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Assessment of the In-depth Analysis Accompanying the Strategic Long-term Vision “A clean planet for all” of the European Commission

Full report

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Assessment of the In-depth Analysis Accompanying the Strategic Long-term Vision “A clean planet for all” of the European Commission

Full report

by

Jakob Wachsmuth, Johannes Eckstein, Anne Held,
Andrea Herbst, Patrick Plötz
Fraunhofer ISI, Karlsruhe

Kjell Bettgenhäuser, Tom Berg, Madeleine Hardy,
Matthias Schimmel
Navigant Energy Germany GmbH, Cologne

Matthias Duwe, Mona Freundt, Ana Frelih-Larsen, Martin
Hirschnitz-Garbers, Ariel Araujo
Ecologic Institut, Berlin

On behalf of the German Environment Agency

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Publisher
Umweltbundesamt
Wörlitzer Platz 1
06844 Dessau-Roßlau
Tel: +49 340-2103-0
Fax: +49 340-2103-2285
info@umweltbundesamt.de
Internet: www.umweltbundesamt.de

/umweltbundesamt.de
/umweltbundesamt

Report performed by:
Fraunhofer Institute for Systems and Innovation Research ISI
Breslauer Str. 48
76139 Karlsruhe
Germany

Navigant Energy Germany GmbH
Am Wassermann 36
50829 Cologne
Germany

Ecologic Institut gemeinnützige GmbH
Pfalzburger Str. 43/44
10717 Berlin
Germany

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Guido Knoche

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Abstract: Assessment of the In-depth Analysis Accompanying the Strategic Long-term Vision “A clean planet for all” of the European Commission

In 2018, the European Commission presented its long-term Strategic Vision “A clean planet for all”, which calls for net-zero greenhouse gas emissions (GHG) of the European Union by 2050. The Strategic Vision is accompanied by the In-depth Analysis containing a detailed impact assessment based on a scenario analysis. This paper presents the findings of an assessment of the In-depth Analysis, in particular its suitability as the analytical input for the Strategic Vision.

In summary, the In-depth Analysis covers the key aspects for building an adequate long-term climate strategy and is thus a strong foundation for the Strategic Vision, in spite of certain limitations. The presented pathways to net-zero emissions cover all the relevant sectors and GHGs and are in accordance with other studies. However, they are not fully assessable, because important input and output data are not provided for all scenarios. Moreover, it is unclear why none of the scenarios maximises the use of renewable energies. The variety of models used provides evidence for the economic feasibility of such a transition. In this regard, the restricted set of scenarios used for the macro-economic assessment is a shortcoming. In the scenarios with net-zero GHG emissions in 2050, all sectors have to pursue very ambitious emission reductions early on. Nonetheless, some remaining GHG emissions have to be compensated by a combination of natural and artificial carbon sinks. Detailed considerations of the economic and social implications of the mitigation scenarios show moderate impacts on GDP and labor in comparison to other societal drivers, but also indicate the need for a strong shift from consumption to investment in mitigation technologies and infrastructure. International cooperation is seen as essential to foster the transformation to net-zero GHG emissions.

Kurzbeschreibung: Auswertung der Folgenabschätzung zur Strategischen Vision „A clean planet for all“ der Europäischen Kommission

Im Jahr 2018 hat die Europäische Kommission ihre langfristige Strategische Vision “A clean planet for all” vorgelegt, die als Ziel für 2050 Netto-Null-Emissionen an Treibhausgasen (THGs) in der Europäischen Union propagiert. Die Strategische Vision ist mit der sogenannten „In-depth Analysis“ hinterlegt, die eine detaillierte Folgenabschätzung auf Basis einer Szenarienanalyse enthält. Dieses Papier stellt die Ergebnisse einer Auswertung der In-depth Analysis dar, mit dem Fokus auf ihrer Eignung als analytischer Input für die Strategische Vision.

Insgesamt gesehen deckt die In-depth Analysis die Kernelemente zum Erstellen einer adäquaten Langfrist-Klimastrategie trotz einiger Einschränkungen ab und ist daher eine starke Grundlage für die Strategische Vision. Die dargestellten Pfade zum Erreichen von Netto-Null-Emissionen decken alle Sektoren und THGs ab und sind in Übereinstimmung mit anderen Studien. Allerdings sind die Pfade nicht vollständig zu beurteilen, weil wichtige Ein- und Ausgangsgrößen nicht für alle Szenarien zur Verfügung stehen. Auch bleibt unklar, warum keins der Szenarien die Nutzung erneuerbarer Energien maximiert. Die Breite der eingesetzten Modelle belegt die ökonomische Machbarkeit einer solchen Transformation. In dieser Hinsicht stellt das eingeschränkte Set an Szenarien für die makroökonomische Analyse einen Mangel dar. In den Szenarien mit Netto-Null-THG-Emissionen in 2050 müssen alle Sektoren frühzeitig sehr ambitionierte Minderungen angehen. Nichtsdestotrotz sind einige verbleibende Emissionen durch eine Kombination von natürlichen und künstlichen Kohlenstoffsenken auszugleichen. Detailbetrachtungen der ökonomischen und sozialen Implikationen der Vermeidungsszenarien zeigen zwar im Vergleich zu anderen gesellschaftlichen Treibern moderate Auswirkungen auf Bruttoinlandsprodukt und den Arbeitsmarkt, weisen aber auf den Bedarf für eine starke Verschiebung von Konsum hin zu Investitionen in Vermeidungstechnologien und Infrastrukturen hin. Internationale Kooperation wird als Schlüssel für das Gelingen eines Übergangs hin zu Netto-Null-Emissionen angesehen.

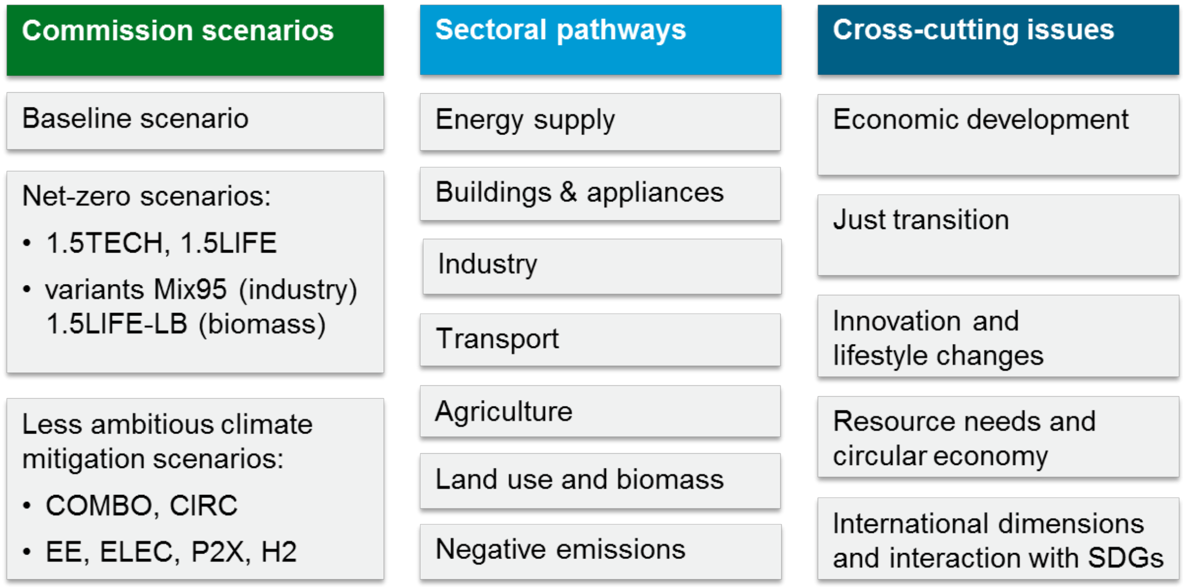
Technical summary

On 28 November 2018, the European Commission published its **long-term strategic vision “A clean planet for all”, which presents its analysis of options for long-term climate policy in the European Union** (EU). This document forms the basis for discussions in EU institutions on how to deliver the EU’s formal long-term climate strategy to the United Nations by 2020, as per the Paris Agreement. In the strategic vision, the European Commission lays out a pathway for a transition to a climate-neutral economy by 2050 - meaning the EU’s net greenhouse gas (GHG) emissions will be zero in that year. **The strategic vision states that a GHG-neutral EU is technologically feasible and achievable in a socially fair and cost-efficient manner.** A brief summary of the strategic vision is given by the factsheet by the German Environment Agency (Duwe and Freundt 2018).

The strategic vision is accompanied by an in-depth analysis containing a detailed impact assessment based on a scenario analysis. The in-depth analysis builds on one baseline scenario and eight mitigation scenarios, which meet the EU’s current 2030 targets, but differ in their ambition and mitigation focus afterwards. Only **two of these scenarios (1.5TECH and 1.5LIFE) achieve net-zero GHG emissions by 2050** – the target defined in the strategic vision. In addition, there is one further variant with limited biomass (1.5LIFE-LB), and one more detailed industry scenario (Mix95) that are both compatible with net-zero GHG emissions in 2050. This group of scenarios is called net-zero scenarios in the following.

This section summarises the **findings of an assessment made of the In-depth Analysis accompanying the European Commission’s strategic vision *A clean planet for all*.** It addresses to what extent the in-depth analysis is suitable as the analytical input for the strategic vision and flags key issues with regard to three areas: (1) the net-zero scenarios in comparison to the baseline scenario, (2) the corresponding sectoral pathways (energy supply, buildings, transport, industry, agriculture, land use and negative emissions) and (3) cross-cutting issues (economic development, just transition, innovation and lifestyle changes, resource needs and circular economy as well as international dimensions including SDGs (see Figure PB1)).

Figure PB1 Focus areas for the assessment of the in-depth analysis underlying the European Commission’s long-term strategic vision “A clean planet for all”



Source: own illustration, Fraunhofer ISI

The assessment focuses on the net-zero scenarios in comparison to the baseline, but also considers the others.

The strategic vision itself is assessed in a companion report (Wachsmuth et al. 2019). This report addresses the level of ambition required by the long-term temperature goal of the Paris Agreement. Its finding is that **it is questionable whether any of the scenarios other than the net-zero ones are compatible with the Paris target.**

Sectoral pathways

The sectoral pathways of the scenarios were assessed using a common set of criteria, which led to the following central findings (see Section 2):

- **In general, all sectors have to pursue very ambitious GHG emission reductions early on in the net-zero scenarios.** 1.5LIFE differs from 1.5TECH by including circular economy approaches and lifestyle changes in addition to technological approaches. Nevertheless, some GHG emissions remain in both scenarios, in particular CO_2 emissions from international transport, energy-intensive industries as well as non-CO_2 emissions from agriculture and waste. These emissions are compensated by both natural carbon sinks from land use and artificial sinks based on carbon capture and storage (CCS), with triple the amount of negative emissions in 1.5TECH than in 1.5LIFE.

- **With regard to energy supply, all scenarios are characterised by the vastly increasing relevance of renewable energy sources.** The power sector has to reduce emissions particularly rapidly to enable strong emission reductions via electrification. In both net-zero scenarios, there is also a substantial use of electricity-based fuels and gases. Nonetheless, none of the scenarios maximises the use of renewables in combination with strong energy demand reductions. The renewable share could be increased to limit negative emissions more stringently. Furthermore, nuclear capacity increases after 2030, which is highly debatable given social acceptance concerns and the adverse financing environment for new nuclear power plants.

- **For the buildings sector, the presented pathways appear plausible when compared to other studies.** The renovation rates in the net-zero scenarios are moderate, although still ambitious when compared to the current empirical rates. In contrast, the assumptions about energy savings due to renovations are very high, and imply that nearly all renovations have to meet the highest energy efficiency standards. Due to the high level of electrification, there is a substantial increase in electricity demand in spite of greater efficiency measures.

- **For industry, the sectoral pathways show that it is possible to transform industry to close to CO_2-neutrality by the middle of the century.** However, the technologies available today are not sufficient because it is often not possible to switch from fossil fuels to RES due to the high temperature levels required and the competition for biomass with other sectors. Therefore, early development of radical process innovations such as the direct reduction of steel with hydrogen and new kinds of low-carbon cements need to be part of the strategic considerations. At the same time, the potentials for material efficiency and circularity are not yet fully covered in the modeling and should be explored in more detail.

- **For the transport sector, the scenario results appear plausible when compared to in view of other studies.** A reduction in demand is required as are strong technology shifts. International aviation is responsible for the major share of remaining CO_2 emissions in 2050.

Almost all scenarios exhibit a mixture of technologies for road transport including electrification, hydrogen, biofuels, e-liquids and natural gas. As many of these technologies require their own infrastructure, scenarios with only one or a few dominant technologies may be more plausible. These infrastructure feedback loops require additional attention.

- **For agriculture, the analysis highlights the key areas with mitigation potential (CH_4 and N_20 emissions) as well as the need to address systemic issues of reducing food waste and the consumption of animal products. However, the list of included measures is limited.** The most obvious omissions are improved crop rotation and improving soil management to reduce soil compaction. In addition, the analysis does not sufficiently consider the trade-offs between the proposed mitigation options and other impacts, e.g. with biodiversity and animal welfare. The analysis does not mention the transformation of the food system and it is unclear if it accounts for the full potential on the demand side. Only the 1.5LIFE scenario assumes a change in consumer preferences.
- **With regard to land-use, mitigation in the net-zero scenarios is primarily achieved in the land-use change and forestry sector. One of the assumptions subject to the greatest doubt is the large role that energy crops are expected to play for bioenergy.** Only in 1.5TECH is mitigation achieved by implementing agricultural practices that improve soil carbon sequestration and turn cropland from a carbon source into a carbon sink. To avoid concerns about the sustainability of biomass, the scenarios assume that nearly all the biomass required for bioenergy is produced within the EU. Moreover, an alternative low-biomass scenario, 1.5LIFE-LB, was created specifically for the land-use category to demonstrate a decarbonisation pathway with a limited use of biomass.
- **With regard to the role of negative emissions, the only artificial sinks considered are bioenergy and direct air capture with CCS (BECCS/DACCS).** Other options such as biochar and enhanced weathering are not considered. 1.5TECH assumes ambitious carbon removal, while 1.5LIFE assumes much lower carbon capture with marginal BECCS. Compared to other studies on the geological storage potential for CO_2 in the EU, the in-depth analysis relies on a moderate use of underground storage in the scenarios. A range of costs is presented for CDR technologies, but it is not clear which values are ultimately used for the modelling. These assumptions can strongly influence the level of negative emissions realised in the scenarios.

Cross-cutting issues

Cross-cutting issues were addressed qualitatively, with the following findings (see Section 3):

- **From an economic point of view, a shift is required from consumption to an investment in GDP of roughly 1%, resulting in a substantial increase in the required capital mobilisation**. Economic development is considered relative to a baseline and assumes an increase in GDP of 68-71% by 2050 relative to 2015. Decarbonisation has a relatively minor influence on this figure (-1.3% to +2.2% depending on the model). The implications for the EU's multi-annual financial framework for 2021-2027 are not assessed.
- **With respect to a just transition**, **decarbonisation has only a low influence on labor, and long-term developments are dominated by demographic change, digitalisation**

and automation. Regions in risk of being left behind are those which depend on contracting or energy-intensive economic sectors. The focus is on labor and reskilling within the EU. The international dimension is not considered. Citizen engagement is seen as important, but the required rise in awareness is assumed to take place in society in general, and is merely supported by labelling and standards.

- **With regard to innovation and lifestyle changes, the in-depth analysis sees the need to make the corresponding investments in innovation, but identifies a lack of funding here compared to other economies worldwide**. Social innovations are also regarded as important, but measures to bring about changes in behaviour are not described. With respect to technological innovations, the in-depth analysis describes neither the necessary market diffusion and corresponding upscaling of key innovative technologies nor possibly disruptive transitions.
- **The in-depth analysis associates two major benefits with a circular economy: (1) GHG emissions can be strongly reduced if raw materials are increasingly recycled; (2) the dependency on the respective imports is reduced.** Resource needs and the circular economy constitute a recurring theme throughout the in-depth analysis although there is no section dedicated specifically to this topic. The required regulatory framework for a circular economy is not described in any detail. Nor is there any discussion of possible rebound effects, i.e. increased use overcompensating the increased supply from recycling.
- **With respect to international dimensions and the interaction with SDGs, the in-depth analysis sees international collaboration as essential to tackling global problems, including those related to climate change.** A deeper dialogue with countries in financial straits is addressed; in particular, it is proposed to pursue a dialogue with fossil-fuel exporting nations to encourage them to diversify their economic portfolio in the direction of renewable energies. Overall, climate action is seen to have many co-benefits with other SDGs, especially internationally and considering health benefits and the eradication of water shortages and poverty.

Methodological considerations

The assessment of the sectoral pathways included methodological considerations and produced the following central findings (see Sections 2, 3.1 and 3.2):

- While technology assumptions have been reviewed and published, key **input and output parameters** such as sectoral activities and energy demands are **only partially available**.
- The techno-economic assumptions in the power sector seem to be in line with assumptions in other studies. In particular, the widely criticised **risk premiums for renewable electricity generation are no longer used**.
- In the buildings sector, the modeling still applies **relatively high discount rates on private investments**, which may have limited the efficiency gains.
- In the agricultural sector, it is **unclear whether yield stability is considered**, for which additional soil management measures would be needed.

- In the LULUCF sector, a crucial factor that is **not sufficiently discussed is the CO_2 removal rate**. Given the strong use of biomass in 1.5TECH/1.5LIFE, it is important to reflect that CO_2 is only re-sequestered gradually at a rate that depends on the type of land and biomass.
- With regard to negative emissions, **carbon capture and negative emissions are used almost interchangeably** so that it remains unclear how carbon is accounted in the model.
- Results for the **economic development** are **based on a reduced set of scenarios** that includes 1.5TECH but excludes 1.5LIFE. This is a drawback for the comparison of the net-zero scenarios.

Summary

In summary, **the analytical input provided in the in-depth analysis covers the key aspects for building an adequate long-term climate strategy and is thus a strong foundation for the Strategic Vision, in spite of certain limitations**:

- **The in-depth analysis is comprehensive** in the way that it covers mitigation pathways for all relevant sectors and GHGs as well as economic and social implications. The sectoral pathways to net-zero GHG emissions are plausible **and in accordance with the ranges resulting from other studies**.
- The in-depth analysis serves as a basis for the discussion of a long-term GHG development strategy only for the EU. Nevertheless, its **extensive efforts on assessing the feasibility of net-zero GHG emissions may be helpful to a lot of other countries as well.**
- It is positive that **the net-zero scenarios 1.5TECH and 1.5LIFE show the trade-off between behavioural changes and higher negative emissions** rather explicitly, but there is almost no discussion of the political implications, in particular no prioritisation of measures.
- While the set of scenarios with 80% GHG reduction in 2050 explore many different options, the set of only two full net-zero scenarios is rather limited. For instance, **it is unclear why there is no scenario that maximises the use of RES**.
- The analysis is not fully transparent, because important input and output data are not provided for all scenarios and they are therefore difficult to assess. **Greater transparency is important to foster its acceptability by the relevant stakeholders**.
- The in-depth analysis also contains detailed considerations of economic and social implications and projects a minor impact of decarbonisation relative to other developments. However, **a strong shift of capital from consumption to investment is needed**.
- **The variety of models used underpins the robustness of the findings**, in particular the economic feasibility of a transformation to net-zero GHG emissions. However, the restricted set of scenarios for the macro-economic assessment is a shortcoming.

- **There is detailed information on the role of technical and also social innovations, including the current status of the EU’s innovation framework, but future requirements remain vague**. The role of lifestyle changes is also only touched upon briefly.
- **While resource efficiency is addressed** throughout, there is no section dedicated specifically to this important issue so that its **implications are not clear**.
- **International cooperation is seen as having multiple benefits and as being key to fostering the transformation to net-zero GHG emissions.**

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1.5LIFE	IDA scenario with net-zero GHG emissions in 2050 focussing on a circular economy approach and lifestyle changes
1.5TECH	IDA scenario with net-zero GHG emissions in 2050 focussing on technological approaches
AR	Afforestation and reforestation
BECCS	Bioenergy with carbon capture and storage
CCS	Carbon capture and storage
CDR	Carbon dioxide removal
CO_2	Carbon dioxide
COP	Conference of the Parties
DACCS	Direct air carbon capture and storage
EC	European Commission
EU	European Union
EU-ETS	EU Emissions Trading Scheme
GHG	Greenhouse gases
HDV	Heavy-duty vehicle
IDA	In-depth analysis underlying the EC's SV
IPCC	Intergovernmental Panel on Climate Change
IPCC SR1.5	The IPCC's Special Report on Global Warming of 1.5°C
LTCS	Long-term climate strategy
LTTG	Long-term temperature goal
LULUCF	Land use, land use change and forestry
Mha	Million of hectares
MSW	Municipal solid waste
Net-zero scenarios	IDA scenarios with net-zero GHG emissions in 2050 (1.5TECH, 1.5LIFE)
nZEB	Nearly zero-energy buildings
PA	Paris Agreement
N_2O	Nitrous oxide (laughing gas)
PtG / PtL	Power-to-Gas / Power-to-Liquid (any power-based gaseous/liquid fuels)
RES	Renewable energy sources
RES-E	Renewable energy sources in the electricity sector
SDG	Sustainable development goals of the United Nations
SV	EC's strategic vision "A clean planet for all"
toe	Tons of oil equivalents (energy measuring unit)
TRL	Technology-readiness level
UNFCCC	United Nations Framework Convention on Climate Change
WLTP	Worldwide Harmonised Light Vehicle Test Procedure

1 Introduction

1.1 Background and objectives

In November 2016, the Paris Agreement (PA) entered into force. With the PA, the international community has agreed on ambitious goals, in particular the long-term temperature goal (LTTG) to hold global warming well-below 2°C and to pursue efforts to limit global warming even to 1.5°C (UNFCCC 2016). In Article 4, this is linked to the requirement of reaching a global balance of greenhouse gas (GHG) emissions and sinks in the second half of the 21st century. Furthermore, Art. 4 requires the parties to the PA to prepare long-term low GHG development strategies until 2020, which are consistent with the goals of the PA (cf. Bodle et al. 2016).

