil fuel industries	-32.9%	-59.4%	-73.0%	-63.1%	-72.9%	-65.2%	-73.1%
Energy intensive industries	17.6%	27.6%	39.7%	25.8%	39.4%	25.5%	39.1%
Transport equipment	15.3%	30.8%	43.3%	30.0%	43.1%	29.4%	43.0%
Other equipment goods	21.5%	38.7%	58.6%	38.0%	58.3%	38.3%	58.1%
Consumer goods industries	12.6%	21.3%	31.4%	20.4%	31.3%	19.7%	31.2%
Transport	25.7%	44.5%	68.1%	41.7%	67.9%	40.2%	67.6%
Construction	27.9%	47.9%	70.7%	47.9%	70.3%	48.7%	70.2%
Market services	22.6%	40.5%	62.6%	39.9%	62.4%	39.5%	62.4%
Non-market services	21.3%	38.3%	59.7%	38.0%	59.7%	37.8%	59.7%
Agriculture and forestry	9.7%	33.6%	47.8%	36.6%	47.4%	36.3%	46.3%
Memo:							
GDP	22.8%	40.6%	62.1%	39.9%	61.9%	39.5%	61.8%

Source: JRC-GEM-E3.

The secular trend towards a relatively higher growth rate in services than in industry nevertheless implies that the share of energy intensive industries, consumer goods industries and transport equipment is projected to decline across scenarios over the coming decades, with a corresponding increase in the share of market services. The share of fossil fuel industries in total sectoral output would become negligible by 2040 already across scenarios, at about 0.5% of the total (Table 42).

Table 42: Sectoral output, share of total (%)

	S1				S2		S3	
	2020	**2030**	**2040**	**2050**	**2040**	**2050**	**2040**	**2050**
Fossil fuel industries	1.6%	1.1%	0.6%	0.3%	0.5%	0.3%	0.5%	0.3%
Energy intensive industries	10.4%	9.7%	9.3%	8.9%	9.2%	8.9%	9.2%	8.9%
Transport equipment	3.8%	3.5%	3.5%	3.4%	3.5%	3.4%	3.5%	3.4%
Other equipment goods	6.3%	6.2%	6.3%	6.2%	6.3%	6.2%	6.3%	6.2%
Consumer goods industries	6.0%	5.7%	5.4%	5.1%	5.4%	5.1%	5.4%	5.1%
Transport	4.6%	5.1%	5.2%	5.3%	5.1%	5.3%	5.1%	5.3%
Construction	7.3%	7.2%	7.3%	7.3%	7.3%	7.3%	7.4%	7.3%
Market services	38.3%	39.3%	39.6%	39.9%	39.6%	39.9%	39.6%	39.9%
Non-market services	14.7%	15.0%	15.0%	15.1%	15.1%	15.1%	15.1%	15.1%
Agriculture and forestry	1.8%	1.7%	1.8%	1.7%	1.8%	1.7%	1.8%	1.7%
Other	5.2%	5.5%	6.0%	6.7%	6.1%	6.7%	6.1%	6.7%

Source: JRC-GEM-E3.

The extent to which SMEs are affected by the trends described above is in good part determined by the sectors of activity in which SMEs are most prominent. As indicated in Table 27 (section 2.2.3), around 66% of SMEs are active in services sectors and close to 55% of their total gross value added and employment are generated in services. Another 20% of SMEs and 16-18% of gross value added and employment are accounted for by the construction sector. Overall, SMEs therefore seem to be well positioned to gain from the projected continued rise in the share of market services in the economy and from a very resilient construction sector. In contrast, a very small proportion of SMEs are involved in fossil fuel industries, mining and extraction or energy intensive industries, and they account for a very small share of the gross value added and employment of the SME sector.

The impact of the scenarios on EU businesses, particularly on competitiveness, can also be viewed through the lens of their impact on the EU's export market shares across a range of sectors. The EU is not only the world's largest economy, but also the largest trading block, with a share of around 17% of global exports currently (Table 43). Export market shares are somewhat larger than this overall figure for energy intensive industries and significantly larger for transport equipment and market services. Given that the EU economy is projected to grow slower than most other large economies in the world, mainly as a result of contrasted population trends and the maturity of its economy, the share in global exports is set to decline in the coming decades. This pattern is unlikely to be much affected by the degree of climate ambition by 2040 and the three main scenarios show very similar patterns for all key sectors of the economy.

A more relevant factor concerning export market shares lies in the degree to which the rest of the world is projected to step up efforts to mitigate greenhouse gas emissions. A higher degree of ambition outside the EU (global action) is projected to increase the EU's export market shares across the board compared to a scenario with lower ambition (fragmented action). The benefits of a "first-mover" advantage for EU exporters is significant for most sectors, with the exception of market services, where decarbonisation is a less relevant factor.

Table 43: EU shares in global exports (% of total)

	Fragmented					Global		
	2015	**2020**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
Scenario 3								
All exports	17.8%	17.2%	16.8%	16.1%	15.9%	17.6%	16.6%	16.8%
Energy intensive industries	19.1%	19.7%	18.3%	17.1%	16.8%	19.8%	17.6%	17.5%
Transport equipment	28.7%	28.4%	26.4%	25.0%	24.1%	26.9%	25.0%	24.3%
Other equipment goods	22.1%	21.1%	19.2%	17.1%	16.7%	21.1%	17.8%	18.7%
Consumer goods industries	15.0%	14.1%	13.4%	12.3%	12.0%	14.1%	13.0%	13.6%
Market services	25.2%	23.9%	23.7%	22.7%	21.5%	21.4%	21.7%	19.1%
Agriculture and forestry	8.2%	7.6%	7.8%	6.7%	6.0%	9.2%	7.1%	6.3%

Source: JRC-GEM-E3.

Besides affecting domestic businesses, the level of ambition for 2040 is susceptible to affect partner countries via trade channels, as the EU is also a major importer, with a share in world imports similar to its share in world exports of close to 18%. As is the case on the export side, this share is set to decline in the coming decades with higher economic growth rates elsewhere, but the EU will remain a major global trading partner, also on account of its openness and number of free trade agreements. As is again the case on the export side, there is very little differentiation across scenarios (level of ambition) in terms of the absolute amounts of EU imports or their share in global imports. The changing nature of the EU economy, however, implies that the share of the EU's imports in global imports could decline faster for some sectors than for others. In particular, the EU's share of imports of goods from energy intensive industries in world trade could decline significantly, while its share in global imports of consumer goods and market services could remain broadly stable. In turn, the EU's place as an importer of agriculture and forestry products is projected to increase in relative terms (Table 44).

As is the case on the export side, a bigger impact is projected to arise depending on whether the rest of the world implements a higher degree of climate ambition (global action) or not (fragmented action). Under a global action scenario, the EU's share in world imports is projected to be slightly higher than under a fragmented action scenario overall, with a most significant positive impact in terms of market services. As far as more carbon-intensive products are concerned (e.g., energy intensive industries, transport equipment or consumer goods), the EU would account for a smaller share of global imports under a global action scenario than under a fragmented action scenario. This is the converse of the “first mover advantage” highlighted above, as trading partners would be in a situation of “second mover” under a global action scenario, which would reduce imports by the EU as domestic producers gain in terms of competitiveness.

Table 44: EU shares in global imports (% of total)

	Fragmented					**Global**		
	2015	**2020**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
Scenario 3								
All imports	17.6%	17.3%	16.4%	15.7%	15.4%	16.4%	15.8%	15.7%
Energy intensive industries	14.8%	14.4%	12.8%	12.0%	11.2%	12.2%	11.8%	11.0%
Transport equipment	11.2%	11.6%	10.7%	10.6%	10.1%	10.7%	10.7%	10.3%
Other equipment goods	13.4%	13.1%	12.3%	11.8%	10.9%	11.7%	11.5%	10.4%
Consumer goods industries	18.7%	18.9%	18.6%	18.5%	18.4%	18.2%	18.1%	17.3%
Market services	29.6%	31.0%	30.1%	29.6%	29.9%	31.8%	30.1%	31.4%
Agriculture and forestry	17.6%	17.3%	16.3%	18.5%	19.7%	15.5%	17.3%	17.4%

Source: JRC-GEM-E3.

The extent to which the EU’s trade partners may be affected by the transition and the level of ambition for 2040 also depend to a significant extent on the type of goods that the EU imports, and how this may change over time and across scenarios. Table 45 provides further detail on the projected structure of EU imports. Fossil fuels (coal, crude oil, oil and gas) currently represent an important share of the EU’s total imports. The share and absolute value of such imports are projected to decline sharply as the EU decarbonises its energy system (Section 2.6.1) across all scenarios. A higher level of ambition (S3) is associated with an even faster drop than a lower level of ambition (S1 and S2), but the trend is clear and inevitable with fossil fuel imports projected to account for no more than 3% of the EU’s total imports by 2050 (Table 45). Although trade in the raw materials critical for the climate and energy transition is not captured explicitly in the JRC-GEM-E3 macro-economic model, the EU is likely to import a higher level of such goods as the transition progresses (Section 1.9.4).

The share of imports of goods from energy intensive industries and transport equipment in total EU imports is projected to decline across scenarios, but this is likely mostly due to factors unrelated to the climate transition and the level of ambition for 2040, such as the maturity of the economy and the gradual decline in the EU population in the long term. In contrast, the share of imports of consumer goods, equipment goods, market services and agriculture and forestry in total EU imports could increase over the coming decades. The share of market services, in particular, could rise sharply as it offsets the falling share of fossil fuel imports. Finally, the contrast between trends under fragmented action vs. global action scenarios are confirmed by figures regarding sectoral shares in EU total imports.

Table 45: Structure of EU imports (% of total)

	Fragmented					Global		
	2015	2020	2030	2040	2050	2030	2040	2050
Scenario 3								
Coal	0.5%	0.3%	0.2%	0.0%	0.0%	0.1%	0.0%	0.0%
Crude oil	10.5%	8.7%	6.0%	2.9%	1.6%	6.7%	2.8%	1.5%
Oil	2.4%	2.5%	2.4%	1.2%	0.9%	2.0%	1.1%	0.8%
Gas	2.2%	2.6%	1.3%	0.7%	0.4%	1.4%	0.7%	0.4%
Energy intensive industries	17.5%	17.5%	16.1%	15.6%	14.5%	15.5%	15.4%	14.2%
Transport equipment	4.8%	4.9%	4.6%	4.5%	4.1%	4.6%	4.6%	4.1%
Other equipment goods	8.3%	9.1%	10.0%	11.2%	11.5%	9.5%	11.0%	11.0%
Consumer good industries	10.3%	10.5%	11.0%	11.6%	11.8%	10.7%	11.3%	10.9%
Electric goods	11.1%	11.5%	11.5%	11.6%	11.0%	11.3%	11.5%	10.9%
Market services	18.2%	19.9%	22.1%	24.0%	26.3%	23.8%	25.0%	28.5%
Agriculture and forestry	2.9%	2.8%	3.0%	3.7%	4.0%	2.8%	3.7%	4.1%
Other	11.2%	9.7%	11.8%	13.0%	13.9%	11.6%	12.9%	13.6%

Source: JRC-GEM-E3.

How such trends in the composition of EU imports and in the size of the EU in global imports could affect trading partners will depend on the composition of their own exports and the extent to which they depend on the EU as a market for their goods and services. The JRC-GEM-E3 model cannot be the basis for a detailed assessment of how individual countries and trade in specific commodities could be affected by the transition to climate neutrality and the level of ambition for the 2040 target as it lacks the level of granularity required to do so. It nevertheless provides useful indications of what could be the impact of the transition in terms of broad trade aggregates and possible trends.

The sharp decline in fossil fuel imports over the course of the transition will affect the Middle East most negatively, together with other major exporters of fossil fuels elsewhere. The share of imports from the Middle East in total EU imports could fall by as much as 2 percentage points between 2015 and 2050 under all scenarios (Table 46). This trend could potentially be reduced if trade in RFNBOs were to pick up, though the modelling does not suggest that the latter could compensate for the fall in exports of fossil fuels (295).

In contrast, the modelling indicates that Africa could benefit from an increase in the share it represents as the place of origin for total EU imports. The increase in the continent's share as the origin of EU imports could be significant for primary goods, namely crops, livestock and forestry, but the modelling shows a positive evolution for other sectors, including energy intensive goods and market services. Overall, the rising share of Africa in EU imports and the increase in imports over time could lead total EU imports from Africa to more than double between 2020 and 2050.

The difference across scenarios is minimal, as the trends are driven by the overall climate and energy transition and wider economic considerations. Similarly, the geographic origin of EU imports does not change much between the fragmented and global action scenarios, at last as far as total imports are concerned. This is likely linked to the fact that

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(295) This was analysed in more details in the Joint Research Centre's [Global Energy and Climate Outlook 2022: Energy trade in a decarbonised world](#).

all EU partners are required to significantly step up mitigation efforts under the global action scenario, which means they are all similarly affected. One can notice, however, that the share of imports from the OECD slightly increases between the fragmented and global action scenarios, which is likely linked to their lower initial carbon intensity than other regions, including as far as energy intensive industries are concerned.

Table 46: Origin of EU imports by main trading parterns (% of total EU imports, S3)

	Fragmented					Global		
	2015	**2020**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
Total imports								
Africa	6.9%	6.8%	7.5%	8.7%	10.2%	7.8%	8.7%	10.3%
China	15.2%	16.2%	17.5%	17.5%	16.4%	16.8%	17.1%	16.1%
India	3.0%	3.2%	4.3%	5.0%	5.6%	4.4%	5.0%	5.5%
Latin America	4.7%	4.4%	4.6%	4.8%	4.9%	4.7%	4.8%	4.8%
Middle East	5.4%	5.2%	4.4%	4.3%	4.3%	4.5%	4.5%	4.9%
OECD	44.2%	43.5%	42.6%	41.7%	40.6%	43.0%	42.2%	41.4%
Other Asia	9.3%	9.4%	10.4%	11.5%	12.3%	10.6%	11.6%	11.7%
Rest of Euro-Asia	11.3%	11.3%	8.6%	6.6%	5.7%	8.2%	6.1%	5.4%
Crops, livestock and forestry								
Africa	18.7%	19.8%	22.1%	26.7%	30.9%	24.0%	29.9%	38.5%
China	4.4%	4.7%	5.1%	4.7%	4.3%	4.8%	4.6%	7.2%
India	2.6%	2.7%	3.5%	3.9%	4.5%	3.5%	3.1%	3.4%
Latin America	23.6%	22.7%	21.4%	19.4%	18.0%	23.4%	20.1%	17.9%
Middle East	3.3%	3.5%	3.3%	3.6%	3.5%	3.5%	4.3%	4.3%
OECD	29.6%	28.7%	28.1%	25.3%	23.4%	23.6%	22.3%	17.1%
Other Asia	6.4%	6.5%	7.0%	6.9%	6.8%	7.8%	5.7%	2.4%
Rest of Euro-Asia	11.3%	11.3%	9.6%	9.6%	8.6%	9.3%	10.0%	9.2%
Energy intensive goods								
Africa	6.1%	6.5%	7.4%	8.4%	8.1%	8.2%	8.8%	8.1%
China	9.3%	9.8%	10.6%	10.6%	10.6%	9.6%	10.5%	10.3%
India	2.3%	2.4%	2.7%	2.9%	2.9%	2.5%	2.8%	2.7%
Latin America	5.5%	4.9%	5.2%	5.3%	5.5%	5.7%	5.4%	5.5%
Middle East	4.7%	4.4%	3.9%	4.0%	4.0%	3.7%	4.1%	4.1%
OECD	56.0%	55.8%	54.7%	53.2%	53.0%	59.1%	55.0%	56.1%
Other Asia	4.7%	5.1%	6.0%	7.1%	8.5%	6.5%	7.4%	8.7%
Rest of Euro-Asia	11.4%	11.2%	9.4%	8.5%	7.4%	4.7%	6.0%	4.6%
Market services								
Africa	2.3%	2.5%	2.9%	3.7%	4.5%	2.5%	3.5%	4.2%
China	11.5%	12.4%	13.5%	13.2%	12.4%	14.2%	12.4%	10.6%
India	6.9%	7.0%	9.0%	9.9%	10.9%	10.6%	10.0%	11.9%
Latin America	4.2%	4.0%	4.1%	4.2%	4.2%	3.6%	4.1%	4.1%
Middle East	5.8%	5.8%	4.6%	5.0%	5.1%	6.7%	7.6%	9.1%
OECD	53.8%	52.2%	50.2%	48.0%	46.5%	46.6%	46.7%	42.6%
Other Asia	11.6%	11.8%	12.4%	12.9%	13.4%	11.1%	12.4%	14.6%
Rest of Euro-Asia	4.0%	4.3%	3.2%	3.1%	3.0%	4.8%	3.3%	2.9%

Source: JRC-GEM-E3.

The cost-efficient decarbonisation relies on the deployment of net-zero technologies with varying but sufficient degree of maturity to be used on a large scale. The maturity of technologies is an important driver of the projected portfolio of net-zero technologies. In recent years, pressing innovation gaps have been addressed which resulted in significant improvements of the technology readiness (296). For the bulk of net-zero technologies needed to reach the 2040 targets, the Technology Readiness Level (TRL) already amounts to at least 8 (out of 9) which means that they are in an advanced deployment stage. (297)

DAC is at the lower end of the deployment stage having a TRL of 7. Bioenergy with carbon capture and storage (BECCS) is the only technology that has a TRL of 5-6 ("Technology demonstrated in relevant environment") indicating that is not fully established. However, there are already a variety of BECCS demonstration projects in Japan, Norway, Sweden and the United Kingdom.