The European Commission (EC) had developed such a long-term climate strategy (LTCS) for the European Union (EU) already back in 2011, namely the Low-Carbon Roadmap (European Commission (EC) 2011). While the latter was never formally adopted due to the resistance of some Member States, it has been formative for the discussion about the long-term mitigation pathway of the EU, in particular also for the EU Energy and Mobility Roadmaps. Although the target formally adopted by the EU covers the range of 80 – 95% GHG reduction by 2050, the scenarios underlying the Low-Carbon Roadmap have shifted the focus of the debate to an 80% GHG reduction compared to 1990. However, there are strong arguments that a GHG reduction of the EU by only 80% in 2050 is not consistent with PA's LTTG (cf. Wachsmuth et al. 2018). Hence, the Low-Carbon Roadmap can be seen to be outdated because of the more ambitious LTTG set in the PA but also because of the recent technological development (cf. Graichen 2016).

Accordingly, the EU Governance Regulation (European Commission (EC) 2018b), Art. 15) asked the EC to draft a new LTCS that includes a scenario with net-zero GHG emissions in 2050. In turn, the EC presented its strategic vision (SV) for the EU entitled "A Clean Planet for all" in November 2018. The SV is accompanied by extensive supporting material, in particular a comprehensive impact assessment, for which a number of highly complex (computer-based) models are used and different scenarios are developed that cover the entire range of relevant sectors and fields of action. Both the depth and breadth of this investigation make it difficult to penetrate the assumptions, results and conclusions from beginning to end.

Against this background, the central objective of this report is to enable a detailed understanding of the material underlying the strategic vision and its implications, in particular the supporting in-depth analysis (IDA), which contains the underlying scenario assessments. In addition to a general evaluation of the material, this report aims in particular to derive the consequences for the entire range of sectors and fields of action concerned and to identify needs and recommendations for further steps in the development of the LTCS before a formal adoption by the EU and the following submission to the UNFCCC. The SV itself is assessed in a companion study to this report (cf. Wachsmuth et al. 2019).

1.2 Assessed material and applied methodology

In conjunction with the SV "A Clean Planet for all - A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy" presented in the run-up to the COP 24 in Katowice in 2018, the EC has published the following accompanying material:

- European Commission (EC) (2018d): IN-DEPTH ANALYSIS IN SUPPORT OF THE COMMISSION COMMUNICATION COM(2018) 773: A Clean Planet for all - A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy
- EPSC (2018): European Political Strategy Centre, "10 Trends reshaping Climate and Energy"

- European Commission (EC) (2018c): European Commission, “Final Report by the High-Level Panel of the European Decarbonisation Pathways Initiative”
- Chan et al. (2019) / Fleiter et al. (2019): Industrial Innovation: Pathways to deep decarbonisation of Industry. Part 1: Technology Analysis / Part 2: Scenario analysis.

This report focuses on the analysis of the IDA, which is the central document that the Strategic Vision (SV) rests on, as is shown by the prominent summary of the IDA’s results in the SV. An understanding of the IDA is, hence, key to judge the validity of the corresponding conclusions in the SV. The remaining documents listed above are relevant for some distinctive aspects of the IDA and will be assessed only as far as necessary to understand those aspects.

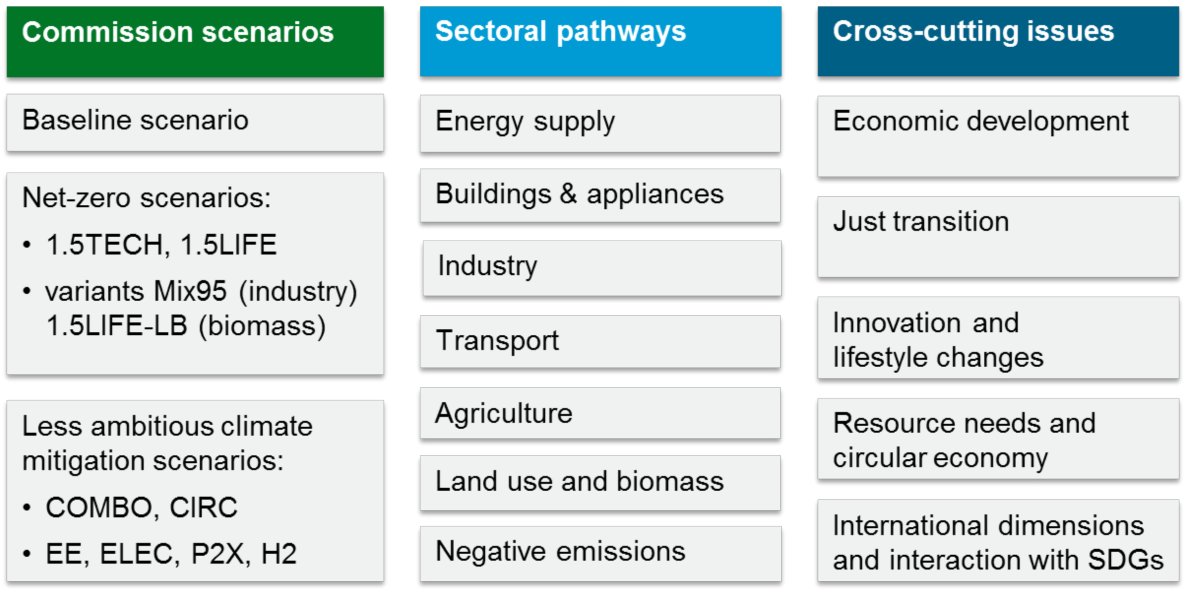
In a first step of the analysis, the accompanying material was screened and further documents particularly relevant to the IDA were identified. These were:

- E3-Modelling et al. (2018): Review of technology assumptions for decarbonisation scenarios
- European Commission (EC) (2016b): EU Reference Scenario 2016
- European Commission (EC) (2018b): EU Governance Regulation

The EU Governance Regulation is particularly relevant, as its Article 15 defines certain conditions for the setup of the EU LTCS. These conditions are reflected in the assessment of the IDA. The EU Reference Scenario 2016 and the study E3-Modelling et al. (2018) are key inputs to understand the modelled scenario and are therefore also assessed in some detail.

In a second step, focus areas for the assessment of in-depth analysis were chosen in discussion with the German Environmental Agency (see Figure 1).

Figure 1 Overview of the focus areas of the assessments in this report



Commission scenarios	Sectoral pathways	Cross-cutting issues
Baseline scenario	Energy supply	Economic development
Net-zero scenarios: • 1.5TECH, 1.5LIFE • variants Mix95 (industry) 1.5LIFE-LB (biomass)	Buildings & appliances	Just transition
	Industry	Innovation and lifestyle changes
	Transport	Resource needs and circular economy
Less ambitious climate mitigation scenarios: • COMBO, CIRC • EE, ELEC, P2X, H2	Agriculture	International dimensions and interaction with SDGs
	Land use and biomass	
	Negative emissions	

Source: own illustration, Fraunhofer ISI

The assessment focuses on the net-zero scenarios in comparison to the baseline, but also considers the others.

These focus areas are (1) the scenarios in the IDA, in particular those compatible with the SV’s goal of net-zero GHG emissions by 2050, (2) the corresponding sectoral pathways described in Section 4 of the IDA (with sub-topics energy supply, buildings, transport, industry, agriculture, land use and negative emissions) and (3) cross-cutting issues, some of which are explicitly addressed in Section 5 of the IDA and some of which are scattered in the IDA (sub-topics economic development, just transition, innovation and lifestyle changes, resource needs and circular economy as well as international dimensions including SDGs). For each of the two focus areas, a set of guiding questions was compiled.

An assessment of the sectoral pathways mainly means to analyze the long-term scenarios, which the IDA is based on. In a study for the German Environmental Agency (Duwe et al., to be published), the Ecologic Institute and Fraunhofer ISI have developed a criteria catalogue that enables an assessment and comparison of long-term scenarios. The criteria refer to quantitative indicators such as emission reductions but also qualitative indicators such as the sectoral coverage. The catalogue is both descriptive and normative, as it facilitates a comparative analysis (e.g. of the scenarios) as well as an evaluation of the quality of an individual scenario. In this report, the focus is on the descriptive evaluation of the criteria. Instead of a normative evaluation, the descriptive criteria are compared to similar studies to enable a judgement of the relative quality of the scenario analysis. The criteria catalogue is based on four guiding questions:

1. How much mitigation is foreseen?
2. How will mitigation be achieved?
3. What are the contextual circumstances?
4. Is the scenario based on appropriate and robust methodology?

These guiding questions are meant to cover all relevant aspects of any long-term scenario study. As the IDA assessed here is subordinate to the SV, not all aspects apply to it. In particular, the first and the third guiding questions are more related to the SV itself then to the IDA. They are therefore covered in the companion study to this report, which assesses the SV (Wachsmuth et al. 2019). Accordingly, here the focus is on the second and the fourth guiding question.

The guiding question “**How will mitigation be achieved**?” assesses which measures a scenario includes to achieve the required GHG emission reductions, focussing on the following aspects:

- *Technology focus*: Some scenarios may pursue one technological path more vigorously than another. With regard to energy-related GHG emissions, RES and energy efficiency are two key strategies for all relevant sectors, but other mitigation options may also be included, such as nuclear energy, CCS and new industrial processes. Accordingly, there may also be different technology foci for the non-energy-related GHG emissions

- *Transitions:* Transitions include changes in individual behaviours (e.g. driving, dietary habits, etc.) and changes in sectoral structures (e.g. structural change within industry or a shift to the tertiary sector). Such transitions can lead to further GHG emission reductions over and above a technological focus and also get at emissions originating from other economic sectors (e.g. behavioural change measures promoting sustainable meat consumption have the potential to decrease agriculture sector emissions).

- *Sector coupling:* Sector coupling means to achieve GHG reductions and/or efficiency gains by exploiting certain options from another sector (i.e. electrification of heating and electrification of transport, power-to-gas, power-to-liquid). Sector coupling becomes more important, the more challenging it becomes to reduce emissions from current production and consumption patterns within the sector.

- *Sustainability:* Sustainability considerations probe whether the scenario considers the sustainability concerns and environmentally harmful effects of some mitigation strategies, in particular with regard to land use and biomass, such as the production of biofuels in place of food crops.
- *Policy relevance:* While some scenarios describe the measures to achieve emission reductions in an abstract way, others also deal with the conditions to realise the measures, e.g. a sufficient level of carbon pricing, or even concrete policy instruments to foster the realisation of the measures. A concretisation is to a certain extent important to enable strategic considerations, so to make the scenarios policy-relevant.

Different methodological aspects are considered to answer the guiding question: “**Is the scenario based on appropriate and robust methodology?”** The appropriateness of the data sources a study is based on refers to the transparency and the relevance of the study as follows:

- *Relevance:* For a study to be of relevance to international climate policy, it has to take into account the official datasets, in particular the GHG data reported under the UNFCCC protocol and the national energy balances.
- *Transparency:* For a study to be transparent, both its input data and its output data for socio-economic, energy and climate parameters (e.g. annual economic activity, energy consumption and GHG emissions for each sector) should be publicly available. A peer review may increase the validity of the assumptions and the results.

With regard to the robustness criterion, the following aspect are taken into account.

- *Analytical assessment:* An analytical assessment of mitigation pathways should be based on assessment of the potential of the various mitigation options. While technical potentials are usually included in models as constraints, economic potentials can be assessed via an economic optimisation. The assessment of multiple options/pathways enables a more comprehensive understanding of trade-offs. A cost-benefit analysis may foster setting priorities between options.
- *Model setup and assumptions*: Different types of models can be used, with different types of benefits and caveats. Those should be reflected in the interpretation of the results. A comparison of the results with other studies can make the results more plausible and/or compensate for some of the caveats. Moreover, assumptions driving the results such as implementation of certain policies should be clearly mentioned.
- *Sensitivity analysis:* It is important for climate protection pathways to be robust, i.e. not to be sensitive to the modelling uncertainties. This can be tested by a sensitivity analysis, which varies the central parameters related to the main uncertainties. In the best case, ranges resulting from a sensitivity analysis are provided by a study. Most studies at least qualitatively discuss the sensitivity of their findings, while others do not address the issue at all.

The dimensions considered under the cross-cutting issues are much more diverse than those in the sectoral pathways. Therefore, the assessment cannot follow a criteria catalogue of similar stringency. Each cross-cutting issue is hence treated separately, but the following set of questions has roughly guided the assessment, with limited adjustments to reflect the individual characteristics of the cross-cutting issues:

- What is the general relevance of the specific cross-cutting issue in the context of 2050 climate policy?
- To what extent is the cross-cutting issues considered by the Commission?
- Are both challenges and opportunities being considered, and in what balance?
- Does its cover all relevant aspects and the corresponding existing literature? What source material is being used?
- Is the consideration of the issue appropriate? Does the Commission propose a proactive approach to addressing the issue?

Finally, it has to be emphasised that the assessment of the IDA was solely based on the material made available by the EC and secondary literature. For this report, neither own estimations nor own modeling was carried out.

2 Sectoral pathways

This section assesses the sectoral mitigation pathways mainly described in Section 4 of the IDA. The first subsection on “Overall setup” assesses the general setup of the scenario analysis and the model suite based on IDA sections 4.1, 4.9 and 7.2. The following subsections focus on certain sectors and the corresponding sections in the IDA:

- energy supply: IDA section 4.2;
- buildings and appliances: IDA section 4.3;
- transport: IDA section 4.4;
- industry: IDA section 4.5 and 7.6;
- agriculture: IDA section 4.6;
- land use: IDA section 4.7;
- negative emissions: IDA section 4.8.

Each subsection answers the two guiding questions “How will mitigation be achieved?“ and “Is the scenario based on appropriate and robust methodology?” with regard to the aspects described in detail in Section 1.2.

2.1 Overall setup

The IDA is built upon one baseline scenario and eight more ambitious scenarios of future pathways for the EU. These scenarios agree in the general socio-economic assumptions (rise of population by 3.4% and of GDP by 68% in 2015-2050) and in reaching the EU’s 2030 targets, but are characterised by different levels of GHG reductions in 2050 (see Table 1). Only the two most ambitious scenarios (1.5TECH and 1.5LIFE) achieve net-zero GHG emissions in 2050, thus actually being in line with the target chosen in the Strategic Vision(thus called “net-zero scenarios” in the following). Nevertheless, the Commission’s documents (European Commission (EC) 2018a, 2018d) refer to the other six scenarios as in line with the Paris Agreement as well, as those are claimed to be consistent with global well-below-2°C pathways. However, this is questionable for a GHG reduction of less than 90% in 2050, as explained in (Wachsmuth et al. 2018). The analysis, hence, focuses on the two net-zero scenarios but mentions key aspects of the other six scenarios as well.

While these six scenarios all rely on a strong use of renewable energies and energy efficiency, they differ with regard to technology preferences (electrification, energy efficiency, hydrogen, power-to-x, circular economy). All considered technologies are already available today but some at relatively low technology-readiness level (TRL), e.g. direct reduction of hydrogen in the steel industry and direct air capture of CO_2. To achieve net-zero GHG emissions in 2050, the net-zero scenarios apply the most ambitious mitigation options in all sectors. The technologies and measures included in the sectoral pathways cover a very broad portfolio with different foci in the various sectors (see the following subsections). Different options for sector coupling are covered, in particular electricity-based synthetic fuels play a key role to minimise the residual GHG emissions in the industry and transport sector with 154 – 227 Mt CO_2. While most scenarios take a business-as-usual perspective towards socio-economic development, the scenario CIRC includes options to limit sectoral activities in all sectors. The scenario 1.5LIFE builds upon this and also includes behavioral changes such as dietary changes.

Still, both net-zero scenarios need to make use of carbon-dioxide removal (CDR) to achieve GHG neutrality. CDR options included in the modeling are land management and carbon capture and storage (CCS), both in combination with bioenergy and with direct air capture of carbon, while other promising CDR options (cf. Fuss et al. 2018) are only shortly discussed. The extent of negative emissions is substantially larger in the scenario 1.5TECH, which therefore makes strong use of CCS (298 Mt CO_2 in 2050), while in the scenario 1.5LIFE CCS is less prominent (80 Mt CO_2 in 2050) due to higher land use sinks. The negative emissions in 1.5TECH are higher than in former EU-model-based assessments of the EU, while scenarios based on global models have included comparable and even much higher amounts of negative emissions for the EU (cf. Duscha et al. 2018). The assessment includes some **sustainability considerations**, in particular with regard to biomass and a just transition. In the scenario variant 1.5LIFE-LB, the sensitivity with regard to low biomass availability due to higher sustainability standards is analyzed. The considerations of a just transition concern distributional aspects based on the macro-economic assessments (cf. Section 3.2). Other sustainability aspects like land use issues and nuclear safety are treated in low detail or not at all.

The scenarios apply a shadow carbon price to realise the GHG reduction within the optimisation models. After 28 EUR/t CO_2eq in 2030, this carbon price reaches 350 EUR/t CO_2eq in 2050 in the net-zero scenarios, while it is only 250 EUR/t CO_2eq in the less ambitious scenarios. The order of magnitude falls in the wide range of carbon prices in similar scenarios, with 200 EUR/t in the German Climate Protection Scenario with 95% GHG reduction (Öko-Institut und Fraunhofer ISI 2015) and 540 USD/t in the global Below-2°C Scenario of the World Energy Outlook (IEA 2018). Policy instruments that foster the realisation of those measures are usually not addressed.

Table 1: GHG emission levels in the scenarios of the In-depth Analysis in the year 2050

	Baseline 2050	ELEC, H2, P2X, EE	CIRC	COMBO	1.5TECH	1.5LIFE
2050 GHG emissions excl. LULUCF [MtCO_2]	2214	1004-1054	976	868	343	489
reduction vs 1990	*- 62%*	*- 82-83%*	*- 83%*	*- 85%*	*- 94%*	*- 92%*
2050 GHG emissions incl. LULUCF [MtCO_2]	1978	763-816	684	620	26	25
reduction vs 1990	*- 64%*	*- 85-86%*	*- 88%*	*- 89%*	*- 100%*	*- 100%*
Cumulative CO_2 emissions incl. removal 2018-2050 [GtCO_2]	71	59-61	58	58	49	48

Source: own representation of European Commission (EC) 2018d

2.1.1 Assessment

The scenarios were analyzed based on a well-established **model** suite, which had been applied in earlier impact assessments of the Commission, namely the energy system model PRIMES in combination with the models GAINS and GLOBIOM for land use and non-CO_2 emissions. In addition, the techno-economic model FORECAST was used to cover the industry sector in more detail. Together these models include a very broad set of mitigation options and the correspondding mitigation potentials. Where this was not the case, additional analyses were included (e.g. for international navigation). In total, the modelling covers all relevant sectors and GHGs in a level of detail that is at least comparable to similar assessments, in some sectors above average. The main energy system model used (PRIMES) is a partial equilibrium model with a high level of techno-economic details. It does not include macro-economic feedbacks though. As a remedy, the assessment included a detailed comparison of investment requirements and macroeconomic impacts as well as of distributional aspects. To this end, the models JRC-GEM-E3, E3ME, and QUEST were applied (see Section 3.1). However, this does not enable to assess the feedback of macro-economic impacts on the energy system scenarios.

All scenarios build upon the **socio-economic assumptions** of the EU Reference Scenario 2016 (cf. European Commission (EC) 2016b). This enables comparability of the results. However, while the assumed fuel price developments and discount rates have decreased in comparison with the former EU Reference Scenarios, these are still high with regard to current fuel prices and discount rates. Thereby, PRIMES distinguishes between private discount rates used for individual investment decision making of the agents and a social discount rate for the calculation of system costs. The social discount rate in the EU Reference Scenario is 10%. With regard to the private discount rates, a particularity of the PRIMES model is that it uses high private discount rates (> 10%) for some sectors to reflect non-financial barriers and lower discount rates to model the removal of those barriers by policies. This is a rather abstract way for including policies, which is difficult to judge and does not provide insights in how to design suitable policies. Both the high discount rates for private investments and the abstract modeling of policies have been a critical issue of ongoing debates (cf. Steinbach et al. 2015; Earl et al. 2018). The high discount rates, in particular for private investments, may result in underscoring the benefits of energy efficiency improvements (Santini und Scheuer 2018). Discount rates used in the Reference Scenario 2016 in the energy supply range from 7.5% to 11.5%. Whilst risk premiums are added for immature technologies, there is no consideration of regulatory or policy risk e.g. with regard to renewables policies (cf. European Commission (EC) 2016b, S. 44–45). Discount rates of individuals in energy demand sectors are higher and reach up to 14.75%, if no energy efficiency policies are applied.

The baseline **scenario** is built in a usual way by implementing current policies and regulations, and it is up to date, as it includes the recent revisions of the Energy Efficiency Directive and the Renewable Energy Directive. However, it does not take into account the draft National Energy and Climate Plans of the Member States and is thus not in accordance with Article 15 of the Governance Regulation (European Commission (EC) 2018b). Note here that draft National Energy and Climate Plans were due in December 2018 and therefore not available when the Vision was published. The other scenarios differ from the baseline mainly only after 2030, which may cloud that there may occur lock-ins on the way to net-zero emissions that need to be addressed before 2030. It is appreciable that the two net-zero scenarios show the trade-off between behavioural changes and higher negative emissions rather explicit, although the discussion of its political implications is limited. Furthermore, while the set of scenarios with an 80% GHG reduction in 2050 explores many different options, the set of only two net-zero scenarios is rather limited. In particular, it is unclear why a scenario with close to 100% renewable energies has not been explored.