Due to their relatively low maturity, DAC and BECCS come into play only between 2030 and 2040 allowing the technology to be further developed over the coming years. In 2040, DAC and BECCS is projected to capture 16 MtCO2 (S1) to 155 MtCO2 (S3) making up around 0.3% (S1) to 3.3% (S3) of 1990 total GHG emissions. The S3 scenario anticipates decarbonisation via DAC up to 2040.

2.4. Social impacts and just transition

2.4.1. Fuel expenses, energy and transport poverty, distributional impacts

Energy-related expenses (298) represent a high share of total expenditure for a large proportion of EU households, in particular middle- and low-income households. The recent increase in energy prices has generated major negative social impacts and increased the rates of energy (and transport) poverty. Assessing the implications of the energy transition and the 2040 policy options on energy system costs for households is therefore of critical importance.

The following assessment is based on model results, reflecting the current legislation and understanding of the possible evolution of technologies and costs. This assessment will feed into the development of the future policy framework and support measures in the coming years to meet the 2040 target and will determine the actual costs and how they impact individuals, regions and society.

The cost structure is characterised by an increase of capital-related costs in purchasing more efficient appliances and investment in enhancing the energy insulation of dwellings. This increase allows savings on energy purchases despite the assumed increasing fossil fuels international prices over time and the impact of ETS revenues and diffusion of new low carbon fuels.

The relative importance of energy-related cost for households in private consumption is projected to decline in 2041-2050 compared to 2031-2040, due to the decreasing importance of fuel purchases in all scenarios. For instance, the share of private

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(296) IEA (2023): "Net Zero Roadmap. A Global Pathway to Keep the 1.5°C Goal in Reach"

(297) The TRL evaluation is based on the EU's Clean Energy Technology Observatory (CETO).

(298) The model-based analysis is a technical exercise based on a number of assumptions that are shared across scenarios. Its results do not prejudge the future design of the post-2030 policy framework.

consumption dedicated to energy-related expenditures decreases from 8.1%-8.2% to 7.1% between the decades 2031-2040 and 2041-2050. Anticipated action in S3, driven by a larger direct efficiency investments (see section 2.2), also translates in a slightly higher share of energy-related expenses in S3 in 2031-2040, where it represents 8.2% of private consumption as opposed to 8% in S1 and 8.1% in S2. Electricity prices are projected to be very similar across both periods in real terms.

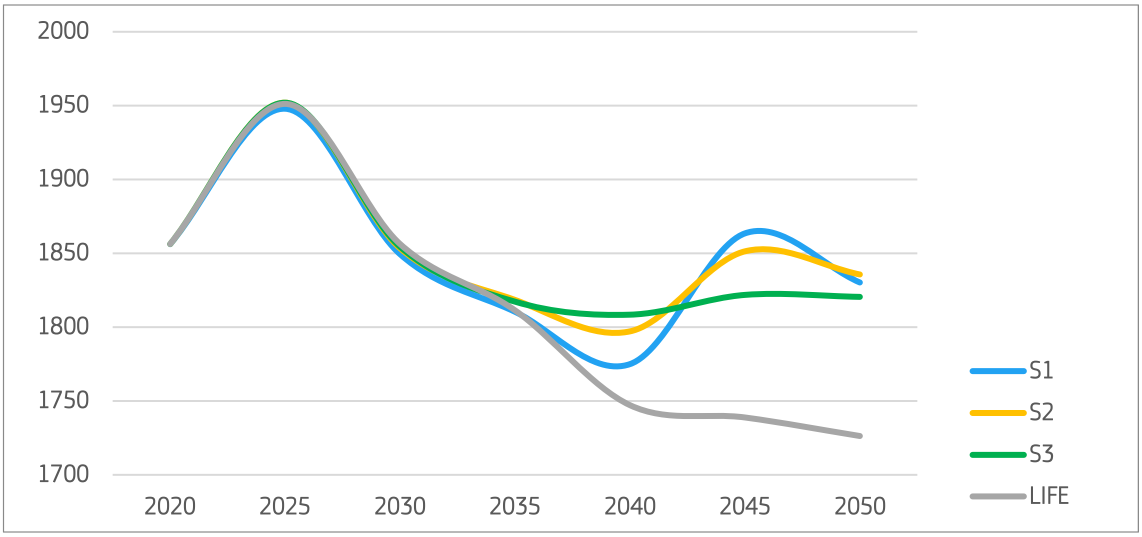
Table 47: Average annual energy system costs as % of private consumption and average final price of electricity for households in the residential sector

Average across all income categories	**2031-2040**				**2041-2050**			
	S1	**S2**	**S3**	**LIFE**	**S1**	**S2**	**S3**	**LIFE**
Total (% of private consumption)	8.0%	8.1%	8.2%	8.1%	7.1%	7.1%	7.1%	7.0%
Capital related costs*	4.5%	4.6%	4.7%	4.6%	4.1%	4.1%	4.1%	4.1%
Energy purchases**	3.4%	3.5%	3.5%	3.4%	3.0%	3.0%	3.0%	2.8%
Low Income Categories	**S1**	**S2**	**S3**	**LIFE**	**S1**	**S2**	**S3**	**LIFE**
Total (% of private consumption)	14.0%	14.3%	14.4%	14.2%	12.0%	12.0%	12.1%	11.8%
Capital related costs	*7.8%*	*7.9%*	*8.1%*	*7.9%*	*6.5%*	*6.5%*	*6.6%*	*6.6%*
Energy purchases	*6.3%*	*6.3%*	*6.3%*	*6.3%*	*5.5%*	*5.5%*	*5.4%*	*5.2%*
*Electricity price (EUR/MWh)****								
Residential	*288*	*288*	*288*	*288*	*289*	*290*	*290*	*290*

*Note: * includes purchase of appliances and cost of renovation. ** It does not include carbon revenues.*
**** Average final price of electricity. The electricity price shown here reflects the evolution of the average electricity production cost to supply the sector (i.e. considering its load profile) as well as the taxes applied to the sector.*

Source: PRIMES.

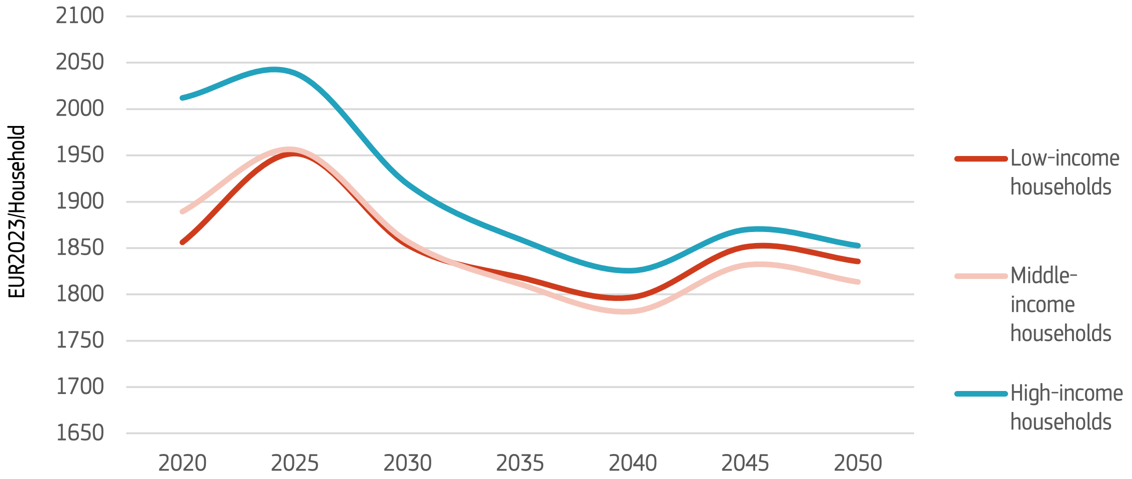
Figure 115: Annual fuel purchasing expenses in buildings per low-income household



Source: PRIMES model.

Figure 116 illustrates that improved insulation leads to a decrease in annual fuel purchasing expenses, in particular for high-income households. As a result, the gap between expenses of different types of households closes and the level of expenses is closer for all categories in 2040 than in 2020. Low-income households have higher annual fuel expenses than middle-income households as of 2030, due to their dwellings not being as well insulated, despite significant efforts in renovation. For all households, fuel expenses are on a downward trend as of 2025 (despite a temporary increase in 2045), illustrating that investments in renovation of buildings pay off.

Figure 116: Annual fuel purchasing expenses in buildings in S2

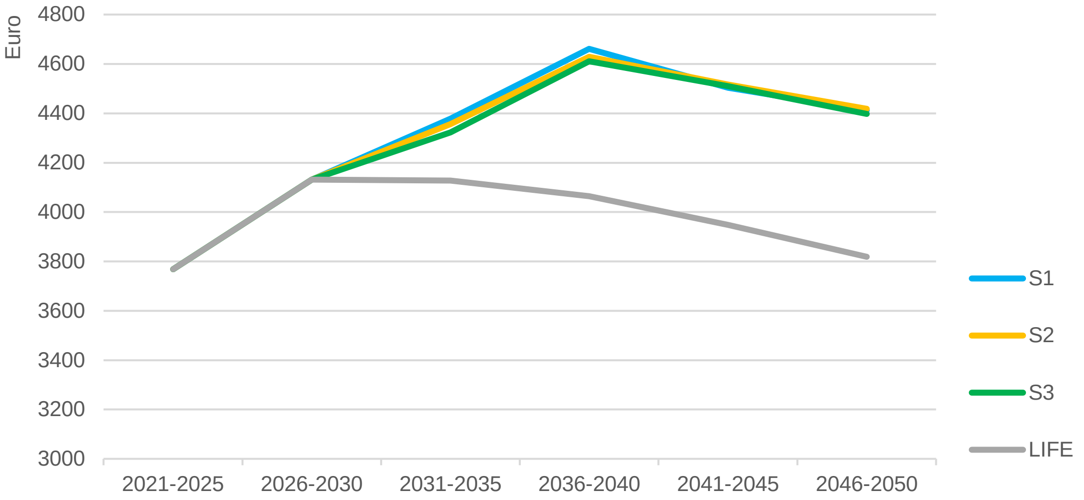


Source: PRIMES model.

Following the post-COVID recovery, annual expenditures for private vehicles ([299]) are projected to increase in all scenarios by 2040, from around EUR 3770 per year per household during 2021-2025 to around EUR 4610-4660 per year per household in the S1, S2 and S3 scenarios and around EUR 4065 in LIFE during 2036-2040 (see Figure 117). These changes are driven by the increase in the capital expenditures for the replacement of the vehicle fleet, including for meeting the CO2 standards regulation. Post-2040, households' expenditures for private vehicles are projected to remain stable or slightly go down. In LIFE, the annual expenditures for private vehicles are lower, mostly because of lower activity by passenger car (expressed in passenger-km) due to modal shift to active modes and collective transport, and because of higher use of shared mobility. Expressed as share of private consumption, annual expenditures for private vehicles are however projected to be stable over time until 2040 and decrease after 2040, from around 7.5-8.5% during 2021-2025 and 2036-2040 to 6-7% during 2046-2050. This is mainly due to the sustained increase in the private consumption over time following the post-COVID recovery.

([299]) The annual expenditures for private vehicles cover the total expenditures to purchase vehicles as well as the fixed operation costs (excluding taxes).

Figure 117: Annual expenditures for private vehicles per household

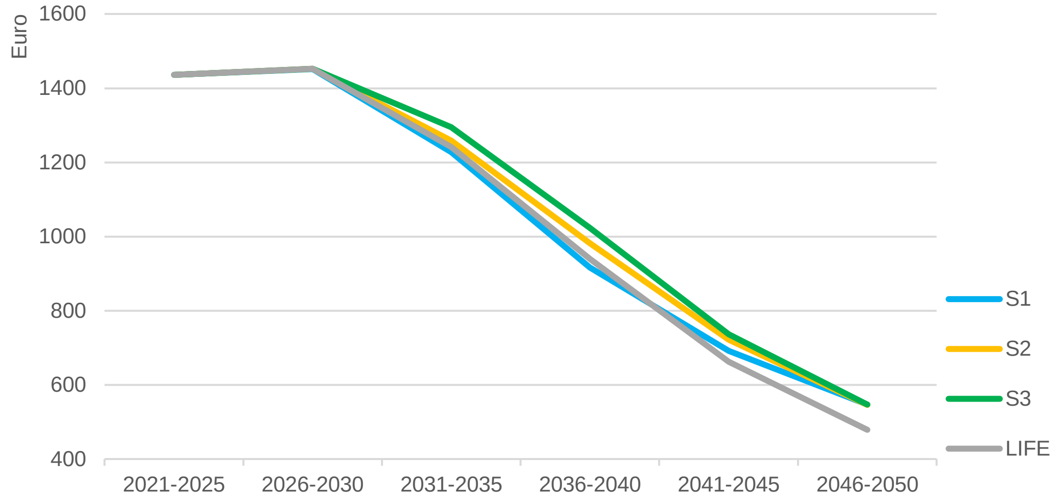


Note: Expenditures are expressed in EUR'2023.

Source: PRIMES.

Expenditures for transport-related energy purchases by households are projected to reduce from around EUR 1450 per year per household during 2021-2030 (21-23% of total transport expenditures per household) to around EUR 915-1025 per year per household during 2036-2040 (13-15% of total transport expenditures per household) and EUR 480-550 during 2046-2050 (around 7-9% of total transport expenditures), driven by the use of more energy efficient vehicles and multimodality. Scenario S1 shows the highest decrease in expenditures for energy purchases by 2040, around EUR 65 higher per year per household than in scenario S2 and around EUR 105 higher than in scenario S3 (see Figure 118). Expressed as share of private consumption, total annual expenditures on energy products are projected to decrease over time (from 3.2% during 2021-2025 to 1.7-1.9% during 2036-2040 and 0.8-0.9% during 2046-2050), due to the sustained increase in the private consumption over time.

Figure 118: Annual expenditures for transport-related energy purchases per household

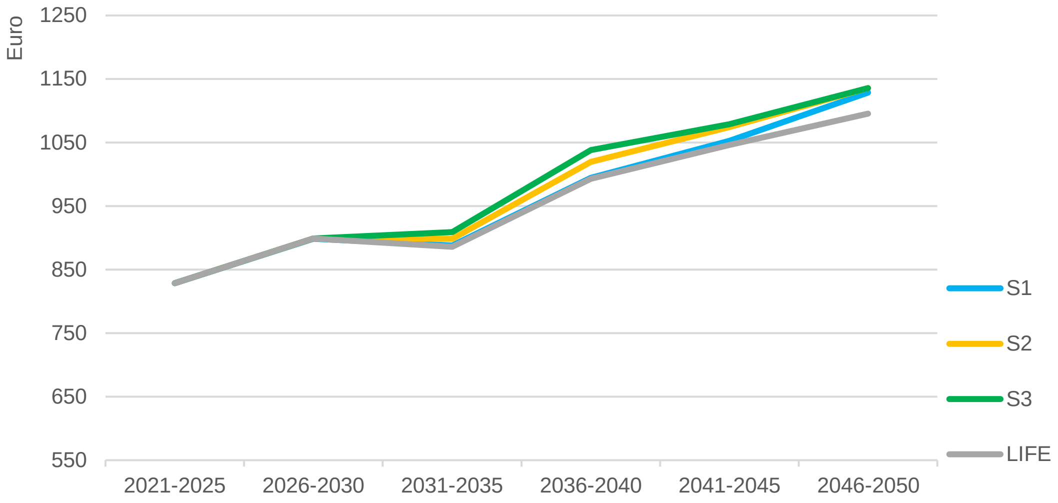


Note: Expenditures are expressed in EUR'2023.

Source: PRIMES

Annual expenditures on transport services are projected to increase from EUR 830 per year per household in 2021-2025 (13% of total transport expenditures per household) to around EUR 995-1040 per year per household during 2036-2040 (14-15% of total transport expenditures per household) and around EUR 1095-1135 during 2046-2050 (17-18% of total transport expenditures), as shown in Figure 119. This projected increase is linked to higher use of public transport and multimodality. Expressed as share of private consumption, total annual expenditures on transport services are however projected to remain relatively stable over time at around 1.8-1.9% due to the sustained increase in private consumption.

Figure 119: Annual expenditures for transport services per household



Note: Expenditures are expressed in EUR'2023.

Source: PRIMES.

The concept of *transport poverty* describes the situation of people who are unable to meet the costs of private or public transport or do not have access (including availability), especially to public transport. The co-legislators agreed on a definition of transport poverty in the context of the Social Climate Fund (300). No appropriate EU indicators currently exist to regularly monitor the affordability of transport services. However, according to the latest available data from Eurostat, 2.4 % of all people in the EU and 5.8% of those at risk of poverty cannot afford to use public transport regularly (301). In addition to costs, access to transport depends on other factors, including the quality and frequency of services, the state of the infrastructure and accessibility (both digital and physical). Due to the lack of data, it is not possible to assess the evolution of the transport

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(300) Regulation (EU) 2023/955 of the European Parliament and of the Council of 10 May 2023 establishing a Social Climate Fund and amending Regulation (EU) 2021/1060: 'transport poverty' means individuals' and households' inability or difficulty to meet the costs of private or public transport, or their lack of or limited access to transport needed for their access to essential socio-economic services and activities, taking into account the national and spatial context.