The **transparency** level of the modeling exercise is moderate only. The GHG emission data is matched with the official EEA inventories and the energy system analysis is in accordance with the EU's energy balances. However, central assumptions and results are scattered throughout the IDA and detailed input and output data is mostly not available. This makes it difficult to assess the robustness of the modeling results. A sensitivity analysis is also provided with regard to the available bioenergy potential only. The modelling exercises for the industry sector and the macroeconomic impacts present the results of two models, which make the findings more plausible. In all sectors, the results are compared to similar studies and similarities and differences are mentioned, which also fosters the **robustness** of the results. An improvement with regard to robustness of the analysis is that technology assumptions have been subject to a stakeholder consultation and been published afterwards (E3-Modelling et al. 2018). Nevertheless, the stakeholder influence on the technology assumptions is not fully clear. Sectoral details can be found in the following subsections.

2.2 Energy supply

The core element of decarbonising the energy sector in all scenarios is a strong increase in the use of renewables and the use of renewables-based electricity to decarbonise other sectors with more limited mitigation options (sector coupling). The detailed technology focus depends on the decarbonisation scenario. Sector-coupling is an important element of all decarbonisation scenarios, whilst the use of e-fuels or hydrogen develop in selected scenarios (e-fuels in P2X, COMBO, hydrogen in H2 as well as e-fuels and hydrogen in both net-zero scenarios).

In general, all scenarios - including the Baseline - are characterised by reductions in primary **energy demand**, ranging from very low reductions in the P2X Scenario (only 22% reductions compared to 2005) to stronger reductions amounting to 50% and 45% respectively for the EE and CIRC Scenario. Thereby, the EE Scenario and the CIRC Scenario show stronger reductions in primary energy consumption than both net-zero scenarios by 2050 due to the lower use of e-fuels. Main other drivers for primary energy demand reductions in these scenarios are efficiency improvements, across all sectors and circular economy impacts in transport and industry. As expected, reductions in primary energy demand in the 1.5LIFE Scenario are higher than in the 1.5TECH Scenario (ca. 42% versus ca. 35%). Final energy consumption is reduced by 26% in 2050 against 2005 in the Baseline, while a 47% reduction is achieved in 1.5 LIFE. In terms of final energy consumption, reductions are highest in the net-zero scenario 1.5 LIFE, whilst reduction in final energy demand amount to 44% in the EE Scenario. Reductions in final energy consumption are most pronounced in the residential sector in most scenarios, followed by the transport sector. Energy demand reductions in industry and services are lower due to the economic development.

With regard to the **energy mix**, the supply sector is mainly dominated by electricity, amounting to a share of roughly 50% in final energy consumption in both net-zero scenarios. The maximum electricity share in all scenarios is slightly higher in ELEC than in the net-zero scenarios and amounts to 53%, whilst 40% electricity share is achieved already in the Baseline Scenario. Provided that final energy consumption diverges considerably among scenarios, differences in absolute values are stronger. Thus, only about 310 Mtoe of final energy consumption consist of electricity in the 1.5LIFE Scenario, whilst the highest electrification rate is observed for the ELEC Scenario with a high share of electricity and comparatively low reduction in final energy consumption (ca. 420 Mtoe of electricity). In all scenarios including the Baseline, solid energy carriers (coal, lignite) almost disappear from the energy system. In addition, the use of natural gas is reduced considerably in all scenarios. Whilst the natural gas share in the Baseline gross inland consumption amounts to roughly 18%, its share in the net-zero scenarios is lower amounting to 5%. In absolute terms this amounts a use of natural gas in the order of about 60 Mtoe (1.5TECH) and 40 Mtoe (1.5LIFE) and an increased use of biogas, gas from waste and e-gases. Thus, e-gas and natural gas co-exist with similar shares in both net-zero scenarios. Assuming that e-gas develops as the more economic option considering high CO_2 prices in the net-zero scenarios, a complete replacement of gas through e-gas would make sense. This is an example where more detailed explanations of the results and the causes would be helpful.

Nuclear energy still plays a prominent role in the energy mix, amounting to about 14-17% of gross inland consumption.

As regards the **development of RES** in the scenarios, about 25% of RES share in gross inland consumption are achieved by 2030. This corresponds to the target of 32% of the recast of the Renewable Energy Directive (RED II), looking at the share of RES in final energy consumption. The RES share in the Baseline (in terms of gross inland consumption) achieves only 36% by 2050. The RES share is highest in both net-zero scenarios and amounts to about 62% taking gross inland consumption as the reference, while about 50-52% RES-share are achieved in the 80% GHG emission reduction scenarios. In terms of RES share calculated according to the Renewable Energy Directive as share in final consumption, the decarbonisation scenarios come up with a share between 67%-84% by 2050. The use of biomass increases in all scenarios, achieving a lower share in the H2 Scenario (14% of gross inland consumption) and a higher share in CIRC with 19%. There is only a limited use of non-biomass based renewables (solar thermal, geothermal, ambient energy) in the heating sector, but it is also stated that geothermal or solar thermal technologies have not been considered in depth. In general, the role of RES in the heating & cooling sector could be higher. District heat keeps its initial share of 4% roughly constant, but increases in industrial sector whilst its share decreases in buildings. The small share of district heat hinders higher RES integration in the heating & cooling sector, as much of the excess heat potentials, geothermal and large-scale solar thermal potentials remain untapped as it is not feasible to fully utilise these potentials through decentral systems. Other studies, such as the Heat Roadmap 4 indicate that at least half of the heating demand in 2050 in 14 selected EU countries that reflect 90% of the EU's heat demand could be cost-effectively supplied by district heat (Fraunhofer-Institut für System- und Innovationsforschung et al. 2019). Thus, the use of additional models able to depict the heating & cooling sector in more detail would probably have led to a different picture.

The **power generation** is characterised by a strongly increasing electricity consumption, meaning that additional electric generation capacity is needed to cover demand. For example, in the ELEC Scenario, the share of electricity in final energy consumption increases by 75% compared to 2005 levels, whilst the net-zero scenarios experience growth by approx. 45% (1.5TECH) and about 30% (1.5LIFE). Higher demand for electricity comes from decarbonisation needs in other sectors, e.g. electricity demand in transport, from hydrogen production, e-fuels or e-gases. Increase in electricity consumption leads to substantial increases in generation capacities to between 1,700 GW (EE) and 2,800 GW (1.5TECH) starting from 985 GW in 2015 (see Table 2 and EU KOMM (2018d, S. 77)). This is recognised in the IDA as a mayor investment challenge, but is also seen as a chance to rejuvenate power generation infrastructure. The example of wind capacity shows that strongly increased growth rates are required. For, the increase of wind capacity from 140 GW in 2015 to 700 GW (EE) or 1,200 GW (1.5TECH) requires capacity additions of between 30 to 50 GW per year, whilst the increase between 2000 and 2015 amounted to only 31 GW in total.

The future **electricity mix** is clearly dominated by domestic renewable energy sources and a considerable share of nuclear power. Whilst the RES-E share in the decarbonisation scenarios amounts to ca. 81-85%, the RES-E share in the Baseline amounts to roughly 75%. The increased share of RES is characterised by a better competitiveness compared to conventional fuels and is enabled by system optimisation using various flexibility options. The strong decarbonisation also leads to strong reductions of energy imports of roughly 250-400 Mtoe and therefore reduces the EU's dependency on other countries. Nuclear electricity still provides between 12-15% of EU electricity supply in all scenarios for 2050. Fossil fuel use in the power sector remains at a rather low level ranging from 2-5% in the decarbonisation scenarios. Nuclear capacity still is about 99-121 GW in 2050, compared to a level of 97 GW by 2030 and compared to a similar level amounting to 122 GW in 2015. According to the Figure 24 of the IDA, this means that 5 GW per year of nuclear capacity are either newly installed, refurbished or extended in lifetime in the time period between 2015 and 2050 (considering retirement of old plants, refurbishment and extension of lifetime). It is questionable whether such a development can be realised in practice considering social acceptance and an adverse financing environment for nuclear power at least for new nuclear power installations. Hydrogen in the power sector only plays a minor role, but it in general it is deployed in particular in the 1.5TECH and the H2-Scenario (mainly used in industry and heavy duty vehicles) achieving 80 Mtoe in 1.5TECH and 150 Mtoe in H2 by 2050. It is assumed that the hydrogen is produced domestically which presents a challenge from a cost perspective but also with respect to building up the necessary electrolysis capacities in time. The role of CCS faces limitations due to sufficient and competitive resource availability of RES as well as the availability of flexibility options. Only in 1.5TECH it plays a noticeable role in combination with biomass amounting to about 5% of total net electricity generation or 66 GW of electricity generation capacity is equipped with CCS.

CO_2 emissions from the power sector in 2050 are reduced to a comparatively low level of between 13 $MtCO_2$ (EE) and 113 $MtCO_2$ (P2X), with the higher emission level in P2X resulting from increased electricity demand and the associated system integration of variable RES-E with CCS-equipped gas installations (see Table 2). The 1.5TECH Scenario already shows negative emissions of about 141 $MtCO_2$ by 2050. For the longer term after 2050 until 2070 all decarbonisation scenarios except for the 1.5LIFE Scenario show negative emissions in the power sector Although the use of CCS in the power sector is currently not economic and plays a restricted role by 2050he CCS technology seems crucial for achieving net-zero emissions on a longer term, in case no massive change in people's behaviour, as assumed in 1.5LIFE, can be achieved.

Increasing electricity demand with a high share of variable RES-E requires **flexibility options**. The IDA does not provide information how the integration of the power system is handled. Thus, there is no information on the required extension of the power grid and no detailed quantitative results about the role of demand side measures. Only the role of storage technologies is described, but no explanation on the use of storage versus other flexibility options such as reinforcing the electricity network is given. The role of storage increases considerably in all decarbonisation scenarios as compared to 2030 and to the Baseline. Thereby, the use of batteries clearly exceeds that of pumped storage in all decarbonisation scenarios looking at 2050. In general, the use of storage in the net-zero scenarios is rather high, amounting to 245 TWh in 1.5LIFE and to 281 TWh in 1.5TECH. However, it is difficult to assess the order of magnitude, since information on other flexibility options is missing. The use of hydrogen as storage option also increases its relevance in all decarbonisation scenarios, with particularly strong use in the H2 Scenario and the P2X Scenario. Thus, a large deployment of electrolysis for hydrogen and e-fuels would be implied, leading to electrolysis capacity of 57 GW in the EE-Scenario to 454 GW in the P2X Scenario and to 511 GW in the 1.5TECH Scenario.

Table 2: Key input and output data of the In-depth Analysis in the power sector in 2050

	Baseline 2050	ELEC, H2, P2X, EE	CIRC	COMBO	1.5TECH	1.5LIFE
CO_2 emissions [$MtCO_2$]	246	13-113	20	56	- 141	24
% of 2015	- 80%	- 91%-99%	- 98%	- 95%	- 111%	- 98%
CCS [$MtCO_2$]	5	6-16	7	7	218	9
Power gen. [Mtoe]	300	283-499	320	434	520	425

	Baseline 2050	ELEC, H2, P2X, EE	CIRC	COMBO	1.5TECH	1.5LIFE
% of 2015	142%	134%-236%	152%	205%	246%	201%
Gen. capacity [GW]	1,600	1,700-2,700	1,800	2,400	2,800	2,300
Import/export [Mtoe]	653	400-420	384	358	268	248

Source: European Commission (EC) 2016b, European Commission (EC) 2018d

2.2.1 Assessment

The EC assigns high **priority** to increasing the RES share and to use electricity in other sectors in their communication, by mentioning it as the second action block, just after "energy efficiency measures". Nuclear power also plays a role providing about 15% of the electricity supply (European Commission (EC) 2018a). The description of the energy supply sector in the IDA mainly consists of a presentation of the different technology mixes in the different scenarios. In addition, there is a presentation and short characterisation of existing decarbonisation options and their future perspectives and (qualitative) potentials. In this context, renewable energy sources but also nuclear are identified as carbon-neutral energy carriers. RES is still considered to be the most important technology for decarbonising the energy sector, which was also a result of the stakeholder consultation. In addition, the EC recognises high costs of e-fuels and e-gases. The presented results in terms of the technology mix are in the range of evidence from other studies. Examples for these other studies are IEA (2017), Shell (2018), IRENA (2018), Greenpeace et al. (2015), and the Öko-Institut (2018).

Transparency of the modelling exercise is limited, in particular regarding the assumptions on techno-economic data. Only for the Baseline, the same assumptions regarding the discount rate are made as in the reference scenario 2016 (see also Section 2.1). Whilst extensive information is available on the modelling tool - although somewhat outdated from 2013-2014[1] - there is no detailed information on how the modelling leads to the different technology mixes. With regard to how the technology mix is achieved, there are only very brief descriptions not going much into detail stating for instance that RES-support is phased-out when competitiveness is achieved, without saying anything about how this support looks like in concrete. The IDA however mentions some limitations of the modelling work, including the fact that not all possible issues related to availability of land, public acceptance, import vs. domestic production, etc. can be captured. In general, the PRIMES model provides a quite complete view of the energy sector, but for some areas, it only considers a lower degree of technological or geographic detail. Thus, there is no detailed consideration of renewables cost-resource curves with a high geographical solution and RES support policies are reflected in a simplified way.

With regard to the **scenarios**, all scenarios are characterised by the increasing relevance of electricity. In addition, all scenarios are clearly dominated by renewable energy sources. The fuel mix in 1.5TECH and 1.5LIFE in terms of gross inland consumption is very similar, but there are slightly different consumption levels - about 1.25 Gtoe in 1.5TECH and 1.1 Gtoe in 1.5LIFE. These differences are mainly due to lifestyle changes in the 1.5LIFE Scenario compared to the 1.5TECH Scenario. In both net-zero scenarios, fossil oil and natural gas are substituted to a certain extent by e-fuels and e-gases. However, there is no scenario with a 100% renewables share, the maximum share of RES in gross inland consumption amounts to 62% in both net-zero scenarios by 2050, compared to 36% in the Baseline. There is no net-zero scenario that

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[1] See https://ec.europa.eu/clima/sites/clima/files/strategies/analysis/models/docs/primes_model_2013-2014_en.pdf

maximises renewables use in combination with strong energy demand reductions. Thus, the RES share in the 1.5LIFE Scenario could potentially be increased to limit negative emissions even further. Moreover, other studies (Öko-Institut 2018) indicate even higher final energy demand reductions amounting to 56% (in 2050 against 2005) than the 47% reduction achieved in the 1.5LIFE Scenario.

In general, the **techno-economic assumptions** provided in E3-Modelling et al. (2018) regarding the most relevant technologies in the power sector seem to be in line with assumptions made in other studies. This includes in particular the investment per kW of generation capacity and its development over time, the electric efficiency and in case of renewables the utilisation factor. In previous modelling exercises, PRIMES has often been criticised for outdated and too high investment assumptions for some renewable technologies, in particular PV, which have shown strong reductions in the investment in recent years. As a consequence, renewable electricity was penalised and their share was partly underestimated due to high costs. However, this has changed and assumptions for PV investments are in line with most recent experiences. One rather minor issue is that PV investment assumptions made in PRIMES vary with the utilisation factor, which is typically not the case. PV investment rather varies with the sise of the plant due to the balance of system components (inverter, wiring, switches,...) entailing higher specific investments for small-scale plants. Data regarding wind energy are also realistic and rather show investments on the lower end of the range in particular for turbines leading to a high capacity factor. Assumptions for the specific investment in nuclear power also seem to be in line with other studies, although costs depend on security requirements, show a broad range and provided experienced cost increases of currently built reactors show a high uncertainty.

2.3 Buildings & appliances

The bandwidth of approaches for the building sector to reach energy- and climate targets is assessed by using the following five general scenario definitions for the building sector:

- Electrification (ELEC): Promoting use of electricity for heating
- Renewable Gases (H2 and P2G): Promoting use of carbon neutral gas
- Energy Efficiency (EE): High rate and depth of renovations, further improved energy efficiency in appliances
- Circular Economy (CIRC): Reduced renovation costs due to efficiency and substitution

Each of the five scenarios for the building sector is defined along the overall targets, where individual scenarios reach 80% GHG emission reduction and the combination leads to 90%. With the additional elements like technology focus or circular economy a net-zero emission level by 2050 is reached (scenarios 1.5TECH and 1.5 LIFE).

In these scenarios, the two elements of **energy efficiency** measures to the building shell and the efficiency of the **technologies** including the energy carriers are important. While the efficiency determines the useful energy demand of the buildings, the technology and the energy carrier have direct impact of the final energy demand and consequently the GHG emissions. A set of assumptions especially on renovation costs, technology costs and technology efficiencies have been published in the ASSET project (E3-Modelling et al. 2018). Since the baseline scenario in the IDA uses the same set of assumptions as the EU Reference Scenario 2016, they can be discussed. The discount rates for private household renovations and heating equipment with 14.75% seems to be very high, even though it has been reduced significantly in comparison to the EU Reference Scenario 2013. The same is valid for the discount rate for household appliances, which is set to 13.5%. However, for all other scenarios the discount rate and other very essential assumptions are not mentioned (such as energy costs and prices etc.). In general, it would be useful to have some more information (graphs and description) on primary energy consumption and GHG emissions specifically for the buildings sector. Instead it is just mentioned, that all sectors are assumed to contribute equally to the target.

All scenarios consider **sector coupling** elements, mainly with heat-pumps using renewable electricity from the power sector or by using e-gases (H2 or methane). However, specific burden-sharing elements the building sector and others are not addressed. Buildings are assumed to reach the target (net-zero) by 2050 for the two net-zero scenarios. Furthermore, consumer choices and behavioural aspects are addressed, esp. in the 1.5LIFE scenario – where lifestyle changes are considered (such as less floor space for living or other sufficiency measures).

In general, the IDA also covers **sustainability and land use** aspects in separate sections. Within the scope of the building sector relatively small (and partly decreasing) shares of biomass and biogas in all scenarios show, that sustainability and land-use is not an issue. However, explicit sustainability questions (i.e. regarding the insulation material and origin of very high shares of renewable electricity and e-gases) are not addressed in this chapter (but which should be covered in the IDA, especially in the 1.5LIFE scenario with a focus of circular economy).

Since the descriptions of scenarios are quite generic, no concreate **measures** behind the scenario definitions are given. It seems, that rather a set of general assumptions (i.e. regarding the building energy efficiency levels) are considered, and a general optimisation of the building sector can choose between distinct efficiency levels and a variety of heat supply options/technologies within the boundaries of the respective scenario. Therefore, a description of concrete **policy options** is not given - it is assumed, that a future policy framework would need to support the assumptions made in the scenario analysis.

In general, the analysis shows that renovation activities are more relevant than new buildings (which need to be built as nearly zero-energy buildings (nZEB) from 2021): All buildings built from 2021-2050 account for 23% for of the residential stock by 2050 only and 28% for service buildings. In all scenarios, the energy efficiency measures are a key enabler for reaching low-carbon intensity levels. In order to reach this target, higher renovation rates and depths of renovation are required. Renovation rates differ per scenario. For the 1.5TECH scenario they are around 1.6% per year for residential buildings and 1.5% for service buildings, while they are slightly higher in the 1.5LIFE scenario with around 1.7% for residential and 1.5% for service sector buildings. The renovation rate for all other scenarios is significantly lower (1.2% - 1.5%), only the EE scenario reaches top levels with 1.8% for residential buildings. The order of magnitude for renovation rates can be considered as realistic target levels, since the lifetime of building shell components must be considered as basis for a renovations rate. Typical lifetimes of building elements range from 20-50 years[2], which can be translated to replacements rates between 2% and 5%. For an average renovation rate, 3% are considered as upper realistically limit (European Commission (EC) 2016a). The highest depth of renovation (reduction of **useful energy** demand (eq. to heat)) is given in the scenarios 1.5LIFE and EE (same level) with -62% by 2050 for residential buildings and -58% for service buildings, while the 1.5TECH scenarios shows minimal higher levels. All other scenarios range between 40-60 kWh/m2a for 2050 values as average for the building sector, which is max. 10 kWh/m2a higher. This relatively small variation in useful energy across all scenarios is unexpected. Typically the depth of renovation varies more for decarbonisation options from -80% GHG reduction to net-zero emissions.

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[2] See VDI 2067 “Wirtschaftlichkeit gebäudetechnischer Anlagen“ (Economic analysis of HVAC Equipment)

Despite a gradual increase of dwellings over time and of their average sises, the heating and cooling **final energy** demand is decreasing in all scenarios, including the Baseline Scenario – while consumptions for appliances and lighting is always increasing over time. The total final energy (heating incl. water heating, cooling, lighting and appliances) decreases by 38% for residential buildings in the Baseline Scenario by 2050 and by 8% in services sector. In the net-zero scenarios for residential buildings the 1.5LIFE scenarios shows a reduction of 57% for total final energy in the residential sector, since the combination of advanced technological deployment and consumer choices is included. For the -80% GHG scenarios in residential buildings, the EE scenario shows with -56% the highest reduction of total final energy, since the focus is on strong action in terms of renovation and equipment performance, while the P2X and H2 scenarios have further decarbonisation options for the energy supply, which allows relatively higher levels of energy demand.

The final energy for heating and cooling in residential buildings is decreasing by 69% in the 1.5LIFE scenario (highest level), while other scenarios rank between 53%-67%. For service buildings the reduction is not as high due to the growing economic activity, but the still range from -41% to -57% (compared to 2005). Regarding the energy demand for appliances, only little variations can be observed between all scenarios, since the same level of service is assumed. The final energy reductions are partly higher than in other studies (Öko-Institut 2018, IEA 2017, Shell 2018 and others), even though the renovation rates are on the same level as other studies. This is because these studies take (at least partly) multiple barriers in finance, split incentives and bottlenecks in construction sector into account. Furthermore, the IDA assumes that these barriers are removed with policies before and after 2030. This results in a higher renovation rate and higher depth of energy-related renovation. The effects of building automation and control systems are considered for all scenarios. They are leading to a reduction of useful energy demand (with focus on service sector). However, the IDA is more conservative regarding similar effects in residential sector – even if other studies have higher effects in residential buildings (e.g. the First Technical Study an IA for the Smart Readiness Indicator[3]). Effects of consumer choices are considered in the 1.5LIFE Scenario, but to a moderate extent. Other studies (not further specified in text) have much higher impacts assumed, but this would lead to a much higher impact on lifestyle and most likely lower acceptability => therefore not considered.

The strongest trend in the scenario analysis is the **electrification**. Already in the Baseline Scenario an increasing number of heat pumps and appliances can be found. Only very little differentiation between the EL-shares in the scenarios ELEC and H2/P2X scenarios in total final energy can be observed. The highest levels for electricity consumption in space heating occur in the ELEC scenario with 60% by 2050 for service sector and 44% for residential sector, while the lowest level is shown for P2X with 22% in residential and 48% in service sector. The electrification rate of heating is at minimum levels in scenarios with alternative energy carriers (such as H2 or P2X). Electrification rates from other studies show values around 74% (Shell Sky study, quite similar values), 35% (IEA ETP, more pessimistic) and 45-63% (Eurelectric Decarbonisation pathways). Other fuels decrease in accordance with increasing electricity rates. The bulk of the remaining energy comes from gas (with 31% in the baseline by2030, 23% for H2 and P2X and 12% in ELEC and the net-zero scenarios by 2050). It is substituted by e-gas in all scenarios where possible (P2X, COMBO, 1.5TECH and 1.5 LIFE). Biogas and H2 play a minor role in scenarios (where availability and costs are considered). Biomass has a stable share across all scenarios (8%-12%). In total the renewable heat shares increase from 19% in 2015, 32% in 2030 to 55% by 2050 in ELEC, 68% in P2X (-80% GHG), and 79% in 1.5TECH and 78% in 1.5LIFE (net-zero). District heat is quite stable over time in all scenarios (approx. 10%), even if

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[3] Source: www.smartreadinessindicator.eu

the potential for green district heating sources (such as solar-thermal and heat pump appliances) is discussed in more detail in the IDA.

Since the model was used with an optimisation constraint to stay within the emission corridor (-80%, -90% and net-zero emissions by 2050), the **GHG emissions** are in line with the corridors (or slightly below, see Table 3). If moderate lifestyle changes are done, the net-zero target is reachable for buildings in a similar way as with a focus on technical measures.

Table 3: Key input and output data of the In-depth Analysis in the buildings and appliances sector in 2050

	Baseline 2050	**EE, ELEC, H2, P2X**	**CIRC**	**COMBO**	**1.5TECH**	**1.5LIFE**
Residential renovation rate 2031-2050 [p.a.]	1.4%	1.5%-1.8%	1.5%	1.6%	1.6%	1.8%
Services renovation rate 2031-2050 [p.a.]	1.2%	1.3%-1.6%	1.3%	1.4%	1.5%	1.5%
CO_2 emissions [$MtCO_2$]	130	45-60	66	19	12	11
Residential [reduction vs. 2015]	- 66%	- 84%-88%	- 83%	- 95%	- 97%	- 97%
Services [reduction vs. 2015]	- 66%	- 81%-87%	- 81%	- 90%	- 92%	- 92%
Residential energy demand [relative to 2005]	- 38%	- 41%-62%	- 58%	- 62%	- 65%	- 70%
Electricity share of total final energy demand (services/res)	80% / n.a.	80%-83% / 53%-68%	80% / -	80% / -	80% / 63%	80% / 63%
Electricity share of space heating demand (services/res)	n.a. / 14%	44%-60% / 22%-44%	n.a.	n.a.	n.a.	n.a.
Residential appliances & lighting [rel. to 2005]	+ 46%	+ 23%-42%	+ 40%	+ 39%	+ 32%	+ 30%
Services appliances & lighting [rel. to 2005]	+ 96%	+ 22%-79%	+ 65%	+ 60%	+ 34%	+ 34%

Source: European Commission (EC) 2016b, European Commission (EC) 2018d

n.a.: not available

2.3.1 Assessment

All in all, the analysis can be considered as **robust** and state of the art. The building sector modelling has been conducted with the Primes modelling suite, which is widely accepted and acknowledged for EU scenarios analysis and impact assessment work. Even if a set of assumptions are documented in the ASSET[4] report, many boundary conditions and assumptions are not documented (such as discount rates, energy prices etc.). The general criticism that was raised against the Primes model regarding discount rates, technology costs and efficiency assumptions etc. has been addressed in recent years (e.g. by the transparent ASSET project on Primes Inputs). The assumptions on **discount rates** in the baseline scenario are equal to the set of assumptions in the EU Reference Scenario 2016. The discount rates are still very high with levels of 13.5% and 14.75% per year. They cannot be considered as realistic discount rates for households, where a typical rate between 2% and 6% is usually applied. A very high discount

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[4] https://ec.europa.eu/energy/sites/ener/files/documents/2018_06_27_technology_pathways_-_finalreportmain2.pdf

rate leads to high overall costs of energy efficiency measures (including technical building systems) in comparison with other options of decarbonisation (e.g. more RES supply in the power sector) (cf. Navigant study Krabbe et al. (2018), which leads to disparity between sectors.

Main assumptions for technology costs for the Primes modelling can be found in the ASSET report (E3-Modelling et al. 2018). The datasets give an overview of costs and efficiencies/energy savings per technology/measure as average number for the EU28. Based on these datasets, the **renovation costs** per household can be considered as rather low. The level does reflect average costs per household in multi-family houses, but not for a household in a detached single-family house. Energy savings seem to be very high, especially for deep renovation (e.g. northern zone with 87% savings). These levels could be reached only for some very inefficient buildings in stock, but the average savings in stock are much less than 87% and most likely to higher costs. Heating **technology costs** are assumed to increase until 2030 in real terms (EUR`13), but at the same time efficiency improvements are assumed. For heat pumps, a price decrease due to economy of scale effects and efficiency improvements are often assumed at the same time in recent studies. Heating technology costs are only shown as average for the EU28, therefore no distinction is possible. However, it is unclear, if only the heating generator (boiler) is included in the costs, or also heat distribution systems (such as pumps and piping, radiators, underfloor-heating). Technologies are less expensive for the service sector, which makes sense with regard to significant larger sises/capacities of the systems. Costs for appliances seem to be on a reasonable level.

A dedicated **mitigation potential** analysis has not been conducted. The GHG-savings have been input to the model and the most **cost-effective** pathway (as combination of pre-defined energy efficiency options and renewable energy) is been determined (also taking the other boundary conditions regarding the focus of the scenario in to account).

Within the **scope** of the building sector, the model includes all relevant parameters for a calculation with yearly energy balances. But regarding the robustness of an energy system with very high shares of renewable electricity, the energy supply (production and transmission) must be secured for every hour, including cold spells and windless winter weeks. This point is not covered by the model and therefore a weak point. Costs of additional transmission and distribution grid capacity in the electricity scenario ELEC can only be determined with an appropriate level of detail in the energy system modelling. In our view, this level is not given with yearly energy balances. An analysis of the energy system with a high time resolution (at least per hour) would be required to draw robust conclusions with regard to the energy system infrastructure (which has not been done with PRIMES).

2.4 Industry

In addition to the PRIMES scenarios 1.5LIFE and the 1.5TECH, the IDA section on industry includes the results of an alternative industrial mitigation scenario - the Mix95 Scenario based on the bottom-up model FORECAST. This additional scenario is also in line with reaching net-zero GHG emissions in 2050. The FORECAST model has been used to complement PRIMES. As described below, PRIMES follows an integrated energy system approach capturing interactions of industry with other sectors while FORECAST examines the industry sector in more detail, following an technologic specific but isolated approach

Both net-zero scenarios of PRIMES and the one of FORECAST achieve 92% GHG emissions reduction or above compared to 2015. It has been shown that target achievement in industry will require combining best available techniques in energy efficiency and traditional fuel-switching with additional options like innovative low-carbon production technologies, circular economy & material efficiency, low-carbon energy carriers and/or ￼/CCU ￼. The scenarios of the different models are not directly comparable, as two different approaches were followed in order to get complementing results. The technology focus in the industrial sector is placed on:

- Energy efficiency (incremental process improvements)
- Fuel switch/Electrification
- Innovative low carbon processes (radical process improvements)
- Carbon capture and sequestration and or use (CCS and CCU)
- Resource efficiency/economy
- Industrial symbiosis
- Material substitution

The PRIMES scenarios 1.5LIFE and the 1.5TECH were both based on the COMBO Scenario (combination of the most cost-efficient options from ELEC, H2, P2X, EE) including additional measures e.g. higher, carbon prices and the relaxation of the limitations assumed on CCS and the introduction of CCU (for the plastics industry) leading to larger amounts of CO_2 stored. The 1.5LIFE scenario also includes the drivers and assumptions of the circular economy scenario, aiming to achieve a higher resource efficiency. In general, higher levels of ambitions will require deployment of all the options described above, including not yet mature or fully deployed technologies. PRIMES identifies clean gas-based solutions (using hydrogen and e-gas) as preferable for meeting the higher ambition in both scenarios. These solutions are combined with significant investments in CCS to capture process emissions, energy efficiency and circular economy (largest effect of demand reduction in the 1.5LIFE scenario). Total final energy consumption decreases by 22% in the 1.5TECH and 31% in the 1.5LIFE scenario. The scenario with the highest electricity demand in industry in PRIMES is 1.5TECH. The overall electricity demand (all industrial sectors including the production of hydrogen and e-fuels consumed) reaches 4,808 TWh, of which 1,344 TWh is final electricity demand in industry, not related to hydrogen or e-fuel production.

The FORECAST scenario Mix95 has as a starting point today's best available energy efficiency techniques and achieves GHG emissions reduction of 92% compared to 2015 (or equivalently 95% compared to 1990). It is driven mainly by electrification, the use of clean gas (95% of conventional gas is assumed to be replaced by clean gas – H2, synthetic methane) in the gas grid and the combination of increased recycling, energy and material efficiency improvements. CCS is added only in major remaining process emissions (lime, bricks, ceramics, clinker). Steam generation technologies are replaced pre-maturely, there is an increased diffusion of innovative low carbon technologies in steel, chemicals and cement, as well as faster transformation of buildings and transport sectors, reducing the demand for conventional fuels. The latter is assumed to result in the halving of output in refineries compared to all other scenarios. In addition, hydrogen takes an important role as a feedstock. In the Mix 95 scenario electricity consumption reaches 2946 TWh, of which 1539 TWh are directly used and 1407 TWh are needed to produce hydrogen and synthetic methane via electrolysis. CCU is not included on a large scale (only in form of concrete that absorbs CO_2 during curing) due to the assumptions that short product lifetimes would not result in long-term emission reductions or require additional carbon capture at the end of the product use chain. It is discussed in the accompanying material (Fleiter et al. 2019) that CCU might play a role in providing the needed carbon to produce synthetic methane from hydrogen (industrial re-use instead of air-capture) not leading to additional CO_2 mitigation as the CO_2 is released into the atmosphere when the methane is burned.

Table 4: Key input and output data of the In-depth Analysis in the industry sector in 2050

	Baseline 2050	**ELEC, H2, P2X, EE**	**CIRC**	**COMBO**	**1.5TECH**	**1.5LIFE**	**Mix95**
GVA industry [bEUR13]	2665	2665	n.a.	2665	2665	n.a.	2665
% of 2015	*152%*	*152%*	*n.a.*	*152%*	*152%*	*n.a.*	*152%*
CO_2 emissions [$MtCO_2$]	484	205-231	192	176	29	53	62
reduction vs. 2015	*-36%*	*- 70%-73%*	*-75%*	*-77%*	*-96%*	*-93%*	*-92%*
CCS [$MtCO_2$]	0	57-61	44	60	80	71	46
Final energy [Mtoe]	253.5	215-254	222.2	230.7	222.2	196.5	232
reduction vs. 2015	*-11%*	*- 12%-25%*	*-22%*	*-19%*	*-22%*	*-31%*	*-28%**

Source European Commission (EC) (2016b), European Commission (EC) (2018d)

n.a. = not available ; * The energy demand in 2015 slightly differs between the PRIMES and the FORECAST model as the FORECAST model is calibrated on Eurostat Energy Balances for 2015.

2.4.1 Assessment

Overall, the assessment can be considered **robust** and state of the art. The analysis is in accordance with other key publications on industrial decarbonisation thus can be deemed plausible**.** The industry sector modelling has been carried out with the FORECAST and PRIMES modelling tools, which are widely accepted and acknowledged for EU scenarios analysis and impact assessment work.

FORECAST is used to develop long-term scenarios for future energy demand of individual countries and world regions until 2050 (EU28+NO, CH, TR, Brazil, etc.) (Fleiter et al. 2018)[5]. It is based on a bottom-up simulation modelling approach considering the dynamics of technologies and socio-economic drivers. The model allows addressing various research questions related to energy demand including scenarios for the future demand of individual energy carriers like electricity or natural gas, calculating energy saving potentials and the impact on GHG emissions as well as abatement cost curves and ex-ante policy impact assessments. The advantages of this modelling approach are:

- high degree of technological detail: more than 70 industrial production routes (e.g. EAF steel production, BOF steel production, H2 plasma steel production, H2 DR+EAF steel production, DR electrolysis); more than 200 different saving options
- plausible technology and innovation developments/diffusion
- detailed evaluation of policies, technologies

PRIMES provides projections of energy demand, supply, prices, investment covering the entire energy system including emissions on country-level and EU-trade of energy commodities. It is based on a partial-equilibrium approach (considering an equilibrium problem with equilibrium constraints) as well as agents' behaviour. PRIMES focus on prices as a means of balancing demand and supply simultaneously in several markets for energy and emissions. The model allows addressing various research questions for the medium- and long-term energy system

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[5] https://www.forecast-model.eu

development as well as system restructuring. It can be used for the assessment of price signals, such as taxation, subsidies, ETS, technology promoting policies, RES supporting policies (in a simplified form), efficiency promoting policies, environmental policies and technology standards, etc. The advantages of this modelling approach are:

- allows macroeconomic feedback loops when used in combination with GEM-E3
- high consistency (e.g. among sectors and between demand and supply)
- stronger focus on price-based instruments & fiscal policies

In summary, PRIMES follows an energy system approach, capturing the interactions of industry with the parallel developments in the other sectors, notably the energy sector, while FORECAST follows a sector specific bottom-up approach, examining in more detail the industry sector, but isolated from the other sectors.

A dedicated **mitigation potential** analysis by technology has not been carried out. Instead, mitigation technologies, and more tangible decarbonisation options, are discussed more qualitatively in the IDA. For the PRIMES scenarios, the extent to which the different options are implemented is not fully transparent (e.g. diffusion rate of technologies, market shares in 2050 for low-carbon innovations). However, the assessments in the annexes provide sectoral information on the industry transformation pathways, e.g. for iron & steel, chemicals, or pulp & paper, including required decarbonisation options. For the FORECAST scenarios complementary information for the decarbonisation pathways is available providing more details on scenario and sub-sector level results as well as assumptions (e.g. technology costs) (Chan et al. 2019). Similar information is also provided in the annexes of the IDA. The complementary documentation shows which mitigation options by sector have been chosen in order to achieve the shown GHG emission reduction. It also states physical production developments of main energy-intensive products and the market shares of the according low-carbon innovations (e.g. for steel and cement) (Fleiter et al. 2019).

All scenarios assume favorable conditions enabling **cost-effective decarbonisation** including the removal of non-market barriers and successful coordination of actors with different aspirations. The underlying **input and output data** is fully available for the FORECAST scenarios only. However, some key in- and output data for the scenarios is provided also for the PRIMES scenario (see Table 4). A fully informed answer on whether the **modelling** was comprehensive cannot be made as the underlying models are not available in detail. However, given the sound methodology and the accordance of the results with other studies, the modelling can be assumed comprehensive. An outside **peer review** of the analysis was not conducted but the main assumptions were reviewed by experts.

2.5 Transport

Transport is the only sector where emissions have been growing since 1990, mainly due to an increase in transport activity. Various CO_2 mitigation options are available for the transport sector: demand reduction, electrification, the use of biofuels, hydrogen or e-fuels. The scenarios apply a mixture of these mitigation options. The more ambitious net zero scenarios apply both stringent technology targets and demand reduction.

All scenarios assume an overall growth in transport activity from 2015 – 2050 both for passenger and freight transport (see Table 5). In passenger transport, the all decarbonisation scenarios assume a demand reduction for road transport and aviation between 2% and 5% relative to the Baseline in 2050. Only the 1.5LIFE Scenario assumes a strong reduction of 18% in aviation relative to the Baseline in 2050 (59% increase for intra-EU and 70% for extra-EU for

2015–2050 in the 1.5LIFE Scenario compared to the Baseline with 94% growth for intra-EU and 104% for extra-EU for 2015-2050). For freight transport, all scenarios assume an activity growth about 49-53% compared to 2015 by 2050. In all scenarios, this growth of road transport is smaller than in the Baseline Scenario. Furthermore, all decarbonisation scenarios assume a stronger growth of rail and navigation than of cars in transport.

The -80% scenarios (ELEC, H2, P2X, EE, and CIRC) achieve about -70% CO_2 emission reduction until 2050 compared 2015 levels (see Table 5). The net-zero scenarios achieve stronger mitigation of slightly more than 90% until 2050 compared to 2015. In the -80% scenarios, about half of the remaining CO_2 emissions are from aviation and the other half from heavy road transport and cars. In the net-zero scenarios the remaining CO_2 emissions from transport are almost only aviation, probably with a large share of international aviation.

All scenarios show an increased stock share of electric vehicles until 2050, mainly achieved by CO_2 fuel economy targets of varying levels of ambition. In the net zero scenarios, 95% of car stock are battery electric (80%) and fuel cell vehicles (16%). This is in line with other assessments of ambitious CO_2 reduction targets for the transport sector (see e.g. Sims et al. 2014; Bergk et al. 2017) and achieved via a 0 gCO_2/km target for newly sold passenger cars in the EU in 2040: if all newly sold cars in 2040 are zero emission vehicles, a large share of stock will be zero emission vehicles by 2050. In the -80% scenarios, CO_2 standards range from 23 to 16 gCO_2/km in the Worldwide Harmonised Light Vehicle Test Procedure (WLTP) for new cars in 2050. In these -80% scenarios, additional CO_2 reduction from passenger cars is achieved via biofuels and e-fuels.

Throughout the text, a number of policies or instruments to achieve the CO_2 mitigation are described (such as the fuel economy targets mentioned above). The lower growth of transport activity compared to the baseline scenario is assumed to stem from the saturation in car ownership in many EU15 states, and from distance-based road pricing. Rail passenger transport activity is expected to grow faster than in the baseline scenario due to the open passenger rail transport service market and the comple-tion of the TEN-T network by 2050. For freight transport, strong modal shift towards rail are expected to in all scenarios due to (1) pricing that takes into account external costs, (2) "support for multimodal travel information," (3) "policies supporting the Single European Rail area (market and interoperability)", and (4) "digitalisation and automation of rail" (EU COM2018b).

Additionally, the CIRC and 1.5LIFE scenarios rely on strong growth of "the sharing economy and automated mobility, and making full use of digitalisation, automation and mobility as a service (including shared/collective mobility)" (European Commission (EC) 2018d). The latter are not yet policies but point towards technologies that are presently discussed as a potential lever to reduce CO_2 emissions from transport. However, they could also lead to a strong modal shift towards the car (Sperling 2018), with a risk of a rebound of activity. Thus, there are potential conflicts between a shift towards rail and shared autonomous electric vehicles that have to be addressed by actual future policies if net zero emissions are to be achieved. For aviation, no strong additional policies are mentioned but a continuation of efficiency trends. For the 1.5LIFE scenario, the strong decline in aviation growth is attributed to lifestyle changes and not to policies.

Table 5: Key input and output data of the In-depth Analysis in the transport sector in 2050

	Baseline 2050	ELEC, H2, P2X, EE	CIRC	COMBO	1.5TECH	1.5LIFE
Passenger transport distance [Gpkm]	9096	Ca. 8800	8800	8800	8800	6398

	Baseline 2050	ELEC, H2, P2X, EE	CIRC	COMBO	1.5TECH	1.5LIFE
% of 2015	*+35%*	*Ca. +30%*	*+30%*	*+30%*	*+30%*	*-5%*
Freight transport distance [Gtkm]	4137	Ca. 4050	4050	4050	4050	4050
% of 2015	*+53%*	*Ca. +50%*	*+50%*	*+50%*	*+50%*	*+50%*
Fuel standard 2050 [gCO_2/km WLTP]	n.a.	16 (ELEC) – 30 (P2X)	30	n.a.	0	0
CO_2 emissions* [$MtCO_2$]	667	309 (P2X) – 328 (ELEC)	317	257	86	95
% of 2015	*-37%*	*-70%*	*-70%*	*-76%*	*-92%*	*-91%*
thereof intern. aviation	*208*	*155*	*155*	*150*	*76*	*73*
Final energy* [Mtoe]	273	204 (EE) – 247 (P2X)	204	222	197	179
% of 2015	*-24%*	*- 43% (EE) – 31% (P2X)*	*-43%*	*-38%*	*-45%*	*-50%*
thereof intern. aviation	*65*	*60*	*61*	*60*	*59*	*51*

Source: European Commission (EC) (2016b), European Commission (EC) (2018d);
Notes: * including domestic and international aviation but excluding international maritime; n.a. = not available

2.5.1 Assessment

The applied PRIMES-TREMOVE model (Capros und Siskos 2011) consists of two parts, a transport demand model (mode choice for activity) and a technology choice model (technology per mode). Many technology specific assumptions (e.g. battery costs etc.) have to be made. In principle, existing studies on these data are referenced, but which specific scenario, e.g. for battery costs, has been taken from the references remains unclear. Sector coupling between the transport and energy sectors is mentioned as part of the whole PRIMES modelling environment, but the explicit form of the coupling is unclear. For example, the more ambitious scenarios rely on synthetic fuels (e-liquids and e-gas, their share for heavy-duty vehicles (HDV) varying between almost zero and about three quarters of HDV energy demand). It is not clear whether the production cost of the e-fuels are integrated into the transport sector and thus part of the market diffusion decision. Similarly, the cost for hydrogen and fast charging infrastructure for heavy duty vehicles is mentioned but their incorporation into the model remains unclear (yet note that the *availability* of infrastructure is modelling as hindering market diffusion factor).