(301) Information collected ad hoc by Eurostat in 2014. New data on affordability of public transport will be collected by Eurostat in 2024, as part of the new ad hoc module on access to services. See Commission Implementing Regulation (EU) 2022/2498 of 9 December 2022 specifying technical items of data sets of the sample survey in the income and living conditions domain on access to services pursuant to Regulation (EU) 2019/1700 of the European Parliament and of the Council.

poverty over time in the scenarios. It is however clear that up-to-date EU-level data on transport affordability is needed to closely monitor developments over time.

2.4.2. *Electricity prices*

Low-income households are particularly vulnerable to electricity price increases. The Commission proposal to reform the electricity market design on 14 March 2023 ([302]) aims at strengthening consumer protection, particularly for the most vulnerable households. With this reform, consumers would be entitled to secure fixed-price contracts, with the option of multiple or combined tailor-made contracts, as well as access to clearer pre-contractual information.

For the most vulnerables, a supplier of last resort would be selected so that no consumer ends up without electricity in case of supplier failure. This is complemented by an obligation on Member States to ensure that vulnerable customers are protected from electricity disconnections. Also, the proposal suggests allowing Member States to extend regulated retail prices to households and SMEs in the event of a crisis. The possibility to access renewable energy directly through participation in energy sharing arrangements allow all consumers to benefit from renewable energy, hence being less subject to electricity wholesale prices movements which depend on fossil fuel prices.

The Social Climate Fund (‘the Fund’) aims at addressing any social impacts that arise from the extension of the emissions trading system to the building and road transport sectors. This is achieved by financing temporary direct income support for vulnerable households and supporting measures and investments that reduce emissions in the road transport and buildings sectors. As a result, this contributes to reducing costs for vulnerable households, micro-enterprises, and transport users.

For the transport sector, the fund grants an improved access to zero- and low-emission mobility and transport with financial support to purchase low emission vehicles. It can also serve to provide free access to public transport or adapted tariffs for access to public transport.

2.4.3. *Sectoral employment, skills and occupation groups*

2.4.3.1.General impacts

As indicated in previous impact assessments and confirmed in Section 2.1.1, the transition to climate neutrality is projected to have a limited impact on aggregate employment, driven primarily by the expected impacts on GDP. However, the consequences of the transition on workers, the labour market and skills will still be significant. While some sectors including a large share of services activities ([303]), which represent a major share of the labour market, are likely to be affected marginally, other sectors will undergo very significant transformations whether in terms of employment levels or skills needs and occupations. A limited number of sectors accounting for a small

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([302]) Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Regulations (EU) 2019/943 and (EU) 2019/942 as well as Directives (EU) 2018/2001 and (EU) 2019/944 to improve the Union’s electricity market design share of total employment will decline sharply, while significant employment opportunities should emerge elsewhere.

While macro-economic models project that the transition will have a limited effect on aggregate employment relative to a business-as-usual scenario, it is important to bear in mind the evolving general context, and in particular demographic and technological changes that impact the labor market independently from climate objectives and policies. The EU's population is projected to decline slowly from the mid-2020s onwards alongside continued ageing. As a result, the overall employment will be on a significant declining trend at EU level. The age dependency ratio is projected to increase from around 55% currently to around 75% by 2050, as the population of working age (15-64) declines by almost 13% (close to 37 million people). Other structural and technological changes will also affect the labour market and skills demand in fundamental ways. The rapid development and uptake of artificial intelligence could upend many services jobs that have been so far relatively sheltered from structural changes and that represent a large share of total employment in the EU.

In addition, it must be noted that the structure of employment in the EU has not been static in recent years. Even looking back only about a decade and in a context of a rising number of total jobs, significant changes have taken place in terms of employment by economic activity, by occupation and by wage dynamics. Services (market and non-market) activities currently represent close to 130 million jobs, or 65% of total EU employment, up from 60% in 2008 (Table 48). Public administration, education, health and social work account for nearly 40% of services employment.

In contrast, the share of industry and manufacturing in total employment declined by around 2 percentage points between 2008 and 2022 (to 16% of the total), even though the number of jobs has remained broadly stable in the past decade. Construction, architecture and engineering are another major source of jobs in the EU at around 8% of the total, though its share also declined by about 1 percentage point between 2008 and 2022. Finally, agriculture, fisheries and fishing, and fossil fuel extraction and refining have experienced a significant decline in the level and share of employment. While the share of agriculture employment remains significant at 3.5% of the total currently, employment in fossil fuel extraction and refining was down to about 370 000 jobs in 2022, 40% below the level in 2008.

Table 48: Employment by economic activity (million people and % of total)

	2010	2015	2020	2021	2022
Fossil fuel sectors	0.60	0.51	0.46	0.41	0.37
(% total)	(0.3%)	(0.3%)	(0.2%)	(0.2%)	(0.2%)
Other mining and extraction activities	0.32	0.30	0.30	0.30	0.33
(% total)	(0.2%)	(0.2%)	(0.2%)	(0.2%)	(0.2%)
Energy intensive industries	5.03	4.70	4.90	4.87	4.98
(% total)	(2.7%)	(2.5%)	(2.6%)	(2.5%)	(2.5%)
Manufacturing of transport equipment (incl. parts and accessories)	3.44	3.84	4.15	4.05	3.84
(% total)	(1.9%)	(2.1%)	(2.2%)	(2.1%)	(1.9%)
Manufacturing of electrical equipment and other machinery	3.97	4.34	4.57	4.57	4.58
(% total)	(2.2%)	(2.3%)	(2.4%)	(2.4%)	(2.3%)
Other manufacturing	18.07	17.60	17.96	17.77	18.08
(% total)	(9.8%)	(9.5%)	(9.4%)	(9.2%)	(9.2%)
Electricity, gas, steam and air conditioning supply	1.47	1.37	1.46	1.50	1.48
(% total)	(0.8%)	(0.7%)	(0.8%)	(0.8%)	(0.7%)
Construction and architecture services	16.29	14.89	15.37	15.68	16.25
(% total)	(8.9%)	(8.0%)	(8.0%)	(8.1%)	(8.2%)
Transport and storage	9.43	9.67	10.06	10.26	10.50
(% total)	(5.1%)	(5.2%)	(5.2%)	(5.3%)	(5.3%)
Services	113.92	118.28	123.20	124.85	128.15
(% total)	(62.0%)	(63.7%)	(64.2%)	(64.7%)	(65.0%)
Water supply, sewerage, waste management	1.37	1.47	1.61	1.62	1.64
(% total)	(0.7%)	(0.8%)	(0.8%)	(0.8%)	(0.8%)
Agriculture, forestry and fishing	9.79	8.76	7.72	6.98	6.91
% total	(5.3%)	(4.7%)	(4.0%)	(3.6%)	(3.5%)

Source: Eurostat. (304)

The recent trends in sectoral employment in the EU are mirrored in the evolution of employment by occupations (Table 49), which also reflects the rising trend in tertiary educational attainment among the population in general and among those aged 25-34 in particular. For the latter, attainment in tertiary education rose from 23.1% of the total population in 2002 to 42% in 2022. The increase was particularly sharp among women with a rate of 47.6% in 2022, compared to a rate of 36.5% for men. The share of professionals and managers in total employment increased by 4.5 percentage points in the past decade to 26.7% of the total in 2022. This contrasts sharply with occupations whose share in total employment declined over the same period, mainly service and sales workers, crafts and trade, elementary occupations and agriculture, forestry and fisheries. The absolute number of workers with these occupations has nevertheless remained broadly stable (except skilled workers in agriculture) as total employment was on a rising trend.

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(304) The table is based on an aggregation of NACE 2 sectors. Fossil fuel sectors (B05, B06, C19); other mining and extraction activities (B07, B08, B09); energy intensive industries (C17, C20, C21, C23, C24); manufacturing of transport equipment (C29, C30); manufacturing of electrical equipment and other machinery (C27, C28); other manufacturing (all other C codes); electricity, gas, steam and air conditioning supply (D35); construction and architecture services (F41, F42, F43, M71); transport and storage (H49 to H53); services (all codes not listed in other sectors); water, treatment and waste (E36 to E39); agriculture, forestry and fishing (A01, A02, A03).

Table 49: Employment by occupations

	Million people			% of total		
	2011	2015	2022	2011	2015	2022
Managers	9.90	9.49	9.93	5.4%	5.1%	5.0%
Professionals	30.87	33.24	42.61	16.8%	17.9%	21.6%
(Science and engineering)	(5.25)	(5.41)	(7.00)	(2.9%)	(2.9%)	(3.6%)
Technicians	29.27	30.76	31.46	15.9%	16.6%	16.0%
(Science and engineering)	(7.33)	(7.25)	(6.86)	(4.0%)	(3.9%)	(3.5%)
Clerical support	18.27	18.06	19.79	9.9%	9.7%	10.0%
Service and sales	30.77	30.93	31.29	16.8%	16.7%	15.9%
Skilled workers in agri, forest. and fish.	7.72	7.24	5.47	4.2%	3.9%	2.8%
Craft and trades	23.50	22.86	22.86	12.8%	12.3%	11.6%
(Building)	(7.96)	(7.40)	(7.75)	(4.3%)	(4.0%)	(3.9%)
(Electrical and eletronic)	(2.89)	(3.05)	(3.07)	(1.6%)	(1.6%)	(1.6%)
(Metal, machinery and related)	(7.49)	(7.28)	(7.22)	(4.1%)	(3.9%)	(3.7%)
Plant and machine operators	14.49	14.43	15.01	7.9%	7.8%	7.6%
Elementary occuptions	17.03	17.22	16.61	9.3%	9.3%	8.4%
(Mining, constr., manuf. and transport)	(5.36)	(4.91)	(5.38)	(2.9%)	(2.6%)	(2.7%)
Other	1.79	1.52	2.09	1.0%	0.8%	1.1%

Source: Eurostat. (305)

Looking forward, modelling under JRC-GEM-E3 projects that recent trends in sectoral employment are set to continue at an accelerated pace (Table 50). These developments will also take place in the context of a decrease in the working age population and declining overall employment levels, contrary to what happened in the past decade when employment was still on a rising trend. Employment in fossil fuel industries will further decline to negligible levels from an already low level. The decline would take place faster still under a higher level of ambition in 2040. Employment trends in energy intensive industries and transport equipment are also projected to continue, in part as the EU economy continues to be more services-oriented. This is a constant across scenarios and there is little difference between S1 and the scenarios with a higher level of ambition in 2040.

Given the scale of services employment, given that services jobs are among those more marginally affected by the climate and energy transition and given that the long-term trend towards a rising share of services sectors in GDP is projected to continue to some extent, the share of market and non-market services jobs is projected to continue growing in the coming decades. The flipside of the increase in the share of services sector jobs is a gradual decrease in the share of employment in energy intensive industries, consumer goods industries and transport equipment. The share of employment in other equipment goods, however, is projected to remain stable as the transition should increase EU and

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(305) The table is based on ISCO-08 two-digit level occupations. Managers (OC1); professionals (OC2); professional (science and engineering) (OC21); technicians (OC3); technicians (science and engineering) (OC31); clerical support (OC4); services and sales (OC5); skilled workers in agriculture, forestry and fisheries (OC6); crafts and trade (OC7); crafts and trade (building) (OC71); crafts and trade (electrical and electronic) (OC74); crafts and trade (metal, machinery related) (OC72); plant and machine operators (OC8); elementary occupations (OC9), elementary occupations (mining, constr., manuf. and transport) (OC93); other (OC0 and NRP).

global demand for the type of equipment needed for decarbonisation. While output in these sectors is projected to grow significantly between 2015 and 2040 or 2040, they will be outpaced by overall GDP growth. In the context of a declining aggregate level of employment, driven by a shrinking labour force, it is therefore not surprising to see these sectors' share of employment (and absolute employment) decline over the coming decades.

In contrast, the shares of construction and transport activities are projected to increase moderately or remain stable. Output growth in these sectors in the period 2015-2050 is projected to outpace GDP growth, driving a reallocation of labour. These trends are not affected to any significant extent by the level of ambition in 2040 (Table 50), but they imply a reallocation of the labour force over time. Such a reallocation is typically not without frictions and costs, and it would require accompanying policies to ensure that reskilling and retraining opportunities are available for workers in need (see Annex 9).

Table 50: Sectoral employment, share in total employment (%)

	S3			
	2020	**2030**	**2040**	**2050**
Fossil fuel industries	0.13%	0.11%	0.05%	0.05%
Energy intensive industries	6.7%	6.5%	6.2%	5.9%
Transport equipment	2.1%	2.0%	1.9%	1.8%
Other equipment goods	6.3%	6.2%	6.1%	6.1%
Consumer goods industries	4.4%	4.2%	4.0%	3.9%
Transport	3.6%	3.9%	3.7%	3.7%
Construction	7.8%	7.6%	7.7%	7.7%
Market services	34.0%	34.6%	34.9%	35.3%
Non-market services	26.6%	27.1%	27.3%	27.5%
Agriculture	3.5%	3.2%	3.1%	2.8%
Forestry	0.4%	0.3%	0.5%	0.4%
Other	4.4%	4.3%	4.6%	5.0%

Source: JRC-GEM-E3 model. (306)

The importance of reskilling and retraining in the course of the transition is further highlighted by projections based on the linking of the macro-economic simulation of the 3 main scenarios and the skills forecast from the European Centre for the Development of Vocational Training (307). These projections show that trends in the share of employment by occupation are broadly projected to continue up to 2040, and that the 3 main scenarios are extremely similar in terms of their impacts on occupation requirements. Two key occupational groups are projected to experience a significant increase in their share of total employment, i.e., professionals and technicians. In the crafts and trade group, occupations related to buildings as well as plant and machine operators are also projected to experience an increase in employment share relative to 2022 (Figure 120). In contrast, the shares of clerical support as well as services and sales occupations are projected to decline significantly.

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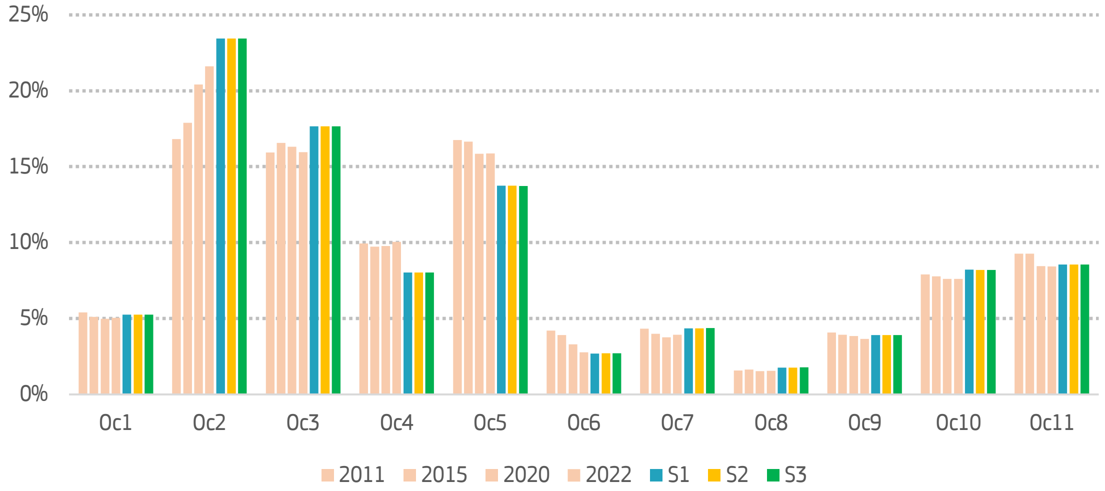
(306) The sectoral classifications resulting from the JRC-GEM-E3 modelling differ to some extent from those based on NACE 2 sectors.

(307) Cedefop skills forecast: green and digital transitions to have positive employment impacts.

Figure 120: Historical and projected shares of employment by occupations in 2040 (% of total)



Oc1	Managers	Oc7	Building
Oc2	Professionals	Oc8	Electrical and eletronic
Oc3	Technicians	Oc9	Metal, machinery and related
Oc4	Clerical support	Oc10	Plant and machine operators
Oc5	Service and sales	Oc11	Elementary occuptions
Oc6	Skilled workers in agri, forest. and fish.		

Source: JRC-GEM-E3 model and CEDEFOP skills forecast.

Useful as they are to assess broad economic trends and, in particular, interactions between a range of factors and developments, macro-economic models are not in the best position to assess the impact of transformations within sectors. A bottom-up analysis of sectors that will be particularly relevant for the transition is therefore provided below, linking projections from the PRIMES model and further building on the results from JRC-GEM-E3. An assessment is provided for the automobile sector, construction and heating systems, and the deployment of renewable power generation.

2.4.3.2.Automobile sector, construction, heating and electricity

Regulation (EU) 2023/851 amending Regulation (EU) 2019/631 imposes a ban on the sale of new non-zero emission cars and vans in the EU from 2035 onwards. This implies a major transformation of the automobile manufacturing sector and has implications across the whole value chain. A version of the JRC-GEM-E3 model was augmented with an explicit representation of vehicle manufacturing and an upgrade of the modelling of vehicle purchase and operation, as electric vehicles (which were assumed as the zero-tailpipe emission technology deployed) have different needs not only in terms of manufacturing, but also operation and maintenance. On this basis, Tamba & al. find that transport electrification alters supply chains and leads to structural shifts in employment from traditional vehicle manufacturing towards battery production, electricity supply and related investments (308). They find that, in the medium term, reaching a given climate target with limited road transport electrification has negative impacts on GDP compared to an alternative option with higher electrification as further efforts are then needed in other sectors with potentially higher abatement costs.

Importantly, the authors find that the shift towards the production of electric vehicles implies a small net increase in employment in the car manufacturing sector overall, driven primarily from costs reductions over time (including learning in batteries and lower maintenance and operation costs) leading to increases in demand for vehicles. In turn, the net employment effect on the services side is projected to be negative due to the lower maintenance services requirements of electric vehicles compared to internal combustion engine ones. The batteries sector and power generation, in contrast, are positively impacted by the electrification of road transport.

As indicated above, the share of the construction sector in total employment is projected to remain broadly stable across all scenarios under the JRC-GEM-E3 model. A major driving force in construction employment, which currently represents about 16 million jobs, will be the need to achieve much higher renovation rates of the existing building stock over the next decade to improve energy efficiency and enable the transition to decarbonised heating systems (mainly heat pumps). The construction sector should also benefit from the building of new green infrastructure, including in power generation and transport. At aggregate level, the requirements for construction jobs will also be influenced by factors that are exogenous to the climate and energy transition, mainly a gradual decline in total population in the long term, ageing and patterns and choices in terms of geographic spread of the population or urban densification.

A sharp increase in renovation rates in the residential sector will be unavoidable as part of the transition to climate neutrality, regardless of the level of ambition for 2040. Annual renovation rates in 2011-2020 were about 0.8% of the residential building stock and were driven mainly by light renovations. Under S1, overall renovation rates are projected to double throughout the transition period to 2050, with a particularly high increase in medium renovations. S2 and S3 would require even higher renovation rates. This would imply more than 4 million renovations per annum on average in 2031-2050 under the 3 main scenarios, with a significant early push under S3, delay under S1 and a more even level of renovation across the two decades under S2 (Table 51).

What is particularly important in terms of employment is that this push in renovation is not only large in terms of scale and compared with previous decades, but also that it is to be sustained over several decades, starting in the current one already. This should therefore provide job opportunities with long-term prospects for a significant number of people. Based on an average labour intensity of 5 full-time jobs equivalent per million euro invested in renovation (309), the renovation drive alone could generate about 250 000 jobs over the period 2031-2050. This represents an additional 160 000 jobs compared to

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(308) Marie Tamba, Jette Krause, Matthias Weitzel, Raileanu Ioan, Louison Duboz, Monica Grosso, Toon Vandyck, Economy-wide impacts of road transport electrification in the EU, Technological Forecasting and Social Change, Volume 182, 2022.

(309) This corresponds to the average number of full-time jobs equivalent per million euro of turnover in the construction of residential and non-residential buildings in 2016-2020, as per Eurostat data.

the level in 2011-2020, as estimated on the basis of the same labour intensity per million euros invested. While this remains small compared to total construction employment (Table 48), it is nevertheless significant, and it is to be noted that this figure accounts only for the direct employment impact, without considering further effects along the value chain (310). Similarly, to the investment requirements, the levels of job creation linked to the renovation drive are highest in 2031-2040 under S3, with S2 generating a more even impact across the two decades than S3 and S1.

Table 51: Average annual renovations in residential and tertiary sectors

	2011-2020	2021-2030	2031-2040	2041-2050
Residential				
S1 units	2.0	5.0	3.7	4.5
S1 floor	137	379	286	384
S2 units	2.0	5.0	4.2	4.0
S2 floor	137	381	331	343
S3 units	2.0	5.0	5.1	3.3
S3 floor	137	380	392	282
LIFE units	2.0	5.0	4.7	4.0
LIFE floor	137	378	370	342
Tertiary				
S1 units	62	155	86	149
S1 floor	24	66	41	79
S2 units	62	158	131	108
S2 floor	24	68	63	57
S3 units	62	162	187	55
S3 floor	24	69	88	30
LIFE units	62	156	165	86
LIFE floor	24	67	77	46

Note: floor stands for floor surface and is in million m2, units in millions (residential) and thousands (tertiary).

Source: PRIMES.

Such significant needs for construction jobs will also require that training and skilling systems are put in place to ensure the availability of workers for all necessary occupations and at all levels of skills, including relevant craft and trades, developers and architects/engineers. The long-term visibility afforded by the sustained requirement in the sector should also enable the establishment of the necessary education and training programmes for the younger segments of the population. By nature, the renovation sector is also one where SMEs are likely to be particularly active, and where they should benefit from business opportunities.

A similar renovation drive will be necessary in the tertiary sector, where around 90 000 units are projected to be renovated on average per annum in 2031-2050 under S1, rising to an annual average of about 140 000 units under S3. While the number of units is much

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(310) SWD(2021) 453 final, part 1/4 provides an additional discussion of the employment impacts of renovations, focusing on the effect of the Commission proposal for a Directive of the European Parliament and of the Council on the energy performance of buildings (recast).

lower than in the residential sector, the floor area to be renovated is still large at around 14% of the floor area in the residential sector.

An additional driver of employment creation and skills requirement in the course of the transition to climate neutrality relates to the decarbonisation of heating and cooling systems, mainly via the installation of heat pumps. This should not only generate job creation in installation and maintenance, but also in manufacturing. The deployment of heat pumps in the residential and tertiary sectors will need to take place rapidly during the transition to climate neutrality, at an estimated average of more than 3 million units per annum in 2031-2050 in the residential sector and around 200 000 to 300 000 (larger scale) units in the tertiary sector. The deployment level is similar across scenarios.

To a large extent, heat pumps will substitute other types of heating equipment that would also require to be replaced at the end of their operational lifetime. Their installation will therefore only impact total employment in the sector at the margin, to the extent that installation may be more labour intensive than for other types of equipment and to the extent that the shifting to heat pumps may anticipate the end of the operational lifetime of the assets they replace. The impacts on the labour market would be significant, however, as the installation levels would require skills adaptation and retraining (311). Based on an estimated labour intensity ratio of 1 full time job equivalent for about 36 heat pumps installed annually (312), around 100 000 full time installers would be required for the time period 2031-2050.

On the manufacturing side, the Commission estimated that producing the entirety of the heat pumps installed up to 2030 in the EU would lead to an increase of about 60 000 jobs (313). The projections for the needs for heat pumps beyond 2030 indicate that the ramping up of production capacity and the associated job creation should be sustained in the long-term.

As far as power generation is concerned, the deployment of on-shore and off-shore wind and solar energy will rise sharply throughout the transition period to 2050. While S3 requires a faster ramp up or renewable electricity generation than S2 and S1, the three pathways rely on similar overall annual new capacity installation. Close to GWe 100 of net power capacity installation will be required for solar and wind energy. The employment opportunities generated by such a level of installation are very large, both in terms of installation and in terms of manufacturing. On the installation side, solar power is more likely to generate business opportunities and job creation among SMEs, while the deployment of wind turbines will be more tilted towards larger companies.

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(311) The Employment and Social Developments in Europe 2023 Annual Review (adressing labour shortages and skills gaps in the EU) provides first estimates of the job creation potential up to 2030 related to the deployment of certain clean technologies, as well as estimates of the necessary spending on retraining, reskilling and upskilling.

(312) The European Heat Pump Association’s European Heat Pump Market and Statistics Report 2023 indicates that close to 3 million heat pumps were installed in the EU in 2022, with 67 000 installers employed in the sector (a ratio of 44 to 1). Similarly, a report from the Heat Pump Association projected the needs for heat pump installation and installers to decarbonise heating the UK up to 2035. Their projections indicate a ratio of 28 to 1 on average for the period.

(313) SWD(2023) 68 final.

On the manufacturing side, the Commission also assessed the job creation potential from the domestic manufacturing of solar panels and wind turbines, in a 2030 horizon. While the solar PV manufacturing industry is extremely small in the EU currently, it estimated that around 66 000 jobs could be created in the sector if the EU were to become self-sufficient in the production of solar PVs. Continued needs in 2031-2050 for the installation of solar PVs at around the level needed to achieve the climate and energy targets under the Fit-for-55 legislation indicates that domestic demand will be sustained for an extended period of time and that employment in the sector could remain large if production capacity is ramped up. Similarly, it was estimated that around 40 000 additional jobs would be needed to make the EU self-sufficient in the production of wind turbines in a 2030 horizon. Given that the annual installation needs for wind power are projected to increase by around 60% between 2021-2030 and 2031-2050, one could foresee the creation of large additional employment opportunities in the technology in the horizon 2050.

As indicated in the same assessment, the scaling-up of manufacturing capacities would not only require investing capital in factories and technologies, but also to ensure that the workforce is available and that it has the necessary type and level of skills to operate in new sectors. The re-skilling and up-skilling investment needs, with a 2030 horizon, were estimated at up to EUR 4.1 billion. Extending this horizon to the 2031-2050 period would clearly also broaden the scope and the scale of skills-related investment needs, as the range of sectors affected widens and the overall capital investment needs remain large.

2.4.3.3.LIFE

Further labour market impacts from a higher uptake of circularity in the economy, as explored under the LIFE setting, could also be expected, even though macro-economic models are not well equipped to assess them. Enhanced circularity will likely entail job creation as well as job destruction in certain sectors, together with job substitution and redefinition. Labour market impacts can be expected to occur at three stages of the materials cycle: (1) as materials are transformed into products, infrastructure and assets, resource efficiency will shift the relative balance of companies' inputs from materials to labour; (2) while products are functional, value retention activities (repair, refurbishment, servicing, upgrading) and use-optimisation services (product-as-a-service and sharing models) imply job creation in proximity to where the products are consumed; and (3) when products and assets become waste, there are generally far more jobs generated through treatment at the higher echelons of the waste hierarchy, with one study showing that in dealing with 10 000 tonnes of waste, 1 job is created by incineration, 36 by recycling and between 300 and 800 by repair and re-use ([314]).

The CAPRI model provides indicators on employment effects from the LIFE setting. The results show limited labour impacts on agriculture. Total labour (in hours/ha) in the crop sector decreases by 0.6%, characterized by a decrease in labour related to cereals (-7%) and a slight decrease in labour on vegetables and permanent crops (-0.4%). Furthermore, a stronger decline in labour hours in cattle activities (-25%) and other animals (-24%) contributes to an overall reduction of total labour of 10.4% on all agricultural activities.

([314]) GAIA. Zero Waste and Economic Recovery. The Job Creation Potential of Zero Waste Solutions.

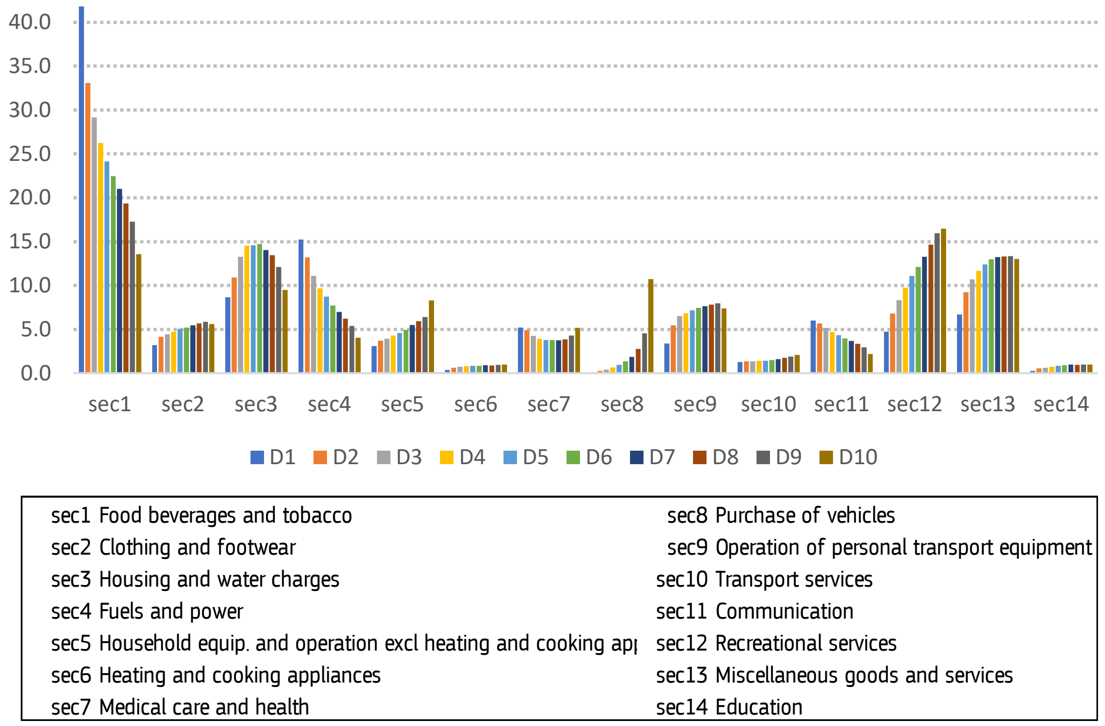
However, it needs to be considered that this assessment based on the CAPRI model ignores the labour requirements for management of second-generation lignocellulosic crops, payment for ecosystem services (PES), and carbon farming activities and it also does not reflect the additional labour requirements from the expansion of organic agriculture, both of which tend to alleviate the decline in agricultural labour use.

2.4.4. Changes in relative prices and distributional impacts

The transition to climate neutrality is susceptible to affect relative prices in the economy, as consumption and production patterns change in accordance with the GHG mitigation needs. Sections 1.1.1 and 1.1.2 assess the direct impact on households of projected changes in fuel expenses and electricity prices. The latter will become particularly important as household energy consumption is set to gradually shift overwhelmingly towards electricity. To complement this analysis, the JRC-GEM-E3 model was used to assess the potential impact on households of changes in relative prices across the economy. A macro-economic model is indeed best suited to capture the full effects and interactions across sectors that will affect relative prices.

Estimating changes in relative prices is a first step towards assessing the impact on welfare for households, as the latter have very different consumption patterns depending on their income or expenditure levels. Poorer households spend a higher share of their disposable income on basic necessities than households with higher income, including on energy consumption or housing and food, whose relative prices are more susceptible to be affected by the transition to climate neutrality (Figure 121).

Figure 121: EU household mean budget shares by expenditure decile, 2015 (%)



Source: Household Budget Survey.

Overall, relative prices are projected to vary relatively little across scenarios. The relative price of housing is nevertheless likely to be somewhat higher under S3 than under S2 in 2040, and slightly lower under S1 than under S2 as higher levels of renovation associate with higher climate ambition increase costs for homeowners and renters alike. Similarly, the relative price of the operation of transport equipment is projected to increase with a higher level of mitigation in 2040. In contrast, the accelerated shift towards electrification and renewables power generation is projected to decrease the relative prices of fuels and power in S3 relative to S2, and increase it in S1 relative to S2 (Table 52).

Table 52: Changes in relative prices, S1 and S3 vs. S2 (% change)

	S1		**S3**	
	2040	**2050**	**2040**	**2050**
Food beverages and tobacco	-0.3%	0.0%	0.2%	0.0%
Clothing and footwear	-0.1%	0.0%	0.1%	0.0%
Housing and water charges	-0.5%	0.0%	0.7%	0.0%
Fuels and power	0.5%	0.5%	-0.9%	-0.6%
Household equipment	-0.2%	0.0%	0.1%	0.0%
Heating and cooking appliances	-0.2%	0.0%	0.1%	0.0%
Medical care and health	-0.1%	0.0%	0.1%	0.0%
Purchase of vehicles	-0.2%	0.0%	0.0%	-0.1%
Operation of transport equip.	-0.7%	0.0%	0.5%	0.0%
Transport services	-1.7%	-0.1%	0.9%	0.2%
Communication	0.0%	0.0%	0.1%	0.0%
Recreational services	-0.2%	0.0%	0.2%	0.0%
Miscellaneous goods and services	-0.1%	0.0%	0.1%	0.0%
Education	0.0%	0.0%	0.1%	0.0%

Source: JRC-GEM-E3.

Linking these estimated changes in relative prices to micro-data from the household budgetary survey, the JRC estimated distribution impacts per expenditure and income deciles (315). This work elaborates on what was done in the impact assessment for the 2030 Climate Target Plan and for the Council Recommendation on fair transition (316). It improves the previous estimation of impacts by allowing the structure of household consumption to vary over time. Previous estimates instead used the household budgetary survey in a fully static manner, i.e., it assumed that the expenditure structure across income groups did not change over time, and it applied changes in relative prices across scenarios to the (static) historical expenditure structure from the data.

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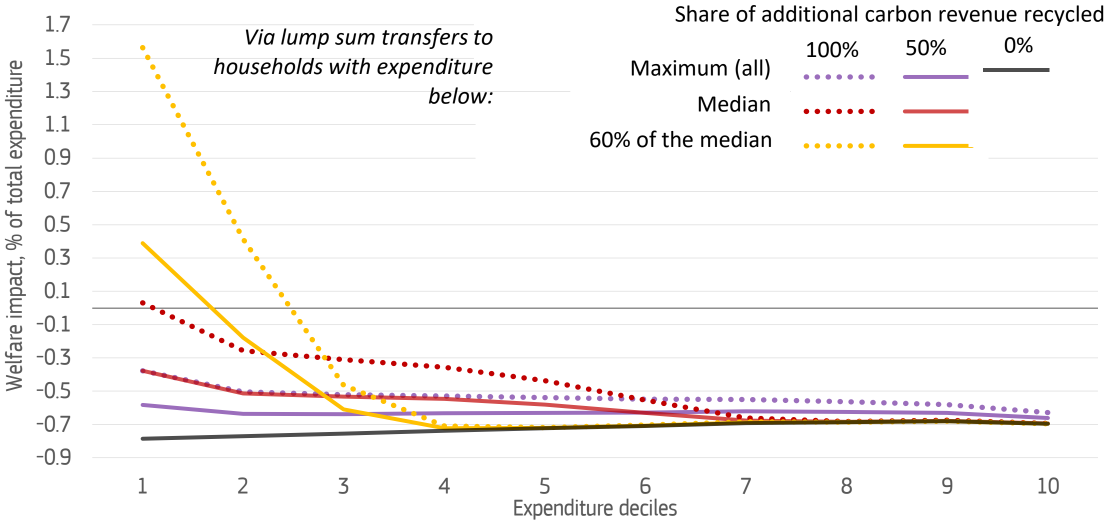
(315) The analytical tool was developed under two joint projects between the Directorate-General Employment, Social Affairs and Inclusion and the Joint Research Centre. The two projects are: “Assessing and monitoring employment and distributional impacts of the Green Deal (GD-AMEDI)” and “Assessing distributional impacts of geopolitical developments and their direct and indirect socio-economic implications, and socio-economic stress tests for future energy price scenarios (AMEDI+)”. The projects combine macro- and micro-economic modelling approaches to enhance the Commission’s analytical capacities for assessing and monitoring employment, social and distributional impacts of climate and energy policies.