Overall, the scenario results appear plausible in comparison with other studies (compare again Sims et al. 2014, Bergk et al. 2017): Demand reduction and strong technology shifts are required in transport for strong CO_2 reductions. Furthermore, individual results are motivated throughout the text with specific examples. One interesting finding is that almost all scenarios exhibit a mixture of technologies/mitigation options for road transport including electrification, hydrogen, biofuels and e-liquids (both e-fuels and e-gas) as well as natural gas (for heavy road transport). This could be a consequence of the discrete choice modelling approach that tends to assign a relevant market share to almost all alternatives (if they do not differ too extreme in their properties). However, from an economic perspective, many of these technologies require their own infrastructure and would benefit from economies of scale such that scenarios with a one or few dominating technologies seem more plausible (e.g. an "all-electric world" or an "electricity and hydrogen world"). These additional feedback loops and infrastructure investments require additional attention and analysis.

In heavy duty road transport, both battery electric trucks and electric road systems are mentioned, but not differentiated in the results. Both technologies are in an early stage of the discussion and their joint mention without more details calls into question whether they actually have been modelled explicitly. Both rely on new infrastructure (just as fuel cell HDV do), but the electric road systems would strongly benefit from a joint European infrastructure planning and design since heavy duty road transport is to a large extent transitional. Interestingly, there are hardly any comments on costs for transport in the scenarios. Cost-competitiveness is referred to as challenge for e-fuels, but no specific values are given. Furthermore, the limited potential for sustainable biomass is stated but fuels and synthetic fuels are sometimes discussed interchangeably. Overall, the costs of transport for households and businesses remain unclear.

In aviation, the international aviation is a responsible for a major share of the remaining CO_2 emissions from transport in 2050. Yet, despite an extensive discussion of aviation in the text, it is not clear what actual share of the remaining aviation energy demand or CO_2 emissions stems from domestic European aviation and what from international aviation. The remaining emissions from aviation could be handled by other mechanisms such as voluntary agreements or compensation schemes, for example the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). However, this is not discussed in the text.

2.6 Agriculture

The two major GHGs in agriculture are CH_4 (methane) and N_20 (nitrous oxide), arising primarily from enteric fermentation, management of agricultural soils and manure management (accounting for 95% of non-CO_2 emissions in agriculture). These non-CO_2 emissions cannot be fully eliminated due to biological processes involved and multiple demands on agriculture to produce food/feed and public goods. Thus, the agricultural sector would make up the largest share of remaining GHG emissions in the EU after 2050 in the case of deep decarbonisation. The IDA states that there are still mitigation options associated with the CH_4 and N_20 emissions and avoiding shifting production outside of the EU is important to avoid carbon leakage.

The IDA focuses on supply but also considers the demand perspective. From the supply (production) perspective, two strategies are stressed. The first is to ‘sustainably’ increase agricultural productivity (the amount produced per animal or unit of land) so that less land is used and thus this improves the GHG efficiency and reduces overall emissions of the agricultural system (land sparing, i.e. production is increased on smaller amount of land while area is expanded for sequestration and increase in carbon sinks under LULUCF). The second strategy is to adopt technological options and farm management practices to reduce emissions. While not explicitly stated, these two strategies can be interlinked. For example, integration of N-fixing crops such as legumes in crop rotation reduces the need for fertilisers and thus N_20 emissions, and contributes overall to better soil health.

Actions for soil carbon sequestration are mentioned as important for productivity increases and adaptation, and as complementary to non-CO_2 measures. Agricultural soil management options entail interaction and trade-offs between CH_4, N_20, and C sequestration, although these are not explicitly addressed. ‘Win-win or no-regret’ measures are highlighted as important to implement, but are not specified, and the actions that are emphasised are not clearly win-win measures. Interaction with the demand side is mentioned, primarily in relation to reductions in dairy and meat consumption and food waste, as these are important drivers for agricultural production. The specific mitigation actions emphasised for having the highest cost-effective potentials are:

- Reducing CH_4 from enteric fermentation through selective breeding, improving health and fertility and productivity of animals; or feed management.
- Anaerobic digestion for biogas production and manure storage management.
- Precision farming for nutrient management and nitrification inhibitors; fallowing organic soils or adjusting water levels on organic soils.

In total, the scenarios with mitigation measures on the supply side achieve a reduction of GHG emissions by 37% compared to 2015, while the emissions decrease by only 8% in the Baseline scenario (see Table 6). In the scenario 1.5LIFE, which also includes a change of consumer preferences with regard to diets, the GHG emissions from agriculture are reduced by 48%. The remaining emissions correspond to about 5% of the total GHG emissions of the EU in 1990, showing the magnitude of required negative emissions to reach net-zero GHG emissions.

Table 6: Key input and output data of the In-depth Analysis in the agricultural sector in 2050

	Baseline 2050	ELEC, H2, P2X, EE	CIRC	COMBO	1.5TECH	1.5LIFE
Productive agricultural land (Mha)	162	152 (P2X) – 158 (EE)	151	153	151	131
% of Baseline 2020	*96%*	*93% (P2X) – 96% (EE)*	*92%*	*93%*	*92%*	*80%*
Non-CO_2 emissions [$MtCO_2eq$]	404	277	277	277	277	230
reduction vs. 2015	*-8%*	*- 37%*	*- 37%*	*- 37%*	*- 37%*	*-48%*
thereof methane	*207*		*165*	*165*	*165*	*139*

Source: European Commission (EC) (2018d)

2.6.1 Assessment

In the IDA, the GAINS model used is based on the order of technology uptake when several different technologies can be used to address emissions in a given sector and this is based on the order of the estimated marginal cost of each technology. The GAINS model identifies precision farming, breeding and nitrification inhibitors (so reducing fertiliser use and N_20 emissions) as having the highest potential by 2050. Leaving organic soils fallow do as well, but at higher costs. The EcAMPA III study by JRC is referenced (Domínguez et al. forthcoming) as confirming that measures addressing enteric fermentation and manure management are the most significant reduction options. Cost-effectiveness is considered, but the list of cost-effective measures is limited compared to other studies (for example, inclusion of legumes in crop rotations, legume grass mixtures, loosening of compacted soils). Since cost-effectiveness depends on the options considered, the robustness of the result may be limited (cf. MacLeod et al. 2015, e.g.). This is in line with the clarification in the report "this leads to a fair representation of the mitigation potential and marginal cost at the sector and country level, however, can overstate the potential from the technology with the lowest marginal cost at the technology level." (p. 163).

The list of mitigation options has further limitations. First, the effectiveness of nitrification inhibitors and their potential risks is still a matter of debate in scientific research. In at least some systems and soil types, nitrification inhibitors do not always have a clear mitigation benefit (Scheer et al 2017). They also carry potential, possibly unknown, risks for water ecosystems, and there is a risk of resistance building against the inhibitors, thus rendering them ineffective. These limitations and potential risks are not identified in the report.

Moreover, agro-ecological options are surprisingly not highlighted at all. Most clearly missing is reference to improved crop-rotations (by including crops that contribute to biological N fixation) or improving soil management to reduce soil compaction (thus increasing soil fertility) (Martineau et al. 2016). These agro-ecological practices are also win-win/no-regret measures for adaptation/environmental objectives. Finally, the trade-offs between the proposed options for mitigation and their other impacts are not sufficiently accounted for. For example, the anaerobic digestion of maize as a feedstock can have significant trade-offs with biodiversity as well as potentially negative impacts on water quality, and thus adaptation. Measures to reduce enteric fermentation (breeding, feeding strategies) can also have animal welfare trade-offs.

Instruments to support the implementation of mitigation actions are also not referred to, although the Common Agricultural Policy is mentioned earlier in the document. For example, the role of carbon audits or capacity building and advisory support (beyond purely the development of technological options) is not mentioned at all. It is acknowledged that while it is agreed that there is significant reduction potential of CH_4 and N_20 emissions, there is variation in literature in terms of the potential of individual measures. This is linked in a large part to the heterogeneity of biophysical and climate conditions (especially in relation to soil management) which affect the mitigation potential. There is also no clearly available benchmarking or reference levels on which to judge what are feasible and ambitious emission targets in what geographic area or production system, so it is not clear how the overall target would be broken down to specific geographies or production systems. In this context, reference to the role of management and capacity building (and associated benchmarking and monitoring) is missing in the document, as well as the need to weigh trade-offs in achieving multiple objectives.

A strength of the report is that the demand side is considered by acknowledging the role of reduced consumption of livestock products and 50% reduction in food waste by 2030. The inclusion of consumption is in line with the recommendations from several reports (e.g. Willett et al. 2019, Bajželj et al. 2014) and also the SDGs. It is also assumed that no leakage occurs, in that the decrease in EU animal products does not result in an increase of exports outside of EU. However, PRIMES-GAINS-GLOBIOM modelling considers that uptake of technical mitigation measures occurs in all scenarios, but only the 1.5LIFE scenario assumes a change in consumer preferences. This scenario assumes a shift towards FAO Diet 4 scenario of reduced meat consumption. It is also not clear why this specific diet scenario was selected for and whether it is fully compatible with sustainable diet guidelines (see Willett et al. 2019). The analysis is also lacking in that it does not consider increased seafood consumption (in particular from on land aquaculture) as a lower-emission source of protein (to replace higher emission sources from ruminant livestock). The food system transformation is not mentioned and it is unclear whether the full potential on the demand side is accounted for.

Yield and productivity improvement assumptions are also not properly specified, and it is unclear whether yield stability is considered, for which additional measures for soil management are needed (e.g. increase in soil organic carbon or protecting soil structure to reduce compaction). Focus on maximizing yields neglects to consider the link with yield fluctuations. Stability of yield is important under drought or water scarcity conditions, a situation which will become much more frequent in years to come. For example, long-term field trials comparing conventional and organic farming systems shows in years affected by drought, flooding or low rainfall, the organic systems out-yield conventional systems.[6] Inefficiencies associated with increased productivity are also not considered. While agricultural yield have

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[6] https://rodaleinstitute.org/wp-content/uploads/fst-30-year-report.pdf

increased and food prices have fallen over the last decades, the burden on human health and environmental degradation has been substantial, linked to inefficient use of crops for animal feed and over-consumption of calories by humans (Alexander et al. 2017). Lastly, no reference is made to peer-review of the analysis conducted. It is also not always clear what underlying data was used and how this was matched to official data.

Overall, the analysis points to the key areas where there is clear consensus on mitigation potential (CH4 and N20 emissions), as well as points to the need to address systemic issues of reduced consumption of animal products and food waste. This argumentation reflects broader scientific consensus. However, the analysis of most relevant and appropriate mitigation options within the agricultural systems has important shortcomings as outlined above, in particular in terms of effectiveness, the range of options considered, and their trade-offs. Finally, consideration of policy instruments and more broadly the supporting environment required to ensure uptake of mitigation options is lacking.

2.7 Land-use

Land is a finite resource that has many competing uses including food and feed production, forestry, bioenergy, and increasingly for housing and infrastructures. It can also be an instrument for decarbonisation, and the options for mitigation considered in the IDA include:

- **Preserving carbon from agricultural soils,** especially by limiting the use of organic soil and peatlands for agriculture production and using sustainable agricultural practices with mineral soil to maintain soil organic carbon (SOC) levels.
- **Maintaining forests as a carbon sink,** by afforestation (planting additional forests), reforestation (replanting previous forests), as well as reducing the amount of wood harvested and having cascading uses of this wood.
- **Using land to cultivate biomass to substitute fossil-based equivalents** for materials like timber, bio-based plastics, bio-based chemicals or for bioenergy uses such as biogas, biofuels and power production.

In the scenarios 1.5TECH and 1.5LIFE, mitigation is primarily achieved in the land use change and forestry sector (LULUCF) with forest management, afforestation, and to a lesser extent with biobased chemicals and materials (categorised as “harvested wood products”). It is only in the 1.5TECH Scenario in which mitigation is achieved with the implementation of agricultural practices that improve soil carbon sequestration and shifts cropland from a carbon source to carbon sink by 2050. Overall, the EU is a net carbon sink, with a net balance of -314 $MtCO_2$ in 2016. The 1.5LIFE scenario assumes an increased net carbon sink of -464 $MtCO_2$ in 2050 and only increasing to -317 $MtCO_2$ in 1.5TECH. This is mainly due to a lower financial incentive to enhance the LULUCF sink in the 1.5TECH scenario, which assumes a carbon sink benefit of €30/tCO_2 compared to €80/tCO_2 in the 1.5LIFE scenario. Mitigation is also achieved across several sectors with the use of biomass for energy. Today, power generation and residential heating are the largest uses of bioenergy, but in the scenarios this shifts to power, industry, and transport in 2050. The power sector represents 48% and 62% of the total use of biomass in the 1.5LIFE and 1.5TECH scenarios and 17% and 14% share in industry. Advanced biofuels in road and air transport account for 13% and 22% but are only assumed to be produced at scale starting after 2030.

An alternative low-biomass scenario, 1.5LIFE-LB, was specifically created for the land-use category to demonstrate the possibility of decarbonisation with the limited use of biomass. It models a scenario similar to 1.5LIFE, but with limited biomass use and increased technology use, particularly in the industrial, residential and transport sectors. In this scenario, the 151 Mtoe biomass and waste used in 2015 increases only to 215 Mtoe in 2050, compared to 322 Mtoe in 1.5TECH. Biomass consumption peaks in 2045 for all scenarios and decreases slowly thereafter due to the deployment of other energy carriers (e.g. e-fuels).

Table 7: Key input and output data of the In-depth Analysis in the land use sector in 2050

	Baseline 2050	ELEC, H2, P2X, EE	CIRC	COMBO	1.5TECH	1.5LIFE	1.5LIFE-LB
Forests [Mha]	162	161	161	161	162	174	175
Productive agricultural land [Mha]	162	149-157	149	151	151	131	134
Other[7] [Mha]	45	49-58	57	57	57	65	59
Net LULUCF emissions [$MtCO_2e$]	-236	- 238-263	-292	-248	-338	-460	-477
Biomass + waste [Mtoe]	205	257-311	321	308	322	287	215
Bioenergy [Mtoe]	170	191-219	233	228	252	209	170

Source: European Commission (EC) 2018d

2.7.1 Assessment

One crucial factor that is not sufficiently discussed is the carbon removal rate. Measures such as afforestation and reforestation do not sequester carbon immediately, rather they occur over longer time scales. Although this is recognised in the IDA, it is not discussed how this consideration is incorporated into the model and a removal rate, (e.g. tCO_2/ha/year) is not explicitly stated. If afforestation and reforestation are considered to immediately remove carbon at the moment of implementation in the model, whereas in reality carbon is gradually sequestered as the trees reach maturity, carbon sinks could be over-estimated in 2050 (Searchinger et al. 2018). In the context of the strong use of biomass, more clarity on the carbon removal rate is important, as the LULUCF sector accounts for -464 Mt CO_2e in 2050 for the 1.5LIFE scenario, and without this mitigation measure carbon neutrality would be impossible to achieve.

The share of biomass used for power is higher than would be expected in the scenarios (48 and 62% for 1.5LIFE and 1.5TECH), given that there are many other renewable alternatives such as solar or wind, and other options to balance the grid with, such as batteries or power-to-liquids. It is expected that biomass would instead be prioritised for advanced biofuels in heavy transport or aviation fuels that have fewer alternatives to decarbonise than the power sector. It is both unclear what drives such a large use in the power sector in the IDA. It should also be mentioned that the Commission performed a sensitivity analysis on this by adding another “low-biomass (LIFE-LB)” model, which has somewhat lower overall use of biomass compared to LIFE and TECH, mainly due to reductions in industry, buildings and transport.

To avoid concerns of sustainability of biomass, the scenarios assume that nearly all biomass for bioenergy will be produced within the EU (only 4 to 6% of the solid biomass imported by 2050). This is a reasonable assumption, as in 2016, 92% of solid biomass consumption for bioenergy was produced in the EU (ECOFYS 2019). However, while only 151 Mtoe of biomass and waste

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[7] Other category includes non-productive grassland and shrub, land for energy crops, and land for first generation biofuels.

was consumed for bioenergy in 2015, this more than doubles to 322 Mtoe in 2050 in the 1.5TECH scenario. Feasibility studies quantifying the amount of organic wastes, agricultural residues, forest biomass and cultivated biomass conclude that a range of 143–717 Mtoe can be collected within the EU in 2050 (Faaij 2018). Although 322 Mtoe falls within this range, the higher end of the range reports the technological potential and does not necessarily consider any sustainability criteria. There is a balance that needs to be struck between biomass cultivation for emissions mitigation or sequestration and potential negative impacts on land such as biodiversity, soil quality, land use change and land use competition. Although these concerns are acknowledged in the IDA, land competition is avoided in the model in potentially unrealistic or uncertain ways given the relatively high amount of biomass that will be sourced from the EU.

In both 1.5LIFE and 1.5TECH, lignocellulosic grasses (grown primarily on unproductive grassland and land currently used for first generation biofuels) account for nearly a quarter of biomass feedstock, but with very little explanation for this assumption. The IDA does state that these fast-growing energy crops will have an important role "if not hampered by upfront investment costs or land availability" (SV, p. 181) but it is highly uncertain whether these crops will indeed be commercially viable by 2050. Currently, there are little to no lignocellulosic grasses cultivated in the EU.

Lastly, the availability of 100 Mtoe of municipal solid waste (MSW) and industrial waste for bioenergy due to improved collection is seemingly overestimated. Other models have shown that even in an optimistic scenario, only 23 Mtoe of MSW (not including industrial waste) would be available in the EU in 2050 (Ruiz et al. 2015). The EU has also set ambitions for 2050 to reduce waste generation, implying that this could be a diminishing feedstock in the future.[8] The 2015 baseline in the IDA of waste utilised for bioenergy is also seemingly high at 60 Mtoe. In 2016, a separate report stated that only 10.3 Mtoe of municipal waste was used for bioenergy, meaning approximately 50 Mtoe is from industry, and most industry uses the renewable fraction of waste for energy internally.[20] It is unclear how the 60 Mtoe waste was calculated, and the source for data should be specified.

The PRIMES-GAINS-GLOBIOM models used for the analysis are very robust and are some of the best available to date. The analysis is also thorough in that an additional low-biomass scenario 1.5LIFE-LB was also developed to highlight the implications of a scenario with less biomass use. The IDA, however, did not explore the climate impacts of biomass being imported which is difficult to exclude if biomass demand is assumed to double by 2050 and is thus an important factor to investigate. Diet choice is also not heavily explored despite its substantial effect on land use. The 1.5LIFE scenario is the only scenario to consider food consumption preferences (reduced meat consumption) and its effect on land availability and biomass potential.

The plausibility of this chapter of the IDA is debatable. One of the assumptions of greatest doubt is the large role that energy crops are expected to play for bioenergy. In the scenario 1.5TECH, 29 Mha of land is needed for energy crop cultivation compared to the less than 10 Mha devoted to energy crops today. These are also assumed to primarily be grown on unused grassland, and would only realistically be grown if there were financial incentives to convince farmers to begin cultivating them. This also holds true for the afforestation measures assumed in the scenarios; these would require financial incentives since afforestation is not a profitable measure.

2.8 Negative emissions

Since the net-zero scenarios still have emissions in 2050 that cannot be eliminated such as non-CO_2 emissions from agriculture, negative emissions are necessary to achieve net carbon

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[8] http://ec.europa.eu/environment/waste/target_review.htm

neutrality. This can be done through the creation of natural carbon sinks, as discussed above, or with technical options to remove CO_2 from the atmosphere. The carbon removal technological options (although not all leading to negative emissions) considered within the IDA are:

- **Bioenergy with carbon capture and storage (BECCS) and bioenergy with carbon capture and utilisation,** referring to the use of biomass for energy and subsequent underground storage of CO_2 or usage for synthetic materials and fuels.
- **Direct air carbon capture and storage (DACCS) and direct air carbon capture and utilisation,** which is the filtering of CO_2 from ambient air and subsequent underground storage or utilisation for synthetic materials or fuels.
- **Fossil fuel energy carbon capture and storage,** referring to the use of fossil fuels in power or industry and subsequent underground storage of CO_2 (and not usage as this would not be considered a carbon neutral process, rather a simple delay in emissions).

Although other technological options such as biochar, enhanced weathering, ocean alkalinisation and ocean fertilisation exist, these were not considered in the IDA as they still have uncertainties regarding the effectiveness in sequestering CO_2, environmental impacts, associated costs and scalability. Of these options, biochar could have been included within the model because it has relatively low costs, high scalability and has high technological readiness. The IDA states that the residence time of biochar into soils is likely to be variable and not well known, however other studies prove otherwise and demonstrate that biochar is recalcitrant enough to contribute to negative emission targets this century (Smith et al. 2016).