(316) Council Recommendation of 16 June 2022 on ensuring a fair transition towards climate neutrality (2022/C 243/04). See also SWD(2021) 452 final, which provides an overview and discussion of the available analytical evidence underpinning the recommended policy interventions.

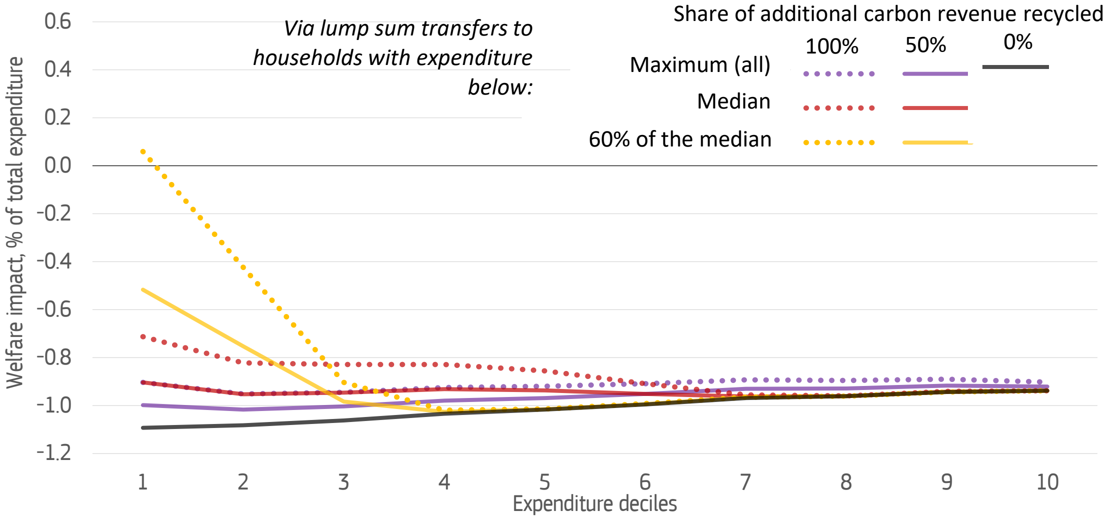
The estimates show that lower income households will be more affected than higher income households as the level of climate ambition rises, as measured in terms of compensating variation, i.e., the monetary transfer that would be necessary to maintain the same level of utility as under the previous set of relative prices. Assuming that none of the additional revenue from carbon pricing are redistributed to households to tamper impacts, the welfare impact of S2 would amount to about -0.8% (% of total expenditure) for the lowest expenditure deciles, and about -0.7% for the highest expenditure decile (Figure 122). The effects would be larger under S3 at about -1.1% and -0.9%, respectively (Figure 123).

Figure 122: Change in relative welfare by expenditure decile, S2



Source: JRC.

Figure 123: Change in relative welfare by expenditure decile, S3



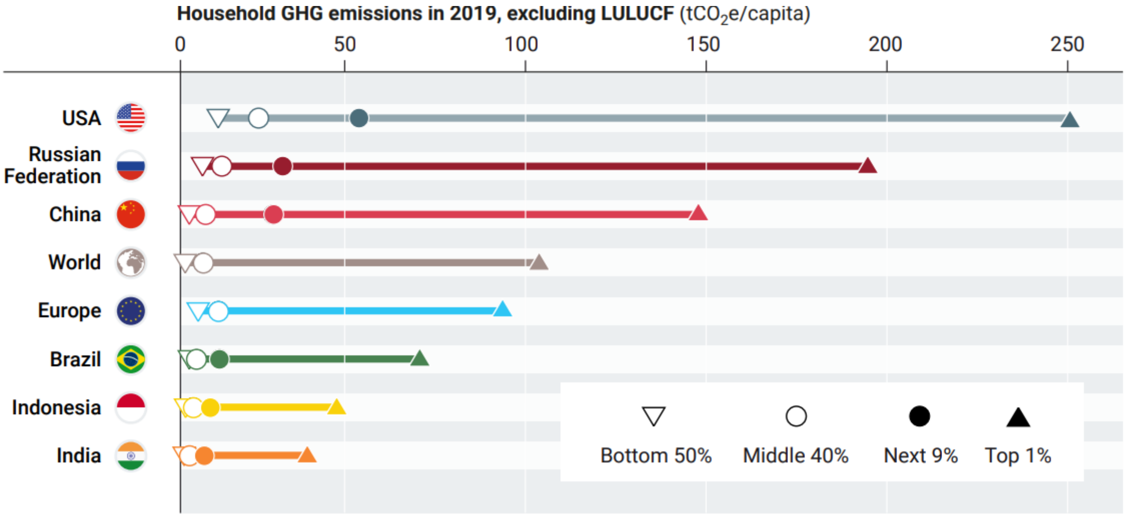
Source: JRC.

Redistributing some or all of the additional carbon revenue would sharply reduce this negative impact on the lower expenditure deciles, and it could even reverse it if the redistribution is targeted, e.g., to the households with expenditure levels below 60% of the median. Even a partial (50%) redistribution of additional carbon revenue would be sufficient to reverse the negative distributional impacts on the lowest expenditure deciles, if it is targeted on households with income below 60% of the median. It is important to note also that the estimates of the effectiveness of redistributing carbon revenues are based on the use of only additional carbon revenue between S2 or S3 and S1. They do not account for full extent of carbon revenues, which would be much larger than the additional ones given that S1 already factors in the vast majority of carbon revenues.

2.4.5. *The equity dimension*

According to the UNEP Gap Report 2022 (Figure 124), there are high-emitting households in all major economies. Different levels of household GHG emissions exist both within and between countries. The low-emitting households have relatively close levels of emissions throughout countries, but the emission range for the top 1% emitting households is quite broad.

Figure 124: Household GHG emissions per income category



Note: Per capita emissions include emissions from domestic consumption, public and private investments, and imports and exports of carbon embedded in trade with the rest of the world. Households are ranked according to total emissions and divided accordingly into groups (e.g., the bottom 50 per cent refers to the 50 per cent of households with the lowest emissions in that country or region).

Source: UNEP Gap Report 2022

2.5. Regional impacts

2.5.1. *Regional exposure to climate change*

For the regional impacts of climate change, we refer to Annex 7 on the cost of climate change.

2.5.2. *Regional exposure to the transition*

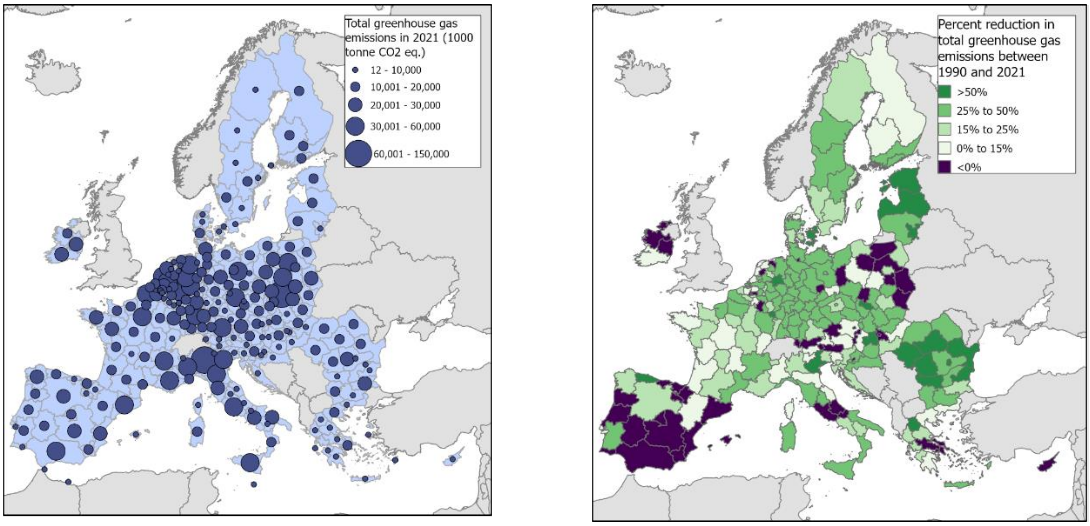
The European Climate Law specifies that, *“[when] proposing the Union 2040 climate target in accordance with paragraph 3, the Commission shall consider […] fairness and solidarity between and within Member States*”. The macro-economic modelling work conducted for 2030-2050 is at the EU and sectoral level (GEM-E3, E3ME, E-QUEST). It does not examine the impacts at the regional level. Below, we characterise regions as they stand today in order to anticipate their exposure to the transition. This is based on EDGAR, regional emissions inventory which monitors the emissions of greenhouse gases since 1990 for 26 broad sectors (317).

2.5.2.1.GHG intensity of the regions

The total emissions at the regional level (Figure 125), the emissions per capita (Figure 126) as well as the emission intensity of the regions (Figure 127) show the diversity of circumstances in which regions are. These figures have to be interpreted carefully as some regions with relative low emissions levels may depend on some emission intensive industries (for example for power generation) that are located in other regions. Changes in regional emissions may be the result of the decarbonisation of economic activities but also of the closure, opening or relocation of activities, as well as of population migrations. Some regions, such as the capital region of Lithuania (Sostinės regionas) and Western Macedonia (EL), have seen their total emissions being reduced by about 70% in the last three decades. Others, such as the Groningen (NL) and central Greece (EL) regions, have a high emission intensity and have not yet shown a strong decarbonisation trend in the last decades (318).

The total emissions at regional level reflect the economic activities of the regions and the emission intensity of these activities. For example, the regions with the highest per capita emissions are Zeeland (NL) and Western Macedonia (Greece). In Zeeland, 60% of emissions are caused by industry, while in Western Macedonia almost 70% of emissions are due to electricity generation.

Figure 125: Total emissions at regional level (left) and corresponding change since 1990 (right)



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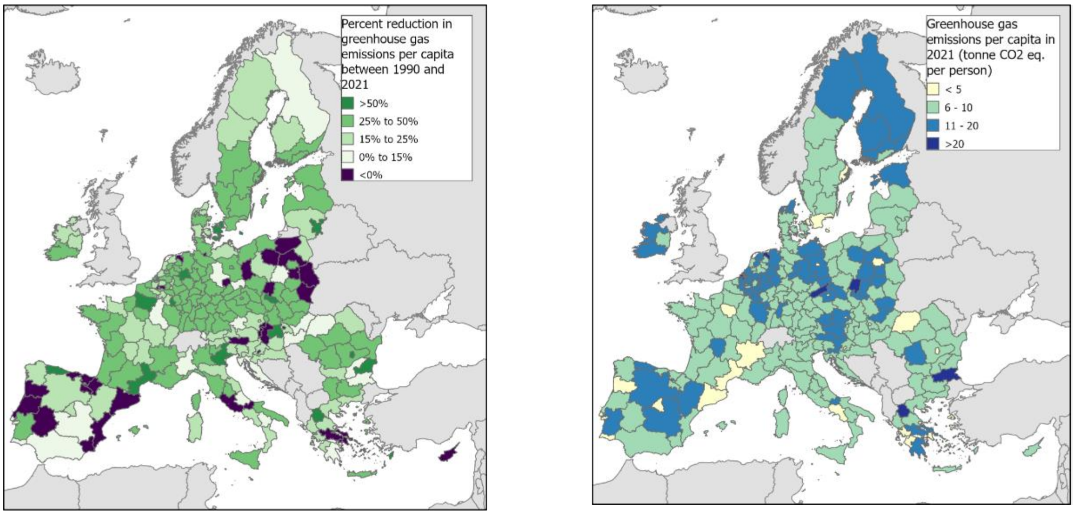
(317) Guizzardi, Diego; Pisoni, Enrico; Pagani, Federico; Crippa, Monica (2023): GHG Emissions at sub-national level. European Commission, Joint Research Centre (JRC) [Dataset] doi: 10.2905/D67EEDA8-C03E-4421-95D0-0ADC460B9658 PID: http://data.europa.eu/89h/d67eeda8-c03e-4421-95d0-0adc460b9658

(318) In the case of Groningen, emissions might decrease after the permanent closure of the region's gas field in 2023.

Note: leaving out aviation and shipping.

Source: EDGAR emissions database

Figure 126: GHG emissions per capita in 2021 and change in GHG emissions per capita between 1990 and 2021



Note: leaving out aviation and shipping.

Source: EDGAR emissions database

For 174 regions out of 242, emissions per capita (Table *53*) in 2021 were above 5 tCO_2-eq per person), which is approximately the emission per capita level implied by the 2030 target. Among the 242 NUTS2 regions, 68 regions reached emission levels below 5 tCO_2-eq per person in 2021. Decarbonization is not a linear process. For the richest western Member States, regional emissions have mostly been declining. But for most of the countries that accessed the EU in or after 2004, the fall in emissions in the years after the collapse of the Soviet Union was followed by a relative stable trend or even an increase. In aggregate, out of the 242 NUTS 2 regions, 155 experienced a downward trend in emissions per capita since 1990, 74 since 2005, eight since 2010, and three since 2015. In two Polish regions, per capita emissions are still increasing.

Overall, between 1990 and 2021, emissions per capita in regions (see Table 53) have decreased. For example, in Denmark, the national average was 6.9 tCO_2-eq per person in 2021, with regional levels ranging from 3.2 to 13.2 tCO_2-eq per person, in comparison with a national average of 13.4 tCO_2-eq per person in 1990 and regional levels between 8.8 and 21.1 tCO_2-eq per person in that year. Only in Hungary the level of emission per capita in the less emitting region has significantly increased between 1990 and 2021 (from 2.9 to 4.5 tCO_2-eq per person). This is due to the installation and closure of coal fired power stations.

Table 53: National per capita emissions and range across regions

TCO$_2$-EQ PER PERSON	1990	2021
Austria	10.8 (4.5 - 15.4)	9.2 (4.2 - 13.7)
Belgium	14.5 (4.4 - 20.8)	10.8 (3.9 - 15.6)
Bulgaria	11.8 (7.5 - 21.5)	8.6 (5.8 - 20.5)
Croatia	7.5 (3 - 10.2)	6.1 (3.5 - 7.9)
Cyprus	9.3	9.5
Czechia	18.9 (7.4 - 39.2)	11.3 (4 - 27.9)
Denmark	13.4 (8.8 - 21.1)	6.9 (3.2 - 13.2)
Estonia	27.2	14.8
Finland	16.9 (2.1 - 22.1)	11.6 (1 - 13.8)
France	9.6 (0.1 - 33.2)	6.3 (0.1 - 21.6)
Germany	15.5 (6.5 - 30.6)	9.3 (4.7 - 19.7)
Greece	9.6 (3.7 - 101.2)	6.7 (3.8 - 33.4)
Hungary	9.3 (2.9 - 20)	7.1 (4.5 - 11.7)
Ireland	16.5 (10.8 - 23.5)	12.4 (8.7 - 16.4)
Italy	9.3 (4.9 - 16.8)	6.6 (4.1 - 13.3)
Latvia	10.5	6.2
Lithuania	12.9 (11.9 - 15.7)	8.4 (5.2 - 9.7)
Luxembourg	33.5	14.7
Malta	7.1	4.2
Netherlands	16.3 (10.4 - 64.2)	11.1 (5.8 - 35.2)
Poland	13.6 (5.2 - 28.2)	11 (4.6 - 22.8)
Portugal	5.9 (2.1 - 24.8)	5.4 (2.5 - 15)
Romania	10.1 (5.3 - 17.1)	6.2 (2.9 - 10.4)
Slovakia	14.2 (10 - 18.9)	8.8 (6.2 - 11.6)
Slovenia	11.6 (8.4 - 14.2)	9.1 (6.4 - 11.5)
Spain	7.4 (2.8 - 35.2)	6.3 (2.3 - 16.7)
Sweden	9.2 (6.6 - 17.2)	5.8 (3.9 - 13.7)

Note: For countries with one region only, a figure instead of a range is reported.

Source: EDGAR emissions database

In 214 out of the 242 EU regions, the GHG intensity (emissions per regional economic output) is above 0.15 (Figure 127), i.e. above the EU average that is compatible with an at least 55% net GHG emission reduction by 2030 (319). However, in all but eight regions emission intensity has declined since 1990. In fact, more than half of the EU's regions (122 out of 242) have seen their emission intensity decrease by more than 50% since 1990, including in several regions that had a very high emission intensity such as Świętokrzyskie (PL) and Western Macedonia (EL).

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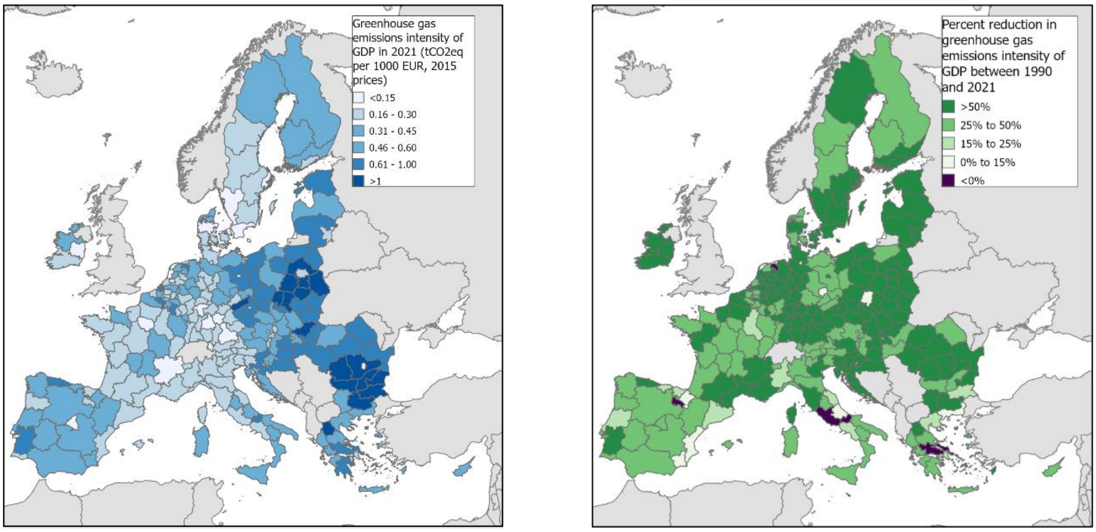
(319) The figure of the EU average GHG intensity compatible with the 55% target depends on the computation method and on the GDP estimates used. Other computations can give an average of 0.10 tCO$_2$eq per 1000 euros instead of 0.15.

Figure 127:Emission intensity (left) and corresponding change since 1990 (right)

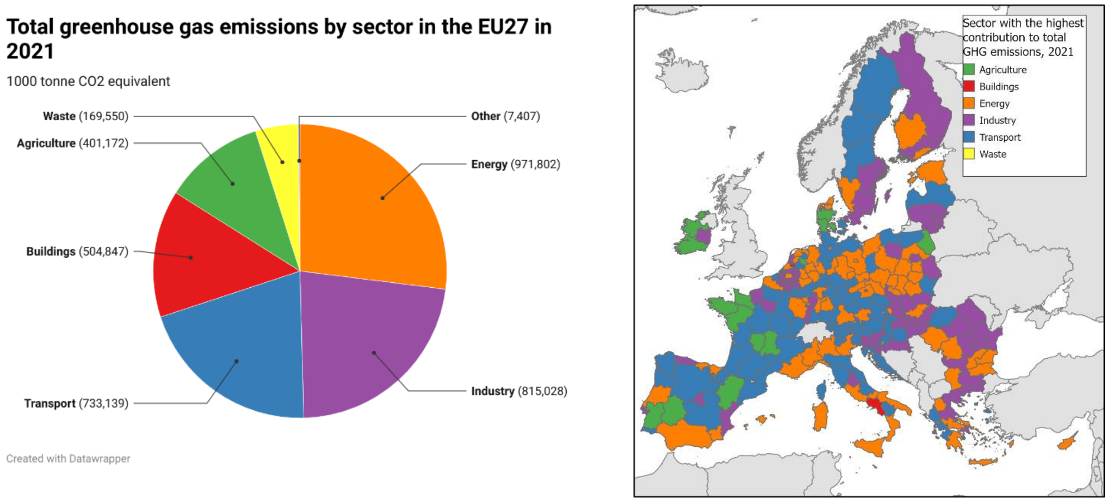


Note: leaving out aviation and shipping

Source: EDGAR emissions database

The exposure of regions to the transition is strongly dependent on their economic activities. While the energy, industry, transport, building and agriculture sectors respectively represent 27, 23, 20, 14 and 11% of total EU GHG emissions (Figure 128), the distribution of sectoral emissions in specific regions is more diverse. For example, the sector contributing the most to GHG emissions is agriculture (39%) in the west of France, industry (33%) in Romania, energy (34%) in most Polish regions, and transport (45%) in the north of Sweden (in the region Mellersta Norrland).

Figure 128: Greenhouse gas emissions by sector in the EU27 and sector with the highest contribution at the regional level in 2021



Note: leaving out aviation and shipping

Source: EDGAR emissions database(320)

Table 54 and Table 55 present the sectoral per capita emissions at the national level and the range of these across regions in each country, in 1990 and 2021 respectively. The

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(320) Emissions data in EDGAR include CO_2, CH_4, N_2O, F-gases.

national averages reflect the structure of the country's economy. For example, emissions in Ireland are largely driven by the agricultural sector (6 tCO_2-eq per person in 1990 and 4.6 in 2021). However, the ranges across regions show the diversity within country. For example, in France, the highest regional agricultural emissions amounted to 18 tCO_2-eq per person in 1990 and decreased to 9.5 in 2021.

For the energy and industry sectors, which have been largely covered by the EU Emissions Trading System (EU ETS) since 2005, the decarbonisation trend is clear. In 1990 national sectoral emissions per capita were ranging from 0.8 (France) to 6.2 tCO_2-eq per person (Czechia) for the energy sector and from 0.1 (Malta) to 6.8 tCO_2-eq per person (Czechia) for the industry sector. In 2021 these emissions are lower and closer to one another, from 0.3 tCO_2-eq per person (Lithuania) to 4.3 (Estonia) for the energy sector, and from 0.7 tCO_2-eq per person (Malta) to 4.7 (Estonia) for industry. Due to the regional concentration of some activities, disparities across a country's regions can be large. For example, in the Netherlands regional emissions from the energy sector range from 0.4 – 22 tCO_2-eq per person and from industry from 1.2 - 21.4 tCO_2-eq per person.

Emissions from the transport and building sectors will be covered by the ETS2. To address potential social impacts of this new instrument, the Social Climate Fund will finance temporary direct income support for vulnerable households and support measures and investments that reduce these emissions (see more details in the enabling framework in Annex 9).

Table 54: Sectoral per capita emissions and range across regions in 1990

tCO$_2$-eq per person	**Agriculture**	**Buildings**	**Energy**	**Industry**	**Transport**	**Waste**
Austria	1.2 (0 - 1.9)	1.8 (1.2 - 2.3)	1.9 (0.3 - 4.2)	3.2 (1.1 - 7.3)	1.8 (0.3 - 2.8)	0.8 (0.1 - 1.8)
Belgium	1.2 (0 - 4.4)	2.7 (2 - 3.2)	2.6 (0.1 - 5.3)	5.3 (1.5 - 11.7)	2 (0.5 - 6.3)	0.7 (0.3 - 2.4)
Bulgaria	1.4 (0.7 - 1.7)	0.9 (0.8 - 1)	5 (1 - 15)	2.7 (0.8 - 3.8)	0.7 (0.6 - 0.9)	1 (0.5 - 1.4)
Croatia	1 (0.1 - 1.5)	0.9 (0.5 - 1.1)	1 (0.4 - 1.5)	3.6 (1.7 - 5.4)	0.8 (0.2 - 1)	0.2 (0.2 - 0.2)
Cyprus	0.8 (0.8 – 0.8)	0.3 (0.3 – 0.3)	3 (3 – 3)	2.6 (2.6 – 2.6)	2.1 (2.1 -2.1)	0.6 (0.6 – 0.6)
Czechia	1.7 (0 - 3.8)	3 (2 - 3.3)	6.2 (1.4 - 27.4)	6.8 (3.2 - 24)	0.7 (0.2 - 1)	0.4 (0.2 - 1)
Denmark	2.4 (0.2 - 4.4)	1.7 (1.6 - 1.8)	4.9 (1.7 - 12.9)	1.9 (1.2 - 2.9)	1.9 (1 - 2.5)	0.4 (0.2 - 0.7)
Estonia	1.9 (1.9 – 1.9)	1.3 (1.3 – 1.3)	16.8 (16.8 – 16.8)	4.5 (4.5 – 4.5)	1.5 (1.5 – 1.5)	1.1 (1.1 – 1.1)
Finland	1.3 (0.3 - 2.5)	1.9 (0.1 - 2)	3.8 (0.7 - 6.2)	4.1 (0 - 6.4)	2.2 (1.2 - 3.7)	3.5 (0 - 4.6)
France	1.5 (0.1 - 18)	1.8 (0 - 2.6)	0.8 (0 - 3.3)	3 (0 - 7.4)	1.9 (0.6 - 3.6)	0.4 (0.1 - 3.6)
Germany	1.1 (0 - 4.1)	2.8 (1.8 - 3.3)	4.8 (0.4 - 17.8)	4.2 (1.6 - 9.6)	2 (0.5 - 4.4)	0.6 (0.1 - 3.2)
Greece	0.9 (0 - 2.8)	0.9 (0.6 - 1.2)	3.5 (0 - 88.6)	2.7 (1.1 - 7.4)	1.2 (0.5 - 2.5)	0.4 (0.1 - 1.1)
Hungary	1.1 (0 - 1.9)	2 (1.1 - 3)	2 (0.1 - 8.5)	2.7 (0.8 - 8.1)	0.8 (0.2 - 1.1)	0.6 (0.5 - 0.9)
Ireland	6 (2.7 - 9.7)	3.1 (2.8 - 3.6)	3.1 (0.2 - 7.7)	2.4 (1.3 - 3.1)	1.4 (1 - 1.9)	0.6 (0.3 - 1.5)
Italy	0.7 (0.1 - 1.9)	1.4 (1.3 - 1.6)	2.2 (0.1 - 6.2)	2.9 (1.3 - 6)	1.7 (0.9 - 5.6)	0.5 (0.1 - 1.5)
Latvia	2.4 (2.4 - 2.4)	1.4 (1.4 – 1.4)	3.7 (3.7 – 3.7)	1.6 (1.6 – 1.6)	1.1 (1.1 – 1.1)	0.2 (0.2 – 0.2)
Lithuania	2.4 (0.8 - 2.9)	2 (1.6 - 2.1)	3.3 (1 - 10)	3.2 (2 - 3.6)	1.5 (1.1 - 1.7)	0.4 (0.1 - 0.5)
Luxembourg	1.7 (1.7 – 1.7)	3.5 (3.5 – 3.5)	4.6 (4.6- 4.6)	16.3 (16.3 – 16.3)	7 (7 - 7)	0.3 (0.3 – 0.3)
Malta	0.3 (0.3 – 0.3)	0.3 (0.3 – 0.3)	5 (5 – 5)	0.1 (0.1 – 0.1)	1.3 (1.3 – 1.3)	0.1 (0.1 – 0.1)
Netherlands	1.5 (0.3 - 4.2)	2.6 (2.3 - 3.9)	2.9 (0.5 - 9.7)	6.3 (1.5 - 41.9)	1.8 (1.2 - 5.3)	1.2 (0.1 - 5.9)
Poland	1.3 (0.3 - 4.5)	1.5 (1.4 - 1.7)	5.9 (0.4 - 15.4)	3.9 (0.9 - 16.5)	0.5 (0.3 - 0.8)	0.5 (0.1 - 3.1)
Portugal	0.8 (0 - 4.8)	0.4 (0.3 - 0.6)	1.5 (0 - 13.7)	1.6 (0.7 - 2.9)	0.9 (0.4 - 1.9)	0.6 (0.2 - 1)
Romania	1.4 (0.1 - 1.8)	0.8 (0.5 - 0.9)	3.2 (0.3 - 11.4)	4 (1.7 - 7.1)	0.5 (0.2 - 0.6)	0.2 (0.1 - 0.3)
Slovakia	1.3 (0.4 - 1.5)	3.3 (3.2 - 3.4)	2.6 (0.5 - 3.8)	5.5 (3.1 - 9.5)	0.8 (0.7 - 0.9)	0.7 (0.2 - 1)
Slovenia	1.4 (1 - 1.7)	1 (1 - 1.1)	3.1 (1.2 - 4.7)	4.1 (3.3 - 4.8)	1.3 (1.3 - 1.4)	0.6 (0.6 - 0.6)
Spain	1 (0 - 4.1)	0.6 (0.4 - 0.7)	1.7 (0 - 11.2)	2.4 (0.8 - 20.8)	1.4 (0.7 - 3.5)	0.4 (0.1 - 1.1)
Sweden	1 (0.1 - 2.2)	1.3 (1.2 - 1.4)	1 (0 - 2.5)	2.5 (1.2 - 5.6)	2.2 (1 - 5.5)	1.2 (0.6 - 1.5)

Note: leaving out aviation and shipping

Source: EDGAR emissions database

Table 55: Sectoral per capita emissions and range across regions in 2021

TCO$_2$-EQ PER PERSON	**AGRICULTURE**	**BUILDINGS**	**ENERGY**	**INDUSTRY**	**TRANSPORT**	**WASTE**
Austria	0.8 (0 - 1.3)	1 (0.8 - 1.2)	1.4 (0.4 - 2.2)	3.1 (1.5 - 6.3)	2.5 (0.4 - 4.3)	0.3 (0.1 - 0.6)
Belgium	0.8 (0 - 2.7)	2 (1.6 - 2.4)	1.3 (0.1 - 2.1)	4.1 (1.5 - 8.2)	2.1 (0.4 - 6.3)	0.4 (0.1 - 2.4)
Bulgaria	0.8 (0.4 - 1.4)	0.3 (0.2 - 0.3)	3.2 (0.1 - 14.3)	2 (1.1 - 3)	1.3 (1 - 1.8)	0.9 (0.4 - 1.2)
Croatia	0.7 (0 - 1.3)	0.8 (0.6 - 0.9)	0.7 (0.4 - 1)	2 (1.2 - 3)	1.5 (0.3 - 1.9)	0.4 (0.4 - 0.5)
Cyprus	0.6 (0.6 - 0.6)	0.6 (0.6 - 0.6)	3.2 (3.2 - 3.2)	2.3 (2.3 - 2.3)	2 (2 - 2)	0.8 (0.8 - 0.8)
Czechia	0.8 (0 - 1.7)	1.2 (1.1 - 1.4)	4.2 (0.8 - 19.8)	2.9 (1.5 - 6.8)	1.7 (0.4 - 2.6)	0.5 (0.1 - 1.3)
Denmark	1.8 (0.1 - 3.5)	0.6 (0.6 - 0.7)	1.2 (0.4 - 3.4)	1.3 (0.8 - 2.9)	1.7 (0.8 - 2.4)	0.2 (0.2 - 0.3)
Estonia	1.3 (1.3 - 1.3)	0.7 (0.7 - 0.7)	4.3 (4.3 - 4.3)	4.7 (4.7 - 4.7)	2 (2 - 2)	1.7 (1.7 - 1.7)
Finland	0.9 (0.1 - 1.8)	0.7 (0.1 - 0.9)	2.5 (0.5 - 4.2)	4.3 (0 - 6.3)	1.7 (0.7 - 3.2)	1.4 (0 - 2.2)
France	1.1 (0.1 - 9.5)	1.1 (0 - 1.6)	0.6 (0 - 3.4)	1.5 (0 - 3.6)	1.7 (0.5 - 3.6)	0.4 (0.1 - 1.7)
Germany	0.7 (0 - 2.4)	1.5 (1.1 - 1.7)	2.8 (0.4 - 7.7)	2.3 (0.9 - 5.6)	1.7 (0.4 - 3.8)	0.3 (0.1 - 1)
Greece	0.6 (0 - 2.2)	0.5 (0.5 - 0.6)	1.9 (0.1 - 23.3)	2 (0.8 - 4)	1.1 (0.4 - 2.8)	0.5 (0 - 1.5)
Hungary	0.8 (0 - 1.4)	1.3 (1.2 - 1.4)	1.1 (0 - 3.4)	2.2 (1.3 - 4.2)	1.4 (0.4 - 2.2)	0.2 (0.2 - 0.3)
Ireland	4.6 (2 - 7.7)	1.7 (1.7 - 1.7)	1.9 (0.8 - 3.3)	1.9 (1.6 - 2.1)	2 (1.4 - 2.8)	0.2 (0.2 - 0.4)
Italy	0.6 (0.1 - 1.7)	1.2 (1.2 - 1.4)	1.6 (0.3 - 5.2)	1.4 (0.8 - 2.4)	1.5 (0.9 - 4.8)	0.3 (0.1 - 0.9)
Latvia	1.3 (1.3 - 1.3)	0.7 (0.7 - 0.7)	0.9 (0.9 - 0.9)	1.3 (1.3 - 1.3)	1.5 (1.5 - 1.5)	0.4 (0.4 - 0.4)
Lithuania	1.5 (0.5 - 1.9)	0.6 (0.5 - 0.6)	0.3 (0.1 - 1)	3.2 (1.6 - 3.9)	2.2 (1.3 - 2.6)	0.5 (0.2 - 0.6)
Luxembourg	1 (1 - 1)	2.4 (2.4 - 2.4)	0.4 (0.4 - 0.4)	2.5 (2.5 - 2.5)	8.3 (8.3 - 8.3)	0.1 (0.1 - 0.1)
Malta	0.1 (0.1 - 0.1)	0.2 (0.2 - 0.2)	1.6 (1.6 - 1.6)	0.7 (0.7 - 0.7)	1.3 (1.3 - 1.3)	0.2 (0.2 - 0.2)
Netherlands	1 (0.2 - 2.9)	1.6 (1.5 - 2.3)	2.7 (0.4 - 22)	3.9 (1.2 - 21.4)	1.6 (1 - 2.8)	0.3 (0.1 - 1.2)
Poland	1 (0.2 - 3.3)	1.4 (1.2 - 1.6)	3.8 (0.5 - 12)	2.8 (1.3 - 6.1)	1.7 (1 - 2.6)	0.2 (0.1 - 0.8)
Portugal	0.7 (0 - 5)	0.4 (0.3 - 0.5)	0.9 (0 - 2.1)	1.6 (0.9 - 3.3)	1.4 (0.5 - 3.2)	0.5 (0.2 - 0.9)
Romania	0.9 (0.1 - 1.1)	0.7 (0.6 - 1)	1.2 (0.1 - 5.7)	2.1 (0.9 - 3.3)	1 (0.3 - 1.3)	0.4 (0.2 - 0.9)
Slovakia	0.5 (0.2 - 0.6)	1 (1 - 1)	1.2 (0.2 - 1.7)	4 (1.9 - 6.8)	1.5 (1.1 - 1.8)	0.6 (0.2 - 0.9)
Slovenia	1 (0.7 - 1.3)	0.6 (0.6 - 0.6)	1.8 (0.5 - 2.9)	3.1 (2.3 - 3.7)	2.4 (2.1 - 2.6)	0.3 (0.3 - 0.3)
Spain	0.9 (0 - 4.4)	0.6 (0.5 - 0.8)	1 (0.1 - 3.9)	1.6 (0.7 - 8.3)	1.6 (0.7 - 4.4)	0.5 (0.1 - 1.6)
Sweden	0.7 (0.1 - 1.6)	0.3 (0.2 - 0.4)	0.8 (0.1 - 2.6)	1.9 (1.2 - 4.6)	1.4 (0.5 - 4.1)	0.8 (0.7 - 1.5)

Note: leaving out aviation and shipping.