Table 8: Key input and output data of the In-depth Analysis for carbon removal in 2050

	Baseline 2050	**ELEC, H2, P2X, EE**	**CIRC**	**COMBO**	**1.5TECH**	**1.5LIFE**
LULUCF [$MtCO_2$]	- 236	- 238-263	- 292	- 248	- 317	- 464
CO_2 capture [$MtCO_2$]	5	65-449	52	239	606	281
from biomass	*0*	*4-114*	*5*	*95*	*276*	*84*
from Direct Air Capture	*0*	*0-264*	*0*	*83*	*210*	*123*
from fossil fuels	*5*	*47-71*	*47*	*61*	*120*	*74*
CO_2 storage/utilisation [$MtCO_2$]	5	63-449	52	239	606	281
Geological storage	*5*	*63-77*	*52*	*67*	*298*	*80*
Synthetic fuels	*0*	*0-372*	*0*	*172*	*227*	*154*
Synthetic materials	*0*	*0*	*0*	*0*	*80*	*47*
BECCS [$MtCO_2$]	0	-4-5	-5	-6	-178	-6
Cumulative carbon removal technologies 2015-2050 [$GtCO_2$][9]	-	-	-	-	1.8	0.5

Source: European Commission (EC) 2018d

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[9] The cumulative emission calculations are an approximation based on the figures provided by the EC. These figures were rounded to the nearest 100 Mt, thus the margin of error could be quite large.

The 1.5TECH scenario assumes ambitious carbon removal of 606 $MtCO_2$ in 2050, with nearly 75% of this captured from the power sector (primarily from biomass) and the remainder from industry. The 1.5LIFE scenario assumes much lower carbon capture of 281 $MtCO_2$ in 2050 with very minimal BECCS of 6 $MtCO_2$. The only other scenario capturing emissions of this magnitude is the P2X scenario at 449 $MtCO_2$, due to the need for CO_2 to produce fuels and chemicals. Instead afforestation is used to a greater degree, as reduced meat demand in this scenario allows for more land being available and it is a cheaper option. The scenarios 1.5TECH and 1.5LIFE require larger volumes of technological carbon removal compared to other scenarios; the Baseline and CIRC scenarios for example assume only 5 and 52 $MtCO_2$ of removal (see Table 8).

2.8.1 Assessment

The title of this section in the IDA "towards negative emissions" can be considered misleading in that the section discusses carbon dioxide removal, some of which do indeed lead to negative emissions, but also others that are considered 'merely' carbon neutral and therefore do not lead to net negative emissions, i.e. the removal of CO_2 from the atmosphere. Carbon capture and negative emissions are almost used interchangeably so that it becomes unclear how carbon is being accounted for in the scenarios. Only after dissecting various tables and figures is it apparent that only BECCS is considered as a carbon negative technology. DACCS is considered carbon neutral since all carbon from direct air capture is assumed to be reused for materials or fuels, which eventually degrades in landfills or is combusted in waste incinerators. The term DACCS is misleading then, as no carbon dioxide with this method is stored underground and can be inferred through interpreting the data by comparing Figure 89 and Table 8 and 9 of the IDA. Similar to DACCS, the combustion of fossil fuels and subsequent capture and storage of carbon is also considered carbon neutral rather than negative.

Compared to studies on the geological storage potential for CO_2 in the EU, it seems that underground storage potential is sufficient by far for the IDA (Vangkilde-Pedersen et al. 2009). From Figure 89 of the IDA one can derive that about 298 $MtCO_2$ is geologically sequestered in the TECH scenario in the year 2050. If CCS is scaled up linearly from today's level, the scenario would see around 4.6 $GtCO_2$ being stored cumulatively by 2050. However, the extent to which CCS is deployed pre-2050 in the IDA scenarios is unclear. References to the estimated available CO_2 storage potential in the EU would therefore be suitable in this section of the IDA. For example, the EU GeoCapacity project conservatively estimated that around 177 $GtCO_2$ of storage capacity is available in Europe (Vangkilde-Pedersen et al. 2009). It could be helpful to understand whether only the most cost-efficient storage reservoirs are considered in the IDA, or only ones where the Commission expects public support to be highest.

The 1.5LIFE scenario favours reuse over underground storage; however the reasoning behind this choice is not explained. The difference between underground storage in 1.5TECH is more than threefold greater than in 1.5LIFE. One could speculate that this is related to the general public's greater acceptance of utilisation over underground storage, but permanence also has to be considered. It seems like the Commission covers this aspect by only using direct air capture and non-fossil CO_2 for the production of CO_2-based materials and fuels. The Commission scenarios rely heavily on direct air capture, but whether this will truly be a viable option in the future is a large unknown. Direct air capture currently requires large amounts of energy, which need to be zero-carbon for it to make sense from a climate perspective, and until now only small-scale pilots have been launched. It is unclear whether this energy usage is reflected in the scenario. Scientists have estimated that the cost to capture CO_2 using direct air capture be around \$600/tCO_2 (Socolow et al. 2011), though a recent engineering assessment based on pilot data suggest this could drop to \$100/tCO_2 in the future (Keith et al. 2018). Given the uncertainty around costs and feasibility of large-scale deployment, this is a less robust element of the modelling.

Costs for other carbon dioxide removal methods are presented in ranges. However, the final values used for the modelling are unknown. Figure 88 (p. 188) from the IDA suggests that the likely future costs within the range of costs in literature have been estimated by experts, which does not give the impression that this is underpinned by sound analysis. Other large-scale studies of costs on land-based carbon dioxide removal are not in line with the range. For example, Griscom et al. (2017) show significant amounts of CO_2 can be sequestered at costs below \$10/tCO_2. However, costs for afforestation seem to be estimated too low in the Commission’s modelling when compared to Griscom et al. (2017).

The IDA does not specify which industries the carbon dioxide is being captured from. The report does recognise that the suitability of CCS technology differs across industrial processes”, but it is unclear how this is reflected in the modelling. If no dynamic approach is used to determine costs for carbon capture, the role in the different scenarios may be over- or underestimated.

3 Cross-cutting issues

This section assesses certain issues that are cross-cutting to the sectoral pathways assessed in the preceding section, namely:

- economic development,
- just transition,
- innovation and lifestyle changes,
- resource needs and circular economy as well as
- international dimensions and interaction with SDGs.

Some of these are explicitly addressed in IDA section 5, while other are scattered throughout the IDA. Therefore, detailed references to the IDA are provided within the subsections. The assessment is based on the guiding questions given in Section 1.2, with limited adjustments depending on the individual cross-cutting issue.
Each subsection is structured in the same way: The different aspects of each subject are first summarised and a table highlights opportunities and challenges. The paragraphs labelled assessment then give an evaluation of the subject before a conclusion rounds off.

3.1 Economic development

Only a well-functioning economy can provide the necessary economic resources, foster innovations and stimulate investments to combat climate change. Therefore, the EU LTS devotes several sections to economic development and discusses aspects related to GDP growth and sectoral development, investment and financing or energy supply and energy prices. In less central chapters, the documents also mention co-benefits of decarbonisation with limiting the impacts of climate change. This section presents and assesses these points. Please note that aspects of employment are discussed in Sec. 3.2, which considers questions of a just transition

Consideration in the Commission proposal

Different aspects of economic development are covered in the IDA, most in Sec. 4.10. The following list summarises the different aspects and gives references to the IDA for further reading.

- **Development of GDP:** Macro-economic modelling suggests that in general, the impact of decarbonisation is limited (IDA p. 218). Compared to a baseline of current policy (68% to 71% GDP growth until 2050 compared to 2015), growth until 2050 reaches 1.3% less than the baseline at worst or 2.2% more at best, depending on the model that is used. Scenarios in which the EU achieves net-zero GHG emissions while the rest of the world adheres to national determined contributions (NDCs) submitted to UNFCCC (fragmented action) are contrasted to those in which other countries also achieve targets more ambitious than current NDCs (global action). The scenarios of global action show a slightly stronger increase of 0.8% of GDP in the EU. Those EU member states starting from low GDP show a strong growth under all scenarios (IDA p. 219).
- **Industrial sectors:** Some sectors will be strongly affected by decarbonisation (IDA p. 217–231). The sector of mining and extraction will contract while energy intensive sectors (steel, cement, chemicals) and car manufacture will need to transform (IDA p. 227). In order to do

so, new technologies need to be brought to maturity and rapidly deployed to the market within the coming decade. In general, climate action is seen by the EU LTS as a driver to increase competitiveness. The EU ETS can only supply part of the incentive to invest in low carbon technologies (IDA p. 240).

- **Required investment:** Excluding transport, annual investment in energy technologies and infrastructure average to 2.6% of GDP for the net-zero 1.5LIFE scenario and 3.0% of GDP for 1.5TECH, compared to 2% today (IDA p. 201). This constitutes a large share of current gross fixed capital formation, which is currently close to 20% of GDP, and represents a large shift from consumption to investment from a macro-economic perspective. Depending on the scenario, the required additional annual investments (without transport) compared to the baseline range from 176 billion Euro for 1.5LIFE (15% increase relative to baseline) to 290 billion Euro for 1.5TECH (24% increase, IDA p. 204). These overarching numbers hide the sectoral investment needs, which can be quite different depending on their role in the transition (IDA p. 225), but highlight the potential of changes in lifestyle to reduce investments.
- **Flows of finance:** The finance sector has an important part to play by financing the way to a decarbonised economy and will need to undergo changes in itself. Capital needs to be reoriented towards green and sustainable growth and investments in carbon-intensive industries reduced (IDA p. 235). Sustainability and a long-term perspective need to become part of risk management. This requires increased transparency that needs to be supported by regulatory measures (IDA p. 238). The IDA points out that these are already under development and planned to be ready by 2019.
- **Energy supply:** Energy system costs are expected to peak in 2025 just below 13% of GDP, dropping to 10.5% by 2050 for 1.5LIFE or 12.3% for 1.5TECH (10.0% for baseline, IDA p. 209). On average, fossil fuel imports amounted to 2.5% of GDP between 2005 and 2018. Switching from imported fossil fuels to renewable energy will thus free up significant resources. On the other hand, import dependency may rise for other energy related materials such as lithium, cobalt or graphite (IDA p. 216). The price for a certificate for one ton of CO_2 may increase to as much as 350 Euro (EUR2013) until 2050 for the remaining emissions (IDA p. 210).
- **Social aspects:** Extensively covered in Sec. 3.2, employment skill requirements also influence economic development. Upskilling and reskilling will be necessary in order to meet the requirements for a highly qualified workforce. Changes in employment however are mainly driven by other trends, in particular demographic change, automation and digitalisation (IDA p. 226 ff.).
- **Co-benefits:** Co-benefits of decarbonisation of the economy are discussed but not directly linked to other economic considerations. These include an improved air quality accompanied by health benefits (IDA p. 273) as well as avoiding financial and all other impacts of climate change (IDA p. 281).

Table 9 lists challenges and opportunities related to economic developments for different policy areas. Each policy area can create specific risks or opportunities depending on the way the transformation to decarbonisation is implemented.

Table 9: Challenges and opportunities with regard to economic development as stated in the IDA

Policy area	Challenges	Opportunities
Economic policy	- Shrinking of energy-intensive sectors that do not engage in the transformation, or do not succeed (IDA p. 229).	- New technologies to support decarbonisation increase competitiveness (IDA p. 239 ff.).
Financial policy	- Losses from stranded assets if decarbonisation is not considered (IDA p. 235).	- Strengthen stability by incorporating long-term risks and increasing transparency (IDA p. 237).
Energy policy	- Dependence on other energy related goods will increase (IDA p. 216).	- Reduction of fossil fuel imports frees the corresponding resources (2.5% of GDP; IDA p. 214). - Total energy system costs could fall to 10.5% of GDP by 2050 (1.5LIFE) after peaking at 13% in 2025 (IDA p. 209).
Social policy	- An increasing skill gap may hinder economic development (IDA p.233).	- Reskilling will help master other trends such as automation and digitalisation (IDA p. 226).

Assessment

The IDA covers similar subjects as other studies investigating the effects of decarbonisation on the economic development: development of GDP, investments and employment (discussed in Section 3.2). GDP and employment are analysed in the form of a macro-economic modelling study (three models, two levels of ambition (1.5TECH or ELEC scenario) and two worlds (global or fragmented action)). It is important to remember that real world fluctuations - e.g. caused by trade war or economic crisis - are not captured by macro-economic modelling and are known to cause a much larger uncertainty than the projected GDP gain from decarbonisation. This needs to be taken into consideration when evaluating the small absolute difference to the baseline of roughly 2% in relation to a projected GDP increase of 68 to 71% compared to 2015. In this respect, an inter-scenario comparison could provide additional insight, as in the case of necessary investment. Currently, however, GDP growth has only been analysed for limited set of scenarios, which includes neither 1.5LIFE nor CIRC.

The results for GDP growth are similar to previous studies, which see a slightly positive effect for decarbonisation on GDP (Pollitt et al. 2014, Capros et al. 2014). The same studies also see a positive effect on employment while the IDA points out that the effect of decarbonisation on employment will be dominated by other trends, see Sec. 3.2. The required investment of 2.8% of GDP on average for the 1.5°C scenarios is in a similar as the numbers given by IPCC SR1.5 (they give 2.5% of global GDP in order to reach 1.5°C, IDA p. 201). The social discount rate of 10% used in modelling investments (EU COMM 2016b) is relatively high, also see the discussion in Section 2.1. The analysis of the different sectors (supply, buildings, transport, industry, LULUCF) and the more specific industrial sectors is not re-iterated with macro-economic modelling, as is often the case in scenario studies. This has the drawback that rebounds (e.g. higher activity of the building sector) and synergies (e.g. lower activity of chemical sector due to recycling) are not included.

While the IDA also discusses co-benefits of climate action and improving air quality (IDA p. 274), these numbers are not put in relation with GDP growth or investment, as done e.g. by Bollen et al. 2009. Similarly, co-benefits of mitigation and adaptation to climate change are discussed (IDA p. 278), but this is again not linked back to the macro-economic modelling. Finally, implications for the upcoming multi-annual financial framework (MFF) of the EU for the period 2021-2027 are not addressed, although important to be considered in the long-term strategy development.

Conclusion

Economic development is a central theme in the EU strategy documents. Next to a section clearly devoted to directly related aspects, other points can be found throughout the IDA. The analysis builds on macro-economic modelling studies, which provide data on GDP, employment and investment. Overall, the effect of decarbonisation on GDP is small. The transition requires a considerable increase of investments from 2% of GDP to 2.6% in case of 1.5LIFE and 3.0% in case of 1.5TECH and a corresponding decrease of consumption. These findings are similar to studies in the literature. In this regard, a consideration of implications for the upcoming MFF is lacking.

The sectoral changes and shifts are inevitable in any transformation. The upcoming changes described in the IDA do not compare to transformation that have happened in the past. This might bring in complementary aspects. Co-benefits of decarbonisation with improving air quality and limiting the effects of climate change are discussed, but not put in relation to other considerations of economic development. This is a gap in the analysis of the matter, considering the importance of economic development on the one side and the influence and potential costs of climate change impacts on the other. It is questionable whether the type of economy projected for 2050 by the IDA can be adequately described by our current measures and modelling tools. Since the welfare increase of decarbonisation and the services provided by a climate system similar to todays are not accounted for, the benefits of the transition are likely to exceed those described in the IDA.

3.2 Just transition

The transition required to decarbonise economy will have positive but also adverse effects on different regions and parts of society. In order to assure cohesion in society, it is important to focus on such social and distributional issues and actively manage the transition, which is subsumed under the term just transition in the IDA. The subject of a just transition is covered in several chapters of the IDA and also given room in the SV (Sec. 4). A public consultation performed before the development of the strategic vision also highlighted subjects related to a just transition like affordability of the energy supply or the development of the job market (IDA p. 293). This points out the relevance of this matter for the development of a climate policy for the year 2050.

Consideration in the Commission proposal

The subject of just transition can be grouped into different themes. The following points give a summary of each of the themes, building on the material provided in the IDA.

- **Effects of climate change**: Climate change is seen as imminent and will have numerous effects on Europe (IDA p. 277). In case of less mitigation, a stronger climate response will increase negative effects on the society and economy and raise the need for costly adaptation. Sustainable Development Goals such as the eradication of hunger, poverty and water scarcity may fail to be reached if action is put off (IDA p. 270).

- **Job market:** According to the IDA, the overall GDP increase may be slightly positive (IDA p. 218 and Sec. 3.1). While the transition to a decarbonised economy also affects the job market, this effect is limited. The future labour market will be dominated by other trends such as demographic change, automation and digitalisation (IDA p. 226, p. 234).
- **Sectoral development:** According to the IDA, mining and extraction is the only sector in which the rate of decline in total jobs will exceed the rate of retirement of the currently active employees in the sector. This is contrasted with sectors that will see an increase in demand of workforce like renewable energies, construction and agriculture. Energy intensive industries (steel, cement, chemicals) and the manufacture of vehicles will need to transform (IDA p. 226 ff.). Changes in these sectors affect individuals and regions that depend on these industries.
- **Regional implications:** In general, the European Union has profited from climate policy in the recent past (IDA p. 231). But depending on the main sectoral activities, there will be regions which will need to undertake stronger efforts than others and the IDA shows a regional analysis (IDA p. 232). In addition, rural areas may see a continued outflow of well-trained employees and young people (IDA p. 230). On the other hand, the transformation will create local green jobs, often in rural areas (IDA p. 233) if the local geography has the potential for renewable energies.
- **Skill development:** Accompanied by digitalisation, automation and demographic change, the transformation to a decarbonized economy will change the demand of required skills (IDA p. 226). It will be a challenge to meet the demand of highly qualified workforce. Lifelong learning, upskilling and reskilling will stay necessary in order to mainstream digital, communication as well as science and technology skills (IDA p. 534).
- **Energy prices:** There is a large spread between lower and higher income households and regions when it comes to relative energy expenditure. Already today, lower income households are spending significantly more on energy related expenses. Up to 2030, the energy related expenses will increase to a share of 7.6% of household income on average before dropping to a share of 5.6% in 2050, which is lower than 2005 (IDA p. 212). These costs need to be socially balanced in order to prevent energy poverty and limit the spread (IDA p. 213)
- **Active civil society:** Citizen engagement is a prerequisite for a successful change (IDA p. 252) and consumer choices are an important driver of decarbonisation (IDA p. 45). Both require a certain awareness, which is created by the civil society (IDA p. 290) and supported by state actions like labelling or certain norms (IDA p. 252). State regulations should provide a favorable environment for an active civil society (IDA p. 291).

Table 10 lists challenges and opportunities related to different policy areas in the context of a just transition. Most opportunities turn into their opposite risks if action is missed.

Table 10: Challenges and opportunities with regard to a just transition as stated in the IDA

Policy area	Challenges	Opportunities
Climate policy	- Meeting sustainable development goals related to poverty, hunger or water scarcity (IDA p.270)	- Synergies with sustainable development goals dominate the adaptation to climate change (IDA p. 272)
Economic policy	Leaving regions behind (IDA p. 232) - if main regional sector contracts, esp. mining and extraction - if main regional sector needs to transform, esp. energy intensive and vehicle manufacturing industry	- Positive development of emerging and growing sectors like renewable energies and construction, partly in rural areas (IDA p. 231)
Energy policy	- Energy poverty of lower income households and regions (IDA p. 212)	- Reduction of the share of energy expenses (IDA p. 213)
Social policy	- Exodus of well-trained personnel from rural areas (IDA p. 230)	- Strengthening civil society to increase awareness and independent control (IDA p. 252)
Educational policy	- Reducing the skill gap, which hinders economic requirements (IDA p. 534)	- Reskilling and upskilling to provide required workforce to the job market also fit to meet demographic change, automation and digitalisation (IDA p. 226) - Increased problem awareness of active consumers (IDA p. 290)

Assessment

The data on the development of the GDP and employment rates are taken from macro-economic modelling, using different setups of two models (JRC-GEM3 and E3ME). This is matched up with data from EUROSTAT to derive regional implications. The data on energy prices are taken from the studying the different scenarios by means of the PRIMES and FORECAST models. The IPCC SR1.5 report is used as a reference for the interaction of the sustainable development goals and climate action as well as the relevance of consumer choices. The IDA report cites several studies on the skill gap. However, the results on labor skills are based on a set of scenarios that is even more limited than that used for macro-economic modeling. In particular, no net-zero scenario is covered explicitly.

The nature of a subject like just transition implies that it touches on many different areas and it is therefore self-understood that the information is spread out in the IDA report. Nevertheless, the position in the report could be more prominent. Only if the transition to a decarbonised society is just and transparent will people accept the need to change and adapt their lifestyles to the necessary changes. Only an informed and involved society will demonstrate the capacity to carry such a transition. Therefore, the subject of a just transition ranks equal with changes in technology or supply. While the IDA discusses necessary education to meet the demand in skills for the economic changes, it devotes only a couple of sentences to this more general education.

Since this is the strategy document of the top European authority, it is surely a sign of humbleness to point to the civil society for control and best practice examples as well as awareness raising. Again, this point requires an educated society, which is not independent of state activity. And the European Union itself could also implement measures of self-control and control of the economy. This option is not discussed in the strategy documents.

Conclusion

A multitude of ideas is discussed in the draft EU LTCS documents that fall under just transition. Most room is given to questions related to employment and sectoral economic development as well as skilling the workforce. Shorter chapters discuss the cost of energy in case of a transition and the role of the civil society. The subjects are developed with the help of different approaches, with macro-economic modelling supporting the analysis related to employment questions as well as models for the technology transition and energy prices. In the discussion, the EU LCTS points out challenges as well as opportunities of a just transition.

With respect to the job market, the requirements of future demand have to be anticipated early on and educational training schemes adjusted accordingly. The IDA puts its emphasis on the demand for jobs and employment, not the fact that training will need to be provided mainly by well-informed state actors.

The nature of just transition as a cross-cutting issue implies that it is not necessarily a central theme, but it could be argued that it is as important as technological development. For the transition to be just, a common understanding about the basic approach throughout the society is essential. The IDA sees most of the required action to raise awareness as a task for the civil society, see above. However, government institutions at all levels including the EU Commission need to increase their efforts to continuously reach out to the society, inform and educate people about the background of the measures and listen to their concerns. This question of acceptance cannot be left to the civil society but must be approached pro-actively.

In general, the subject of a just transition is not limited to a discussion within the EU, but also raises questions of fair effort sharing and international solidarity. These subjects are partly covered in Sec. 3.5, which deals with the international dimensions.

3.3 Innovation and lifestyle changes

Implementing the transformation foreseen in the EU LTCS requires the participation of many different parts of society, reaching from research and development over businesses to the individuals. Lifestyle changes, and innovations fostering them, play a central role and constitute an issue cutting across many different sectors, including the transport, food, and energy sectors. By choosing products and services with lower environmental footprints, consumers could effect significantly the environmental sustainability of consumption and production processes. What such lifestyle changes mean specifically for individuals and how they perceive these changes is essential in this context, as individual citizens are generally reluctant to give up any welfare already achieved and many are seeking to increase their well-being. Ongoing technological and social innovation will thus be necessary to develop zero-carbon alternatives that can out-compete older technologies, increasing social welfare and delivering climate benefits. The Commission stresses in its Communication that transitioning to a net-zero GHG economy can only be successful with support from citizens – embracing change and getting engaged – and for that to happen they need to consider this transition to be an improvement to their lives (European Commission (EC) 2018a, S. 22). In this context, the High-level Panel of the European Decarbonisation Pathways Initiative has proposed priority research and innovation actions towards a low carbon economy (EU COMM 2018c).

Consideration in the Commission proposal

Innovation can be split into two aspects, technological innovation and social innovation including lifestyle changes. Both are important drivers for the decarbonisation and there exist significant overlaps and interdependences, thus a clear division is challenging. While technological innovations influence human behaviour, social innovation including lifestyle changes are focused on consumer choices, citizen engagement and cultural progress (IDA p. 45, IDA p. 246). On the other hand, social innovation and lifestyle changes can also drive technological innovation.

In this sence, the EU long-term strategy, innovation and lifestyle changes are most relevant to Scenario 8, which is called "Lifestyle Changes & Circular Economy" (also referred to as 1.5LIFE). The Commission has incorporated a variety of material in its assessment on innovation and lifestyle changes. In some instances, the former references to sources that are closely connected to the EU, such as a report from the European Environmental Agency and a Eurobarometer survey. Other sources include the Food and Agriculture Organization of the United Nations (FAO) and the International Resources Panel.

The former aspects comprise the following sub-items:

- Technological innovation

  Research & Innovation: The EU has multiple research and innovation programs to further solutions for successful lifestyle chances and to support the transition to a low-carbon economy. Socio-economic co-benefits from research and innovation can far exceed the direct impact of a new technology, such as job growth, social innovations and general wealth creation (IDA p. 246). However, the IDA identifies a lack of public and private funding, especially compared to other industrialised countries (IDA p. 247). Nevertheless, several EU funds direct financing towards supporting zero-carbon technology research and other innovation possibilities. The IDA states there is a significant need for more efforts towards research and innovation to support the EU becoming a global leader in zero-carbon technologies and to capitalise on the many possible synergies and co-benefits for the EU as a centre for commerce and industry (IDA p. 250). Examples of innovation support by the EU are funding for research, amongst others through the Horizon 2020 program and public private partnerships enabled through the Knowledge Innovation Community scheme (KIC) and for (regional) development programs. Additional funding will be made available through the newly established Innovation Fund, partly replenished by the ETS to advance technological breakthroughs. At the international level, the EU is part of several innovation initiatives, namely the Clean Energy Ministerial and the Mission Innovation, initiated through engagement at the COP15 and COP21 on the clean energy transition. Additionally, the EU supports the research of the IPCC (IDA p. 249). However, missing from these examples is a clear goal formulated by the EU, what the concrete aim of these innovation initiatives is. In the IDA, the Commission should state what targets could be achieved by taking part in or leading in certain initiatives. Adding specific objectives in innovation could strengthen the process going forward.

  Besides these overarching topics, the Commission considers five specific themes central to technological research and innovation (R&I):

  - Zero-carbon power
  - Electrification
  - Hydrogen, synthetic fuels, and fuel cells
  - Circular, zero-carbon industry
  - Bio-economy, agriculture and forestry

  Under the theme "Zero-carbon power" the Commission comprises the need to develop (further) renewable energy technologies (ranging from mature to less mature technologies), a broad set of smart grid technologies but also completely new technologies such as nuclear fusion (IDA p. 243). The three sub-themes are discussed on an almost equal footing with only limited discussion of the required innovation dynamics and without a clear prioritisation.

The theme "Electrification" is strongly focused on research and development of battery technologies and system integration technologies needed to foster a strong electrification of energy consumption (IDA p. 243/244). Given the limited alternative mitigation options in the end-use sectors, it is important to also support innovation in the electrification of end-use. The respective section, however, does not refer to the electrification of end-use relied on in the sectoral pathways, in particular catenary vehicles and smart charging infrastructure in transport (IDA p. 138), heat pumps in buildings (IDA p. 95) and new electricity-based processes in industry (IDA p. 142).

The theme "Hydrogen, synthetic fuels, and fuel cells" encompasses a broad spectrum of new kinds of fuels, both fully renewable ones but also intermediate fuels such as stem reforming of fossil methane to hydrogen in combination with CCS (IDA p. 244). It addresses the needs to reduce costs and to build up the necessary infrastructure. The section fails to mention the immense scaling required by the pathways, including the great necessity to develop direct air capture (DAC) of carbon due to the lack of other carbon sources (IDA p. 190).

The theme "Circular, zero-carbon industry" (IDA p. 244/245) includes a brief mention of circular-economy and industrial-symbiosis approaches without specific examples and then focuses on CCS and low/zero-carbon production routes, such as direct reduction of iron with hydrogen in the steel sector and the use of wood-concrete in the cement sector. The theme does not discuss the optimisation of cross-cutting technologies such as high-temperature electric boilers.

The theme "Bio-economy, agriculture and forestry" (IDA p. 245) addresses issues like land use management, use of residues, bioenergy and biomaterials. The theme also clearly points out the link to the required behavioural changes, in particular with regard to food habits and diets. While the need to achieve negative emissions additional to emission reductions is clearly pointed out in the sectoral pathways (IDA p. 187/188), some of the most relevant negative emissions technologies additional to CCS such as biochar and enhanced weathering are not mentioned under this theme.

Digitalisation: The Commission sees advances in digitalisation as strong enabling factors for behavioural changes, as are breakthroughs in information and communication technologies, artificial intelligence and biotechnology (SV, p. 6). Digitalisation can be a cross-sectoral driver for innovative technologies and process optimisations. Digitalisation can also enable significant social innovation, with the Commission seeing important co-benefits to the technological and social changes that digitalisation makes possible.

► Social Innovation and Lifestyle changes

Lifestyle changes can contribute to addressing sustainability challenges in several areas. These areas include consumer choices like food consumption, modes of transport but also general awareness of consumers for climate impacts. While lifestyle change is most specifically connected to individual behavioural change, both societal change and consumer rights play significant roles in facilitating such changes.

Conscious consumers & social acceptance: The EU Commission sees a trend toward more awareness and awareness-driven behaviour in consumers (changing their consumption patterns) and citizens￼ (social acceptance). An example of this would be the trend toward increased energy efficiency and energy savings in households as well as the growth of cycling as a mode of transport. In addition, awareness has grown that such trends can also yield co-benefits, predominantly in health improvement (IDA p.38). While the Commission outlines clearly that information can be a driver for behavioural change, it emphasizes that the transition can only be successful if there are adequate economic and fiscal incentives for consumers in place. This leads to a crucial point made by the Commission towards awareness for the transition: acceptance. A recurring theme by the Commission is that the uptake of innovative solutions depends on their societal and individual acceptability, in which ease of use plays a key role (IDA p. 107).

Transport: Shifts in the mode of transport are crucial to the transition, especially the shift from low-occupancy, individualised, fossil-fuel based mobility to higher-occupancy, shared and low-carbon modes of transport. Approaches to transport are highly dependent on their context: increased walking, cycling and multi-modal public transport are feasible in urban areas, while long-distance travel can be reduced by digitalisation and made more carbon-efficient. Vehicle automation is advancing rapidly but the Commission points out that if not managed well, self-driving vehicles could actually increase traffic and congestion (IDA p. 110). The Commission looks at consumer choices in transport as a combination of lifestyle changes and uptake of technological innovations, which are each significantly affected by planning, policy choices and the comparative cost of transport modes. Addressing all these aspects in an integrated way can drive emission reductions.

Dietary choices: The Commission calculated five different diets, with variation in the consumption of several meat, milk and egg products, along with what the CO_2 reductions would be in different target years (e.g. for 2050, a reduction of 34 $MtCO_2eq$ for Diet 1 compared to 110 $MtCO_2eq$ for Diet 5). The Commission did not include a possible shift towards increased consumption of products coming from the seas, oceans and freshwater resources. As in the transport sector, the Commission sees the need for technological innovation and lifestyle change as two separate issues within the sector, which combined can yield the needed effect on mitigation (IDA p. 163–167).

Circular economy: The concept of circular economy is its own cross-cutting issue (see Section 3.4), yet it is also part of technological and social innovation. Digitalisation can facilitate the transition to a more circular economy and also foster sharing-economy innovations that makes more efficient use of space, equipment and appliances by companies and households (IDA p. 98).

Future innovation-related changes contain both challenges and opportunities for the EU. Table 11 below shows the main challenges and opportunities referenced in the EU LTS for both technological and social innovation.

Table 11: Challenges and opportunities with regard to innovation as stated in the IDA

Policy area	Challenges	Opportunity
Technological innovation	- Lock-in into a technology pathway (IDA p. 250) - Rebound effects lead to increased demand, offsetting efficiency gains (IDA p. 240)	- Replace old technologies with more efficient technologies (IDA p. 250) - Decrease material inputs (IDA p. 252) - Diversify decarbonisation pathways (IDA p. 250) - Support social innovations (IDA p.246)

Policy area	Challenges	Opportunity
Social Innovation	- Consumers unable to make informed decisions and subsequent sustainable consumer choice (IDA p. 253) - Lack of citizen acceptance (IDA p. 253)	- Raise awareness for the issue (IDA p. 253) - Create new markets (IDA p. 240) - Realise health co-benefits, e.g. through cycling and nutritious diets (IDA p. 253, IDA p. 164)

Assessment

The Commission underlines the role of civil society and citizens, and states that consumer choice will increasingly complement technological change and even be a prerequisite for this change to take place (IDA p. 45). For most sectors, the Commission does not provide many details on how changes in policy can induce innovation and lifestyle changes. For instance, regarding final energy consumption, the Commission notes that "[...] only 1.5LIFE has higher reductions than EE (47%) as it builds on all technology solutions but also couples them with consumer choice that further reduces energy demand" (IDA p. 70). However, the Commission fails to provide a concrete explanation on what this behavioral change could look like, and what incentives could support consumers to making climate conscious choices. This casts doubt over the feasibility of achieving the emission reductions that are being attributed to behavioural change.

An issue acknowledged by the Commission is the potential of sector coupling and related change in behavior. Innovations like digitalisation can change the use of appliances (by individuals) in households or the use of mobility. However, this is closely related to the technological innovation needed to have the infrastructure available, such as charging stations for e-mobility. Yet while these innovations are in principle available, the Commission raises the possibility of societal rejection of certain changes, such as a perception that the transition is creating social hardships (e.g. if electric mobility changes the structure of the automobile industry and renders existing jobs redundant), as a clear barrier to a successful decarbonisation (IDA p. 110). However, the Commission does not deal in more detail with the related disruptive transitions, which will come about with such an ambitious transformation of the economy in any case.

The Commission rightly identifies the essential role that technological research and innovation will have when coming up with low-carbon solutions that could out-compete existing technologies. Complementing this, social innovation also needs to be understood and fostered, embedded in a rich understanding of socio-economic issues and climate science. The Commission emphasises the need for a portfolio approach to innovation, as it is not possible to foresee exactly how technological, economic and social dynamics will interact in determining which set of innovations will see broad uptake (IDA pp. 241–242). Entirely new business models, not yet conceived of, could also play a role. The Commission emphasises that low-carbon innovation will be important for the EU's ongoing economic competitiveness in the context of climate change, with an opportunity for global market leadership in developing and selling low-carbon technologies. The Commission points to a need for coordinating the efforts of EU R&I funding, addressing the entire innovation chain (from basic research all the way through market upscaling), and effectively incentivizing the private sector to pursue low-carbon innovations (IDA p. 250). However, the Commission does not derive any implications for the upcoming multi-annual financial framework (MFF) for 2021-2027.

The development of new markets through technological and social innovation such as digitalisation and more sustainable consumption patterns is seen as a significant opportunity by the Commission (IDA p. 37). Along with an increased awareness of consumers, the Commission places some responsibility of the transition on citizens, communities and local authorities.

Consumers are seen to be crucial to the success of the transition. Not only in the acceptance of changes in the economy and society, but as drivers of said change (IDA p. 38).

The statements on the required technological innovations remain rather vague, as they focus on research and development, but only partly address the necessary diffusion of new technologies, which is a major aspect of innovation dynamics. In particular, all five technological themes do not address the scale of innovation, which is huge in a lot cases, e.g. with regard to the necessary upscaling of electrolysis and negative-emission technologies. With regard to research and development (IDA p. 243ff), the themes also fail to differentiate the level of maturity of technologies, e.g. based on TRLs. Accordingly, few concrete approaches of how to tackle the innovation challenges are provided.

For a successful delivery on the SV, the Commission encourages a stronger interaction of companies and civil society. The Commission places responsibility on both business and civil society. Business needs to increase its transparency, increase its uptake of low-carbon technologies and make investments into financing the transition, while civil society empowered by public authorities needs to raise awareness and acceptance (IDA p. 291). At the same time, the Commission places responsibility, yet no specific call for action, on policy makers to set the right incentives. The Commission clearly states that well-designed policy intervention by national governments is necessary to steer consumer behaviour (IDA p. 109). While the Commission acknowledges that a wide range of stakeholders need to play a crucial part in lifestyle changes, not only consumers and citizens, the documents do not contain a specific proposal for how the actions of these groups can be better aligned (IDA p. 109).

The Commission does specify that labelling and standards and economic incentives could help drive lifestyle changes. The Commission identifies lack of information as a key barrier, and states that so-called “soft” measures, such as information and campaigns and labelling programs can help to solve this issue (IDA p. 253). In addition, introducing standards and norms (“hard” measures) also contributes, as well as economic and fiscal instruments, to overcome hurdles. The goal for 2050 is to ensure that consumers are better informed and profit economically from choosing low-carbon alternatives, simultaneously increasing welfare for all (IDA p. 254). The Commission points to several funding programs to further the implementation of labels and standards (IDA p. 252).

Conclusion

While the individual sections of the IDA on innovation and lifestyle changes are brief, the topics are of relevance and importance in many other parts, with a particularly high relevance for the 1.5LIFE scenario. The Commission document states clearly that lifestyle changes must be supplemented by technological innovation to reach the scale of transition needed to achieve the net-zero emission target. While many examples are given by the Commission for specific technologies and more sustainable options for consumers, it lacks a concrete concept for changes towards sustainable lifestyles. The Commission only touches on transitions for consumers and does not specify how to make the behavioral change last, other than emphasizing the ongoing importance of consumer acceptance. Policies for better and widely available information on zero-carbon consumption and possible economic benefits should not be prolonged into the future, rather it should be addressed in the short-term and thus also specifically outlined as a standard in the IDA. Moreover, near-term implications for the upcoming MFF are to be considered.

Considering that innovation and lifestyle changes are seen as a prerequisite for the EU to achieve net-zero GHG emissions by 2050, the Commission does not sufficiently substantiate these issues in the IDA. Additional information on how to drive social innovation and lifestyle changes could increase confidence in the viability of this option for deepened decarbonization.

3.4 Resource needs and circular economy

The global demand for raw materials is continuously increasing, mainly due to global trends such as population growth, urbanisation, the rapid development of a global middle class and the advance of mega-trends such as digitalisation. According to OECD estimates, the global material use (including biomass, fossil energy carriers, metals, and non-metallic minerals) could almost double from 89 Gt in 2017 to 167 Gt in 2060 under current trends (￼(OECD 2019)s could be emitted. Thus, the sustainable use of resources is widely considered a crucial contribution to the emission reductions required by the Paris Agreement, and would also support cost-efficient climate mitigation efforts (see e.g. ￼UNEP 2017Issues around sustainable use of natural resources are mainly addressed in current EU policy through the concept of the Circular Economy (CE), which integrates sustainable and efficient use of resource with value-preservation and circular approaches along the entire value chain of products in a life-cycle perspective. The CE concept is already being actively pursued in existing EU policy.[10]

Consideration in the Commission proposal

The IDA refers mainly to the concept of "*circular economy*". In its analysis, the IDA understands the CE concept as an economic model in which "raw materials are sourced sustainably and used for production more efficiently, taking into consideration from the product design phase the use, repair, disassembly, remanufacturing and reuse of the products." (IDA p.378). Overall, the IDA considers the effect of a CE transition on GHG emissions chiefly in two separate areas:

- **The Circular Economy transition itself provides significant opportunities for GHG emission reduction:** The transition to a circular Economy e.g. through increased recycling and re-use, innovative product design and business models that extend product lifetime, and cascading use of materials and material substitution, can bring about significant GHG emissions reductions. For plastics, for instance, the potential annual energy savings from recycling all global plastic waste is estimated to be the equivalent to 3.5 billion barrels of oil per year (IDA p. 145). The IDA considers circular economy also a key mitigation option. It constitutes the guiding principle of one of the applied scenarios (CIRC), namely the one in which GHG emissions reduction are driven by measures outside the energy system (IDA p. 321). Moreover, in combination with energy efficiency and lifestyle changes, the circular economy concept is a key pillar to one of the two net-zero scenarios (1.5LIFE). Regarding climate mitigation contribution, IDA presents the impact of circular economy as predominantly relevant for the industrial sector, even though it is also deemed beneficial for the transport sector (IDA p.322).
- **Security of access to raw materials required for decarbonisation and low-carbon technologies:** The transformation of Europe's industry to net zero emissions implies the replacement of its dependency on fossil fuels with one on non-energy raw materials, which are required for decarbonisation. Many of these materials, for instance those needed for

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[10] In December 2015, the European Commission tabled an EU Action Plan for the Circular Economy and several proposals to amend waste-related Directives. The Action Plan, which lies at the interphase between environmental policy (e.g. waste and pollution) and production policy (e.g. recycling and new materials), focuses on steps leading to a transition in the economy towards more circularity. At the same time, it aims at boosting its Europe's global competitiveness, fostering sustainable economic growth and generating new jobs. The Circular Economy is seen as a key means to alleviate resource constraints (by reducing dependence on virgin resources and increasing availability of secondary resources), achieve cost savings (through resource efficiency approaches), create opportunities for business models as well as job creation and thus will help boosting competitiveness of the EU economy.

electric storage batteries, are sourced from outside Europe. The rapid uptake of such technologies globally will increase demand for and hence also competition for resources. Thus, EU's industries and businesses may face fiercer competition on global raw materials markets (IDA p.257). Therefore, in order to improve security of access to needed resources for achieving net-zero emissions, fostering a transition to a more circular economy is deemed highly relevant. A circular economy can help reducing the demand for primary raw materials and increasing the availability and demand for recycled, secondary materials that are part of the currently existing stocks within the EU. In that sense, the contribution to increasing the security of access to raw materials is not directly the underlying reason for fostering a circular economy, but it increases the relevance of doing so (IDA p. 265).

The EU long-term vision focuses predominantly on the opportunities that the circular economy provides for dealing with challenges that climate change mitigation faces. For example, fostering secondary resource markets and a more efficient use of resources can both help reduce import dependencies for certain raw materials and save costs, which could help offsetting costs that industry faces for reducing emissions. However, the challenges or risks directly related to the implementation of this transition to a circular economy have been assessed only to a limited extent. Table 12 below presents a summary of the main challenges and opportunities referenced in the IDA, structured according to the two main areas stated above.

Table 12: Challenges and opportunities with regard to resource needs and circular economy as stated in the IDA

Policy area	Challenge	Opportunity
Security of access to raw materials	- Secondary production for most of the raw materials needed in renewable energies or high-tech applications only represents a marginal contribution in meeting fast growing materials demand (IDA p. 259). - An increasing complexity in the composition of products (e.g. electronics) and the significant amounts of waste and scrap containing potentially recyclable, valuable materials that is exported outside of the EU. (IDA p.381)	- The circularity of metals and recycling of raw materials from low carbon technologies is considered an integral part of the low carbon transition. (IDA p.259) - A circular economy would increase the availability of raw materials for energy- and material-intensive industries that will manufacture key technologies for decarbonisation, such as cobalt and li-ion for batteries or rare earths for wind turbines. (IDA p. 244)
Circular Economy transition itself	- A very ambitious CE approach would require significant behavioural changes and deep business model transformation. Moreover, any level of ambition will require a relevant level of changes to the regulatory framework and significant investment and innovation (IDA p.380)	- Increased product efficiency and circular business models can reduce emissions in heavy industry by up to 60% in 2050 compared to 1990 (IDA, p.376). - Circular economy is considered a big opportunity to create new markets, new technologies and new synergies. Next to improving waste management and reducing primary raw material requirements, a more ambitious circular economy approach could bring additional changes in the current supply chains, utilisation patterns and product design, which would bring about large emission reductions cost-effectively. (IDA p. 380)

Assessment

With regard to the literature sources used, the IDA uses findings of leading organisations active in research on the circular economy and/or at the interphase between circular economy and climate action, such as UN Environment's International Resource Panel, the OECD, Material Economics, the Ellen McArthur Foundation, the VDI Centre for Resource Efficiency, and the European Commission itself.