Source: EDGAR emissions database

2.5.2.2. Regional dependency to sectors that will need to transform

Regions with a relatively high share of employment in sectors significantly impacted by the transition are more exposed to the transition. This includes the regions with a high share of employment in sectors which are being phased out in several countries (mining of coal,lignite and oil shale; extraction of crude petroleum, natural gas and peat; and refining of petroleum products),, in energy intensive sectors, as these will have to produce the same goods differently (manufacturing of chemicals and chemical products, manufacturing of other non-metallic mineral products, manufacturing of basic metals), and in sectors that will have to produce different goods (manufacturing of motor vehicles, trailers and semi-trailers) (321).

In 2020, only two EU regions (NUTS-2 level) had employment shares of more than 1% in terms of direct employment in coal and lignite mining, crude petroleum and natural gas extraction. The region with the highest employment share (3.67%) in these sectors is Śląskie/Silesia, in Poland due to its relatively high activity in coal and lignite mining. The other region is Sud-Vest Oltenia in Romania where the mining and fossil fuel extraction sectors employ 1.12% of the work force. The local impact on regions reliant on these sectors is significant as those sectors have a central role in local economies, driving indirect employment as well. Therefore, the employment and social consequences of the decline in extraction activities needs to be mitigated, in line with the European Green Deal's objective to leave no region behind (see Annex 9).

When considering the energy intensive industries or industries that will have to produce different goods (e.g., automobile sector), it becomes apparent that more regions will be affected. Out of the EU's 27 member states, 23 have regions where more than 1% of the working population was employed in 2020 in such a sector. The regions with the highest exposures in 2020 were Śląskie (PL) (10.2%), Közép-Dunántúl (HU) (9.6%) and Střední Čechy (SK) (9.40%). The regions with a relative high employment in carbon intensive manufacturing are also significantly exposed to the transition. For example, for the territories involved in the automobile sector, the move to the manufacturing of electricity vehicles will require companies from the supply chain to adjust their business models.

The development of an industrial carbon management system will require the development of a full supply chain and of the necessary infrastructure to link CO2 emitting energy supply and industrial sites to carbon storage or usage sites (notably to produce e-fuels). The territories with strong presence of energy intensive industries (e.g., cement production, chemicals industries, etc) will have to anticipate and develop the corresponding capacities.

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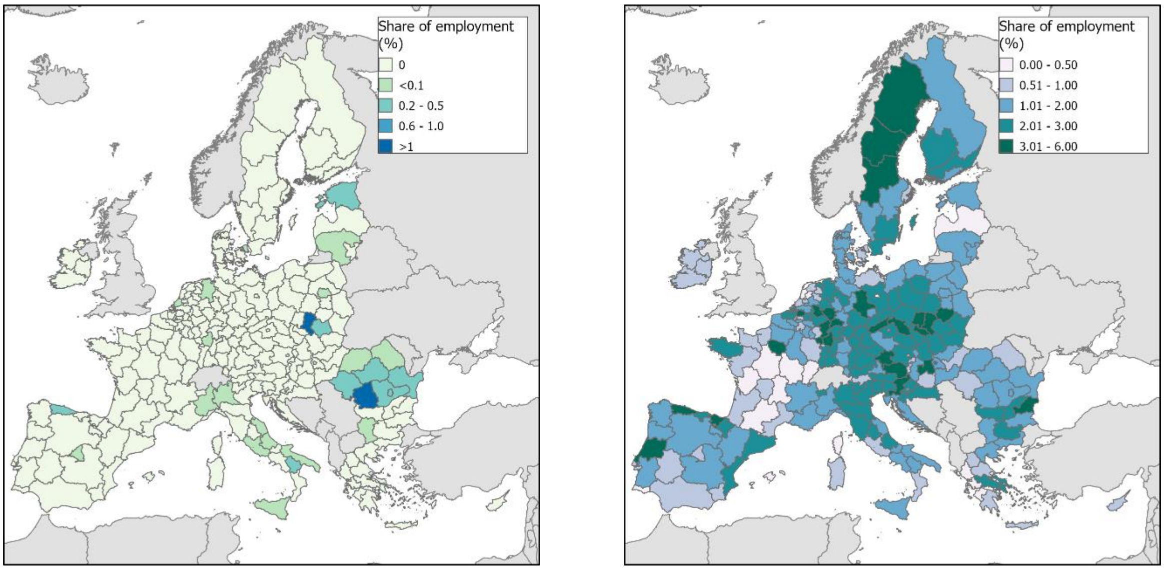
(321) See also OECD (2023), Regional Industrial Transitions to Climate Neutrality, OECD Regional Development Studies, OECD Publishing, Paris.

Figure 129: Share of employment in sectors most negatively impacted



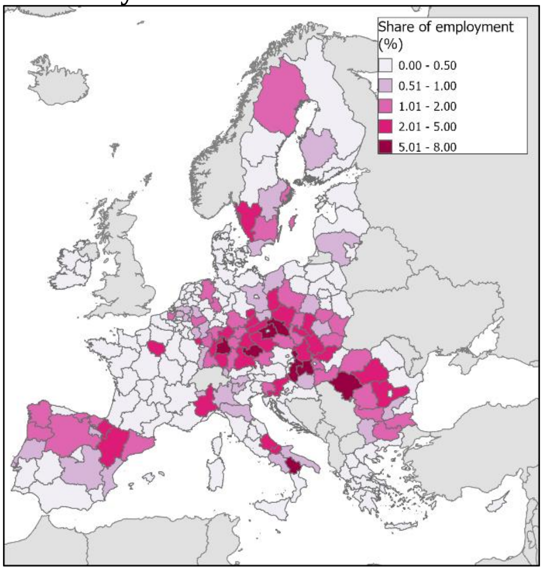
(a) Regional exposure to sectors expected to decline

Share of total employment in mining of coal and lignite (B06) and extraction of crude petroleum and natural gas (B07) in 2020

(b) Regional exposure to energy intensive sectors

Share of total employment paper and paper products (C17), coke and refined petroleum products (C19), chemicals and chemical products (C20), other non-metallic mineral products (C23) and basic metals (C24) in 2020

(c) Regional exposure to sectors that will have to produce the same goods differently

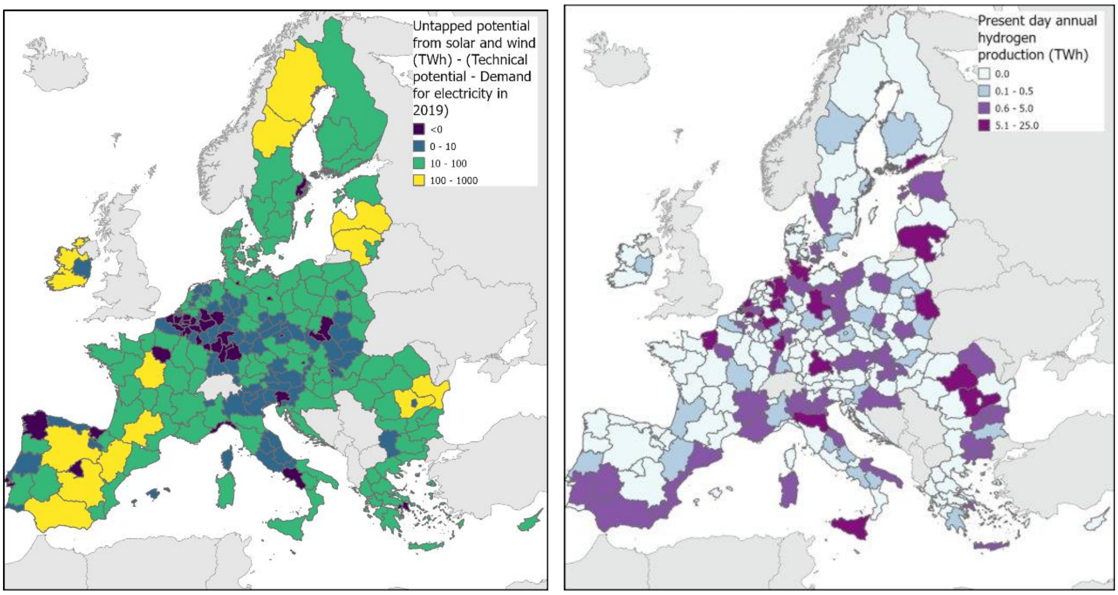


Share of total employment in motor vehicles, trailers and semi-trailers (C29) in 2020

Source: Eurostat structural business statistics and labour force survey

The transition is also an opportunity for new activities or sectors to develop. For example, while Sweden’s Upper Norrland and Middle Norrland regions have a relatively high share of employment in carbon-intensive manufacturing sector, they are also areas where the technical potential for electricity from renewable was more than 100TWh higher than the actual demand in 2019 (see Figure 130). The untapped potential for electricity production from renewable energy technologies is mostly in rural areas. The Member States with the highest absolute green hydrogen potential are Spain (1388 of excess TWh), France (917), Romania (493) and Poland (456). The three EU regions with the highest absolute potential are all located in Spain: Castilla y León (488), Castilla-La Mancha (366), and Aragón (263). (322)

Figure 130: Untapped potential for electricity production from solar and wind in 2019 (left) and present-day annual hydrogen production (right) in EU regions.



Source: Data from Kakoulaki et al., 2021. Green hydrogen in Europe – A regional assessment: Substituting existing production with electrolysis powered by renewables, Energy Conversion and Management 228 (2021) 113649

The potential contribution of the various economic sectors to EU net emission reduction (Figure 131) suggests that rural areas can significantly contribute to emission reductions, for example by carbon sequestration in agriculture. Nature-based removals activities like afforestation and nature restoration may spur investment and economic activity in these areas.

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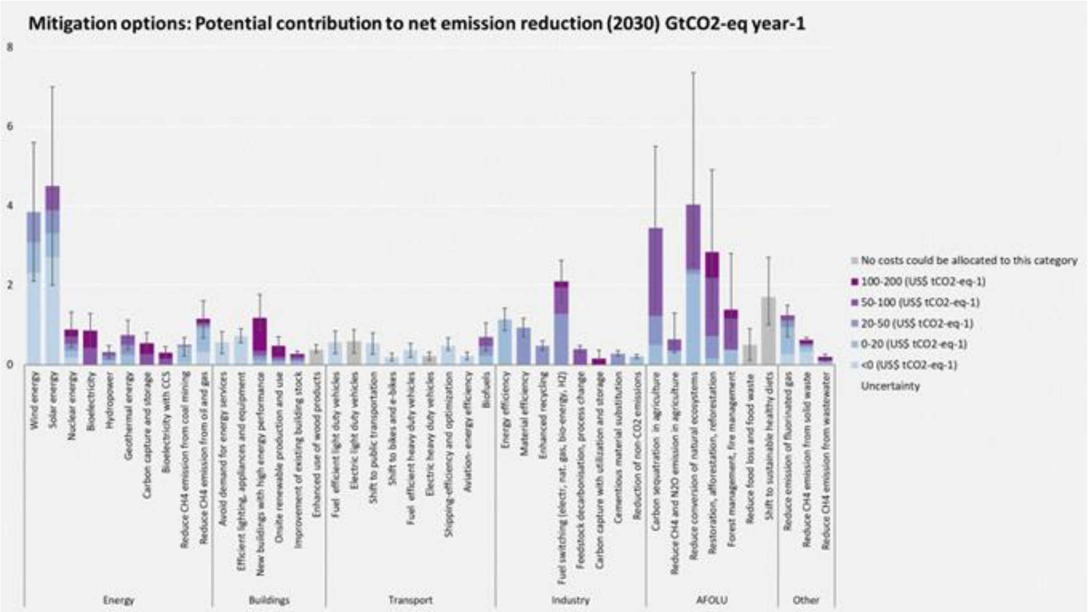
(322) According to Kakoulaki et al. (2021), the technical potential for wind and solar for the EU amounts to 9040 TWh, which is 6441TWh more than the current demand. 10% of this excess (i.e., 644 MWh) is in coal regions in transition with hydrogen infrastructures.

Figure 131: Potential contribution of the various economic sectors to the EU emission reductions



Source: Global outlook based on the IPCC migitation report (323)

Contrary to coal mining, the mining of elements that are useful for the low-carbon transition (e.g. lithium used for batteries) is a growing sector. Many of the EU's regions have a history of raw materials extraction. The possibility to use former mining sites for the extraction or treatment of elements needed for the decarbonisation is worth being examined. It has the potential to create economic value and employment in historical mining regions, which are often declining as a consequence of deindustrialisation. This may be particularly the case for regions with deposits of high-volume commodities such as iron and copper, given these typically co-occur with critical raw materials ([324]). Several regions who are not former coal mining regions are considering new mining activities (e.g., Norte in Portugal).

A downside of the mining of critical raw materials is that it is highly capital intensive and account for a relatively small share of employment in the countries. It also imposes environmental costs ([325]).

The innovation capacities, the level of instruction, and the quality of infrastructure are examples of parameters that contribute to the preparedness of the regions for the transition. Regarding innovation, the ten regions that have contributed the most to the

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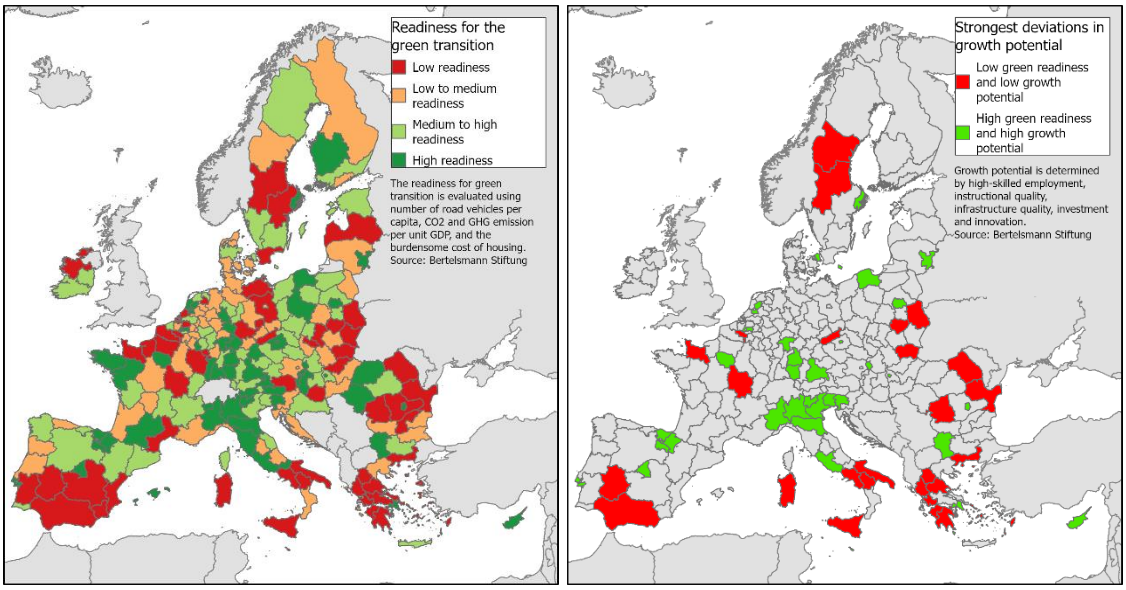
([323]) IPCC. Climate Change 2022. Mitigation of Climate Change. Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. 2022

([324]) Proposal for a Regulation of the European Parliament and of the Council establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) 168/2013, (EU) 2018/858, 2018/1724 and (EU) 2019/1020. Impact Assessment Report accompanying the document: SWD(2023) 161 final.

([325]) IRENA and ILO (2022), Renewable energy and jobs: Annual review 2022, International Renewable Energy Agency, Abu Dhabi and International Labour Organization, Geneva.

total number of patent application to the European Patent Office in the fields of climate change, environment, resource efficiency and materials over the period 2000-2018 are Île de France (FR), Cataluña (ES), Andalucía (ES), Comunidad de Madrid (ES), Lombardia (IT), Lazio (IT), Oberbayern (DE), Hovedstaden (DE), Zuid-Holland (NL), and Helsinki-Uusimaa (FI) ([326]). The study by Maucorps et al. (2022) ([327]) provides indicators of the regional readiness for the green transition (Figure 132). The best prepared regions are mainly metropolitan regions specialised in knowledge-intensive services while rural ones have lower growth potential. In regions such as Madrid (ES) and Attica (EL), a high potential for economic growth might be further increased by the green transition while in others such as Sicilia (IT) or Bourgogne (FR) an already low potential for economic growth might be further reduced by the green transition.

Figure 132: Regional readiness for the green transition and correlation with growth potential



Source: Bertelsmann Stiftung

The climate transition will have heterogenous consequences for the EU's regions. It will both lead to new challenges and opportunities. For instance, the few EU regions significantly exposed to declining sectors and the more numerous regions which rely on energy intensive industries and sectors affected most by the transition will likely be more negatively impacted by the transition. In such regions and territories, the employees from these sectors will have a higher need of reskilling. On the other hand, regions will be able to take advantage of new opportunities offered by the transition. This is particularly the case for regions with higher levels of innovation capacities, which are likely to profit more from the transition than their less-innovative peers. But also, the numerous EU regions with an excess of RES electricity potential can benefit from the transition, for example by developing green hydrogen production. While some extractive facilities have

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([326]) Science, Research and Innovation Performance of the EU, 2022 (SRIP) – Publications Office of the EU.

(327) Maucorps, Ambre, R. Römisch, T. Schwab, N. Vujanovic, (2022). The Future of EU Cohesion. Effects of the Twin Transition on Disparities across European Region, Bertelsmann foundation.

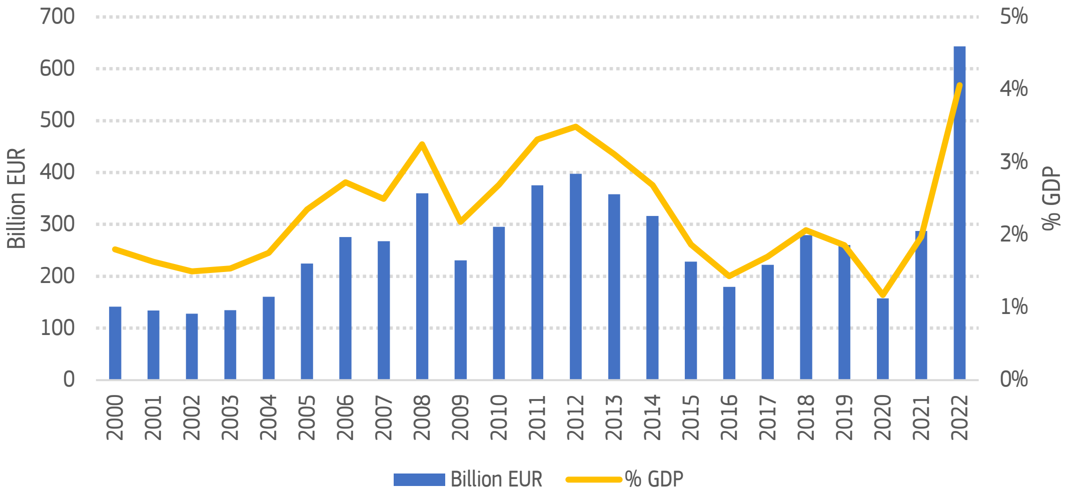
to close, others can be developed for the mining of critical raw materials. The transition to a low carbon economy might widen disparities between regions ([328]). Other EU policies such as the cohesion policy play an important role to address this. Annex 9 provides examples of EU and national measures and programmes that can support regions for the transition.

2.6. Energy security

2.6.1. Strategic independence and fuel imports – energy security ([329])

Imports of fossil fuels have historically weighed heavily on the EU's trade balance. On average in 2000-2021, gross imports of fossil fuels represented about 20% of total merchandise imports, equivalent to 2.8% of GDP. With the surge in energy prices in 2022, gross fossil fuel imports rose to more than EUR 800 billion, equivalent to 5.1% of GDP and 26.9% of merchandise imports, the highest level in the past two decades relative to GDP. On a net basis (imports minus exports), fossil fuel imports represented EUR 640 billion in 2022 or 4.1% of GDP, compared to an average of 2.2% of GDP in 2000-2021 (Figure 133).

Figure 133: Net fossil fuel imports, 2000-2022



Based on Eurostat's trade data for CN code 27, with the exclusion of codes 2712, 2714, 2715 and 2716.
Source: Eurostat.

Figure 134 shows the monetary value of fossil fuels imports in the EU by 2050. Imports decrease significantly in volume between 2020 and 2030 (see Section 1.2) and the import bill is projected to decrease by almost 20% by 2030. This result depends on the assumed trajectories for fossil fuel prices (see Annex 6). These trajectories are input to the PRIMES energy model and significant uncertainties exists on the long-term evolution of fossil fuel prices.

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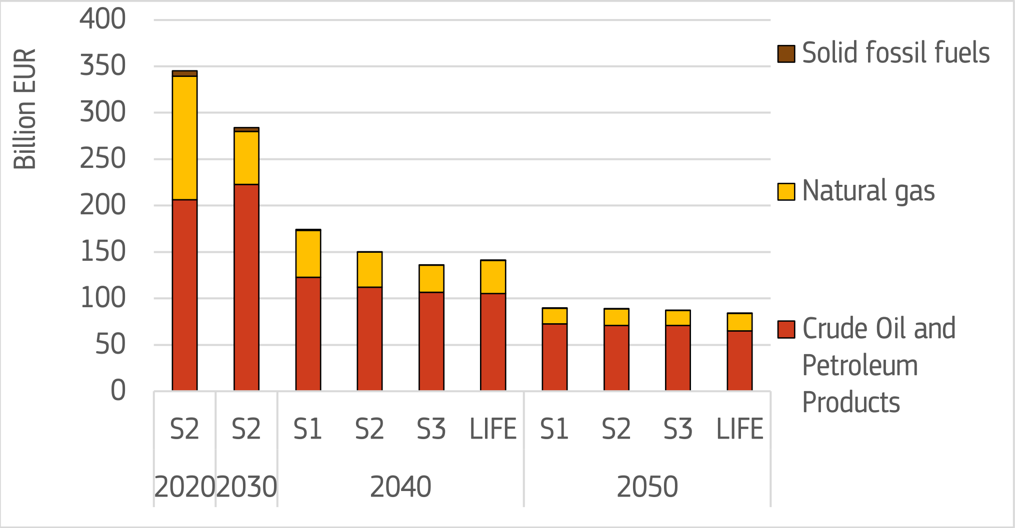
(328) Santos A., J. Barbero, S. Salotti, O. Diukanova and D. Pontikakis. On the road to regional 'Competitive Environmental Sustainability': the role of the European structural funds, Industry and Innovation, 30:7, 801-823, 2023. DOI: 10.1080/13662716.2023.2236048

(329) The model-based analysis is a technical exercise based on a number of assumptions that are shared across scenarios. Its results do not prejudge the future design of the post-2030 policy framework.

With the assumptions used, by 2040, the fossil fuel import bill will be 50% to 63% lower than in 2020 depending on scenarios. Decarbonisation of the energy system will save Europe approximately 1.3 trillion € in the 2031 – 2040 decade compared to 2021 – 2030. With the current assumptions about economic growth, fossil fuels import will decrease from 2.75% of GDP in 2020 to 1.9% in 2030 and to 1% in 2040. This will greatly reduce the economic impact of eventual disruption in fossil fuels supply.

By 2050, imports are dominated by the fossil fuel used for non-energy purposes and are almost 80% lower than in 2020 with very small differences across scenarios.

Figure 134: Annual fossil fuels imports



Source: PRIMES.

While the role of fossil fuels will decline, other dependencies will emerge in the coming decades. Imports of biomass are set to double from approximately 6 Mtoe in 2019 to 12 Mtoe in 2040. While non-existent today, imports of hydrogen and RFNBOs will also become significant reaching approximately 20 Mtoe in 2040 with negligible differences across scenarios. However, these imports will be small compared to the approximately 900 Mtoe of fossil fuels imported in 2019.

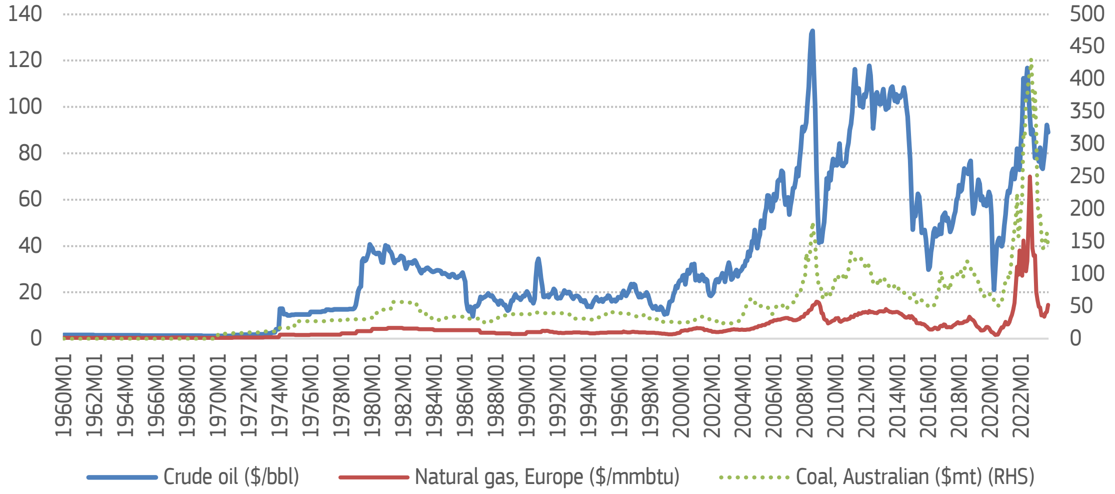
Other relevant dependencies that might emerge are those related to the raw materials needed for decarbonisation technologies. However, the economic consequences of these import will most likely be very different. The risks of import dependency do not depend only their share, but also on other parameters such as market concentration and substitution possibilities. Moreover, the economic implications of scarcity would be very different when dealing with a fuel or a component of specific equipment. Finally, the risk of dependency depends on the possibility to maintain strategic reserves and the cost of storing raw materials varies greatly. The sudden increase in the cost of a raw material used in manufacturing will not have the same macroeconomic impact as the recent stop of gas imports from Russia.

The high decarbonization levels and the corresponding high demand for deployment of renewables, storage and novel technologies may create new dependencies for raw materials or technology imports from other countries. This highlights the role for the Critical Raw Material Act, and the Net Zero Industry Act. The options with a less steeply increasing demand for renewables and novel technologies (e.g., S1) show a lower supply chain and dependence challenges than the higher ambition scenarios (e.g., S3).

2.6.2. Vulnerability to external shocks

Fossil fuel price shocks, particularly for crude oil, have affected the EU and world economy numerous times over the past 50 years or so. Crude oil prices were multiplied by a factor of around 10 within about a year following the first Arab oil embargo in the early 1970s. The Iranian revolution and the onset of the Iran-Iraq war led to another tripling of crude oil prices within a year at the end of the 1970s. Further shocks and high volatility in crudel oil prices have continued ever since, with the Gulf War, the global financial crisis and shifts in policy from the Organization of the Petroleum Exporting Countries (Figure 135). While natural gas (in the EU) and coal prices remained more stable for several decades, they have also become more volatile. These past shocks and the most recent one triggered by the Russian war of aggression in Ukraine have generated large negative economic impacts at the global and EU level, alongside social hardship and a significant redistribution of wealth across countries.

Figure 135: Monthly fossil fuel prices (US$, 1960-October 2023)



Source: World Bank Commodity Price Data.

As a major net fossil fuel importer, the EU has been particularly vulnerable to such price shocks. Reducing the dependency on imported fossil fuels would therefore bring clear socio-economic benefits via improved resilience and strategic autonomy. The JRC-GEM-E3 model was used to quantify the benefits of the transition to climate neutrality on key macro-economic variables. The model assessed the impacts of a doubling of fossil fuel prices (oil, coal and gas) at global level. Some geographic differentiation was integrated into the simulation, as domestic prices in energy-exporting countries were less affected than in net importing countries (including the EU). In one set of simulations, spillovers to electricity prices were not considered, while in the other set of simulations spillovers were integrated for Europe only.

The model simulated the impacts of these two sets of stylised shocks, should they occur in 2025 or in 2040. The JRC-GEM-E3 model mirrors the structure of the energy system as represented in the PRIMES scenarios, which means that a high degree of decarbonisation is achieved in 2040, but also that the EU economy has reduced its reliance on fossil fuels to a significant extent in 2025 compared to the 1990s. The impact of a given shock on the 2025 economy would therefore already be significantly lower than the impact on the 1990 economy.

Table 56 indicates that a doubling of fossil fuel prices in 2025, without spillovers to electricity prices, would generate a negative shock of about 0.8% on GDP, 2.6% on private consumption and 1.1% on employment, with an associated increase of 3.0% in inflation. The same shock in 2040, with the associated progress towards the decarbonisation of the energy system, would halve the negative impacts on the same broad macro-economic aggregates.

Table 56: Macroeconomic impacts of energy price shocks (deviation from baseline)

	Fossil only		**Fossil + elec**	
	2025	**2040**	**2025**	**2040**
GDP	-0.8%	-0.4%	-1.5%	-1.0%
Private consumption	-2.6%	-1.2%	-3.7%	-2.2%
Exports	0.9%	0.4%	0.5%	-0.2%
Imports	-2.4%	-1.2%	-3.0%	-1.9%
Employment	-1.1%	-0.5%	-2.3%	-1.6%
Consumer prices	3.0%	2.0%	3.9%	2.9%
Sectoral output				
Energy intensive industries	0.4%	0.2%	-1.3%	-1.8%
Consumer good manufacturing	-0.5%	-0.5%	-1.1%	-1.1%
Construction	-0.4%	-0.2%	-0.8%	-0.7%
Transport	-1.1%	-0.1%	-1.7%	-1.2%
Market services	-1.1%	-0.6%	-1.6%	-1.0%

Source: JRC-GEM-E3

It must be noted that the one-year GDP impact in 2040 of such a shock is significantly larger than the impact of increasing climate ambition from the level under S2 to that under S3, and that the same shock in 2025 would generate twice that impact on GDP. Similarly, the negative impact on private consumption from a fossil fuel price shock is much larger (both under the 2025 and under the 2040 setting) than the negative impact resulting from an increase in ambition from S2 to S3 (up to -2.2% for the fossil fuel price shock in 2040 compared to -0.5% for the impact of increasing ambition from S2 to S3).

In addition, a closer look at the dissemination channels of a global fossil fuel price shock shows that the EU's lead in decarbonising its economy entails competitiveness gains when/if such shocks arise. A global shock would indeed negatively affect not only the EU economy, but also the global economy and the EU's main trading partners. As a result, the size of the EU's export market would be negatively affected, yet the simulation shows that EU exports would increase overall and that the output of energy-intensive industries would increase somewhat (fossil fuel price shock only). The driving force behind this is the more advanced stage of decarbonisation of the EU economy relative to the rest of the world and hence its reduced vulnerability to increases in fossil fuel prices. EU companies would therefore be in a position to gain export market shares via increased competitiveness, while also gaining shares in the domestic market, to the detriment of imported goods. Decarbonisation therefore reduces the EU's vulnerability to fossil price shocks via two key channels: (1) a lower dependency on fossil fuels overall; and (2) a reduction in the negative impact of a fall in global GDP.

Integrating the effects of spillovers to electricity prices in the EU makes the impacts described above somewhat larger, but the main finding that a higher degree of decarbonisation of the energy system in 2040 than in 2025 shelters the EU economy remains. Further simulations were done to assess the impact of a fossil fuel price shock in 2040 under three main scenarios. The difference between scenarios for the variables listed in Table 56 is small, but a higher level of ambition is nevertheless associated with a smaller impact of a fossil fuel price shock on GDP, private consumption, employment and consumer prices. For energy intensive industries, the positive impact of a higher ambition is more significant in terms of output as they gain further protection under S2 and S3 in case of fossil fuel price shock than under S1.

These modelling results should also be seen in the context of the support that Member States have provided to households and businesses to shelter them from the impact of the recent surge in energy prices following Russia’s war of aggressionin Ukraine. In response to the crisis, and to foster support measures in sectors which are key for the transition to a net-zero economy, the Commission adopted in March 2023 the Temporary Crisis and Transition Framework (TCTF), as subsequently amended. The TCTF replaces the former Temporary Crisis Framework (TCF) which was adopted in March 2022. The TCTF facilitates, on a temporary basis, the granting of the following types of aid: (1) limited aid amounts to companies affected by the crisis; (2) liquidity support in the form of subsidised loans or State guarantees; (3) aid to compensate for exceptionally high energy prices; (4) investment aid for accelerating the rollout of renewable energy, (5) aid for the decarbonisation of industrial production processes, (6) aid for the reduction of electricity consumption, and (7) aid for accelerated investments in sectors strategic for the transition towards a net-zero economy.

As of 23 January 2024, the Commission had issued 431 decisions approving 334 national measures for a cumulative of amount of aid of EUR 777 billion. All Member States notified schemes under the TCTF. Although aid amounts approved are not evenly distributed among Member States, this may be due to a number of reasons, including that aid amounts approved do not equate to aid actually granted or disbursed. Based on a survey of Member States, the Commission estimates that approximately EUR 141 billion of aid was actually granted to companies, representing 19.3% of the aid approved by the end of June 2023 and corresponding to 0.6% of the EU27 GDP in 2022 and first half of 2023.

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