The IDA deals with circular economy in relation to climate change mitigation in a comprehensive way and relates to the concept in almost all of its parts, thereby acknowledging its relevance for many sectors and also cross-cutting issues. For technical reasons, the IDA considers effects of a circular economy (including resource efficiency issues) only in the scenarios CIRC and 1.5LIFE (IDA p.325). A reduction in resource intensity, understood as the resource input (in physical units) per (monetary) unit of economic output (IDA p.322) was thus considered only in these two scenarios (IDA p.325). The main drivers considered for the CIRC scenario, which seem related to a more general concept of resource and material efficiency, are: recycling and re-use, product and process innovation, improved waste management cascading use of materials and material substitution (IDA, p.321–322). The 1.5LIFE scenario also includes the drivers and assumptions of the CIRC scenario and expands them with lifestyle changes towards less carbon intensive food and mobility choices (IDA, p.326).

However, it becomes evident that the analysis was not meant to take into account potential risks and challenges in a comprehensive manner. This shows, for instance, the fact that possible rebound effects, i.e. the potential increase in resource use or in resource and carbon intensive activities deriving from monetary savings by increasing efficiency (i.e. reducing resource intensity) of products and processes, are not considered explicitly in this context. Neither in the CIRC or the 1.5LIFE scenario nor in other parts dealing with circular economy does the IDA refer to the potential risk of rebound-effects related to resource efficiency. They are only mentioned in the context of (i) vehicle automation (IDA p. 110), (ii) agricultural production (IDA p. 163) and deep decarbonisation (IDA p. 242), where innovations and increased efficiency may lead to expanding production and/or use. Furthermore, the IDA does not thoroughly discuss potential solutions to identified challenges for a circular economy, for instance regarding the problems of recycling rare earth metals and their successful supply as secondary materials due to technical (obtaining and extracting rare earth metals from recyclables) and economic (mostly low prices for primary metals on global markets) issues.

Thus, as a particularly important cross-cutting and also nexus issue, circular economy opportunities might be better presented as a sub-chapter in its own right, to draw its many climate mitigation-related benefits, but also potential rebound-related risks together in one place. While this certainly is a matter of priority setting by the Commission, dealing with the Circular Economy's potential effects on climate mitigation would go in line with the increasing relevance that the CE is having as a policy field at EU level on the one hand and with the emerging climate-energy-resource nexus-thinking that not least the UNEP's International Resource Panel actively promotes. The IDA includes various references to it, but these are spread across the document and only the sector industry has a specific part dedicated to it. Furthermore, the IDA appears to be considering the GHG emission reduction potential of a circular economy as most relevant in the industrial sector and in relation to reducing energy need/use in industrial processes (see for instance in relation to energy supply, p. 67, as well as p. 144 – 158). Nonetheless, further GHG emission reduction benefits of a circular economy are mentioned in relation to mobility, stemming from shared mobility. Thus, putting all potential benefits and risks for climate mitigation arising from a circular economy in one stand-alone sub-chapter could also enhance visibility of this concept's climate protection relevance.

Conclusion

The EU LCTS integrates the concept of a circular economy as a key emission reduction option in its vision for an EU with net-zero GHG emissions. It portrays the two key contributions of circular economy to climate mitigation in a balanced way, i.e. highlighting that a circular economy helps both in enhancing and securing supply of crucial raw materials for decarbonisation, as well as in reducing energy need/use in production and consumption processes. However, potential rebound-effects arising from resource efficiency gains in a circular economy are mostly absent from the IDA. Presenting the circular economy concept in a dedicated sub-chapter would help understand how a fuller picture of its climate mitigation potential in (agricultural, industrial) production and (energy, mobility, material) consumption, as well as its risks (rebound-effects, establishing functioning secondary raw material markets) look like. Lastly, this would also enhance the visibility and understanding of circular economy's relevance for achieving net-zero emissions.

3.5 International dimensions and interaction with SDGs

An EU long-term strategy needs to include an international dimension for a variety of reasons. Climate change itself is a global challenge. The international community is trying to tackle it under the joint framework of the Paris Agreement, and the EU seeks to deliver on its commitments under this treaty. The EU has also made other relevant commitments under a range of treaties and international agreements that could be affected, the achievement of the Sustainable Development Goals (SDGs) being a central one of these. Furthermore, the EU's economy is interwoven globally with many trading partners for both imports and exports and depends on these relationships, which could affect the transformation and be affected by it. Additionally, the EU and especially some of the Member States are also closely entangled with countries outside the EU on international security issues, which may also be influenced and need to be considered. In the IDA the Commission dedicates a subsection to each, the international dimension (IDA p. 254) and the SDGs (IDA p. 270), yet both, and especially the international dimension, are reoccurring issues throughout the IDA. Especially on economic and security considerations within different sectors, the Commission takes international developments and partnerships into account.

Consideration in the Commission proposal

The Commission proposal for an EU long-term vision references international components within several areas affected by climate aspects.

- **Economy:** The dependencies on international markets and international competition are considered as important issues by the strategy. Competitiveness of European businesses, availability and accessibility of resources and exports are listed as key considerations under the decarbonisation scenarios of the EU LTS. Relevant parameters include trade, changes in markets and changes in technologies (IDA p. 260–267). The Commission seeks the EU to become the global leader in the transition and its low-carbon technologies (IDA p. 261). International trade and trade agreements should not prevent climate action in the EU, but in contrast the latter should be integrated into world trade. The Commission sees the opportunity for several instruments, such as border taxes, to ensure a level playing field for the European economy (IDA p. 262).

- **Security:** The security aspects considered by the Commission focus on three issues: geopolitical stability, security of supply of energy and raw materials as well as security of critical energy infrastructure and investments (IDA p. 254–260). A significant driver of geopolitical instability are the impacts of climate changes worldwide. The Commission considers the risk of disasters, diseases and conflict as significant and strives in turn to increase international collaboration, for example on developing long-term strategies to address climate change. It is acknowledged by the Commission that geopolitical shifts can uncover new challenges and dependencies, yet also opportunities (IDA p. 254–255). As part of diversifying collaboration with other countries, the Commission aims at securing the supply of raw materials throughout the transition to a low-carbon economy (IDA p. 255–259). Competition for raw materials could intensify due to the industrialisation of other countries. A major challenge in the transition is the transformation of the energy sector. Energy systems in the EU have to stay reliable for the industry, thus the infrastructure has to be kept secure. The Commission raises concerns not only about possible issues in the transformation between different energy sources, but also regarding threats of cross-border issues, cybersecurity and foreign direct investments. In some cases, foreign direct investments can lead to adverse influence on national politics and the economy (IDA p. 259–260).

- **Environmental issues:** The Commission acknowledges that environmental safeguards in third countries, for example in the extraction of raw materials, are significantly less strict and can therefore lead to hazards. Thus the Commission states that sustainability standards are needed internationally to prevent the decarbonisation from having adverse effect on the environment (IDA p. 259). Additional environmental standards could in turn lead to an increase in costs of resources (IDA p. 258). Adaptation is also considered under international environmental aspects. A direct link between adaptation and social impacts is seen by decreasing migration through increased adaptation measures (IDA p. 286).

- **International agreements and collaboration:** The Commission includes overarching considerations of international collaboration and sustainable development. It reinforces the EU’s commitments to international obligations, not only in the climate, environmental and social policy as agreed to in the Paris Agreement and the SDGs, but also its obligation to the WTO and under trade agreements. The contrasts of these areas to one another are discussed in a few instances only (IDA p. 13, p. 262–266, p. 270). The Commission underlines that upholding international agreements and establishing international regulatory frameworks are key to successfully tackling climate change globally and to implementing the net zero vision. The documents underscore that cross-border challenges (including those that arise in a world working towards climate action) can only be tackled in collaboration, whether this refers to markets, energy systems, innovation and digitalisation or other areas. In this context, the Commission reinforces the importance of transparency and of common standards to facilitate collaboration (IDA p. 262–267). Research is mentioned as another area in which collaboration can support international collaboration and sustainable development pathways (IDA p. 267).

- **SDGs:** The IDA refers directly to SDG 13 “Climate Action” and to SDG 7 ("Clean and Affordable Energy"). However, the Commission states that climate change directly or indirectly influences all SDGs, thus it also directly and indirectly addresses all SDGs. The Commission expects a clear positive impact on achieving the SDGs from the implementation of the 2050 vision. The clearest impact is expected in the environmental area, yet many indirect social benefits are expected (IDA p. 270–273). It mentions the co-benefits that could be achieved from connecting climate mitigation policies with health policies and local level quality of life improvements (IDA p. 271). Accordingly, the Commission underlines the importance of international collaboration and transnational partnerships to seize these opportunities (IDA p. 254).

- **Social issues:** The international dimension of the social aspects is closely interlinked with the SDGs. Support of the SDGs will lead to social benefits in many areas, such as poverty and gender issues (IDA p. 271–273). As one point, not directly linked to the SDG's, the Commission expects a drop in the pressure on people to migrate, if the global temperature levels are kept at 1.5°C (IDA p. 286).

The international dimension in the IDA addresses many challenges yet also significant opportunities to the wellbeing of the citizens in the EU. Some issues are equally a challenge and an opportunity. Table 13 below captures the main challenges and opportunities referenced in the EU strategic vision, per main topic area.

Table 13: Challenges and opportunities with regard to international dimensions in the IDA

Policy area	Challenges	Opportunity
Economy	- risk of losing competitiveness due to increasing cost of resources or through a carbon price, yet also a risk of losing competitiveness by inaction (IDA p. 255, p. 263)	- potential for the EU to become a global leader in low-carbon technologies (and services) (IDA p. 261) - jobs growth, economic growth and growth in investments in Europe (p. 261)
Security	- resource conflicts, poverty and terrorism (IDA p. 254) - international influence on the EU economy, politics and society by Foreign direct investments (FDI)/foreign investors (IDA p. 260)	- collaboration opportunities with other countries to increase the quality of international responses to conflicts (IDA p. 267–270)
Environmental issues	- economic setbacks, such as loss of competitiveness through an increase in cost of resources (IDA p. 257) - environmental hazards due to less strict environmental safeguards in third countries (IDA 258)	- reduction of economic, security and social risks internationally (IDA p. 286)
International agreements / collaborations	- obstacles in international agreements and collaboration such as with the WTO, if certain policies would be implemented, yet it is not seen as a clear barrier (IDA p. 263) - New collaborations can also lead to new dependencies (p. 255)	- participation in international agreements (IDA p. 262–263) - new collaborations on several areas related to climate protection with the potential for new trade opportunities (IDA p. 262–270)
SDGs	- poverty, hunger and water shortages could significantly increase through the adverse effects of climate change (IDA p. 271–273)	- potential for both synergies in air quality, health benefits, multiple economic and social benefits, distributional effects on income and energy poverty alleviation,

Policy area	Challenges	Opportunity
		circular economy, cleaner land and water, and healthier oceans, indirect impacts on life on land and gender (IDA p. 271–271)
Social issues	- not mentioned	- reduction in migration (indirect), thus leading to reduced pressure on migration policies (IDA p. 286)

Assessment

The Commission has considered a broad range of sources and material to support its statements and predictions describing the international impacts of ambitious EU climate action. In the selection of resources, the Commission has focused on large, well-established organisations. On trade and economic issues, the EU vision refers to analyses from the OECD and the IEA as well as the WTO. In relation to climate mitigation and adaptation, the Paris Agreement and the IPCC Special Report on 1.5 Degrees are cited as the basis for the Commission’s arguments. Furthermore, the Commission has built on expertise from the different bodies of the UN, the World Bank, the International Resource Panel and the World Energy Outlook (WEO) for information on resources, third countries and the SDGs. Yet the IDA also includes scientific articles published in well-known journals, as source material to support the Commissions arguments across the topics of the international dimension (IDA p. 267–273).

The international linkages and implications are a recurring theme throughout the EU long-term vision and they are addressed also in dedicated sections of the documents (IDA p. 254–270). Many aspects relevant in this context, such as impacts on the global economic competition or impacts of weather extremes (also on supply chains), are, however, often primarily looked at through an EU lens and not from a global perspective. A eurocentric view is a logical starting point, yet the Commission could deepen the understanding of developments in the world affecting the EU with a more global view.

Stability and growth are key objectives for the Commission towards a net-zero economy and, accordingly, the consideration of policies affecting other countries and regions outside the EU are aligned strictly with these two key objectives. Economic and security issues are thus at the heart of the Commissions assessment of the international dimension. Potential positive impacts are identified also (e.g. how economic benefits of climate action, also outside of the EU, could reduce the threat of conflict) (IDA p. 254, p. 263).

In the IDA the Commission considers also (potential changes to) future relations with third countries (IDA p. 267–270). In this context, the EU vision is concerned with future trade agreements and leadership roles globally. The Commission stresses the need to work in particular with major economies, especially in forums such as the G20, to create a level playing field and an international regulatory framework to ensure that climate action does not create negative economic impacts (IDA p. 268). For low-income countries, the Commission refers to the need for climate finance from both public and private sources and considers that deepened partnerships should be formed to support this group of countries (IDA p. 268–269). With fossil-fuel exporting countries, the Commission envisions dialogues on technological diversification with a focus on renewables (IDA p. 270). This shows a differentiated approach, at least by main country group and a consideration of competition concerns and collaboration opportunities.

Considering the SDGs, the IDA does not introduce a clear approach on how to foster the expected benefits strategically. Moreover, no monitoring mechanisms or implementation roadmap are mentioned. Trade-offs are only vaguely mentioned, even though these can be significant between the SDGs.

Conclusion

The IDA covers a broad range of impacts of international dimension following the implementation of the EU vision – but mainly from an EU perspective. Assessing several policy areas (economy, security, social issues and environmental issues), as well as the potential of international agreements and collaboration, the Commission is drawing concrete links between climate action in the EU and the impacts on and its relation with other countries. Of highest importance to the Commission are economic and security issues, less attention is paid to social and environmental aspects. Contributions to the SDGs are mentioned mainly as co-benefits of climate action and the vision acknowledges, that there is so far little understanding of how synergies could be fostered. Yet it is crucial to make use of such synergies and consider trade-offs carefully. The Commission seeks to explore this issue further, however there are no specifics on how this would be done. In order to make use of potential opportunities, the SDG synergies and trade-offs will need to be explored further.

Whilst the Commission considers a wide range of aspects in the international dimension, it lacks a strategic approach on how to bring these aspects together in a coherent approach. However, as this could prove difficult considering the different nature of the policy areas concerned, building frameworks around related issues seems a more practical approach. For some issues, the Commission has put forward related concepts, such as a proposal to establish a framework for screening foreign direct investments into the EU as an approach to tackle the related security risk. Additional approaches to establishing frameworks to address further risks across the policy areas could support the successful implementation of the EU LTS, such as ideas for how climate aspects could be further integrated into trade agreements.

4 Summary and conclusion

The Paris Agreement (PA) invites parties to lay out their long-term low greenhouse gas emission development strategies. Accordingly, the European Commission (EC) came up with a strategic vision (SV) in order to frame the general direction of its goal to strive for net-zero GHG emissions of the EU by 2050. The SV is accompanied by extensive material, above all the IDA containing a detailed impact assessment based on a scenario analysis. In this study, we have taken a deep dive into the IDA in order to provide a better understanding of the complex matters in it, further to assess whether it provides a suitable analytical input for the SV and finally to identify key issues in this context. The IDA is based on eight economy-wide scenarios, which mainly agree in meeting the current EU 2030 targets but differ in their ambition and their mitigation focus afterwards. Only two out of these scenarios (1.5TECH and 1.5LIFE) achieve net-zero GHG emissions by 2050. Therefore, our analysis has focused on these scenarios. We note that the level of ambition required by the long-term temperature goal of the PA has not been assessed in this report, but it is addressed in a companion report (Wachsmuth et al. 2019), with the result that the Paris compatibility of the scenarios other than the two net-zero scenarios is questionable. Key aspects can also be found in Wachsmuth et al. 2018.

Our assessment was two-fold. On the one hand, the sectoral pathways contained in the IDA have been assessed by individual sector experts based on a common set of criteria. On the other hand, cross-cutting issues have been addressed in an overarching way. The assessment of the **sectoral pathways** has focused on economy-wide pathways, energy supply, the buildings sector (incl. appliances), industry, the transport sector, agriculture, land use (including biomass) as well as the role of negative emissions. In the net-zero scenarios, all sectors have to pursue very ambitious GHG emission reductions early on. 1.5LIFE differs from 1.5TECH by including also circular economy approaches and lifestyle changes in addition to technological approaches. Nevertheless, significant GHG emissions remain in both scenarios, in particular from international transport, energy-intensive industries as well as non-CO_2 emissions from agriculture and waste. Those emissions are hardly avoidable and thus compensated by carbon sinks, both natural sinks from the LULUCF sector and artificial sinks based on CCS, with the 1.5TECH relying on a threefold stronger use of negative emissions than 1.5LIFE. In general, the accessibility of the sectoral pathways was negatively affected by the limited amount of data provided by the EC. Though technology assumptions have been reviewed by stakeholders (E3Modelling et al. 2018) and the EC has provided an additional file with the data underlying the figures in the IDA (EU COMM 2019), key input and output parameters such as sectoral activities and energy demands are not available in a transparent way.

With regard to **energy supply**, all scenarios are characterised by the increasing relevance of electricity and renewable energy sources. The power sector has to decarbonise particularly fast to enable strong emission reductions via electrification. The fuel mix in 1.5TECH and 1.5LIFE is very similar, but the consumption levels in 1.5LIFE are slightly lower due to the lifestyle changes assumed, though other studies indicate even higher final energy demand reductions than in 1.5LIFE. In both scenarios, there is also a significant use of e-fuels and e-gases. Nevertheless, there is no net-zero scenario that maximises the use of renewables in combination with strong energy demand reductions. Thus, the RES share could potentially be increased to limit negative emissions more stringently than in the 1.5LIFE Scenario. Furthermore, nuclear capacity increases after 2030, which is debatable, considering social acceptance and an adverse financing environment for new nuclear power installations. In general, the techno-economic assumptions in the power sector seem to be in line with assumptions made in other studies. In particular, risk premiums for RES criticised in former impact assessments of the EC are not used anymore.

For the **buildings sector**, the pathways are in general plausible when compared to other studies. The renovation rates in the net-zero scenarios are moderate compared to other studies, though still ambitious with regard to the current empirical rates. On the contrary, the assumptions about energy savings from renovations are very high, which means that nearly all renovations have to meet highest energy efficiency standards. Due to the high level of electrification, there is a substantial increase of electricity demand, both for space heating and for appliances and lighting in spite of efficiency measures. However, this has to be seen in the context that the PRIMES model still applies rather high discount rates on private investments, which may have limited the efficiency gains in the modeling.

For **industry**, the sectoral pathways in the IDA show that transforming the industrial sector to close to CO_2-neutrality by the middle of the century is possible. However, technologies available today are not sufficient because fuel switching from fossil fuels to RES is often not possible due to the high temperature levels required and the competition for biomass with other sectors. Therefore, early development of radical process innovations such as direct reduction of steel with hydrogen and new kinds of low-carbon cements need to be part of strategical considerations. At the same time, the potentials for material efficiency and circularity are not yet fully covered in the IDA modelling and should thus be explored in more detail in the future.

For the **transport sector**, the scenario results appear plausible when compared to other studies: demand reduction and strong technology shifts are required for strong CO_2 reductions. International aviation is responsible for the major share of remaining CO_2 emissions in 2050. Almost all scenarios exhibit a mixture of technologies for road transport including electrification, hydrogen, biofuels, e-liquids and natural gas. However, from an economic perspective, many of these technologies require their own infrastructure and would benefit from economies of scale such that scenarios with one or few dominating technologies seem more plausible. These infrastructure feedback loops require additional attention from a strategic perspective.

For **agriculture**, the analysis points to the key areas where there is clear consensus on mitigation potential (CH_4 and N_20 emissions) as well as to the need to address systemic issues of reduced consumption of animal products and food waste. However, the list of considered cost-effective measures is limited compared to other studies. Most clearly missing is a reference to improved crop-rotations and improving soil management to reduce soil compaction. In addition, the trade-offs of the proposed options for mitigation with other impacts are not sufficiently accounted for, e.g. with biodiversity and animal welfare. Moreover, the food system transformation is not mentioned and it is unclear whether the full potential on the demand side is accounted for. In particular, only the 1.5LIFE scenario assumes a change in consumer preferences. Finally, it is unclear whether yield stability is considered, for which additional measures for soil management would be needed.

With regard to **land-use,** mitigation in the net-zero scenarios is primarily achieved in the land use change and forestry sector (LULUCF) and to a lesser extent with bio-based materials. Only in the 1.5TECH scenario, mitigation is achieved with the implementation of agricultural practices that improve soil carbon sequestration and shift cropland from a carbon source to carbon sink. To avoid concerns about sustainability of biomass, the scenarios assume that nearly all biomass for bioenergy is produced within the EU. Moreover, an alternative low-biomass scenario, 1.5LIFE-LB, was specifically created for the land-use category to demonstrate the possibility of decarbonisation with a limited use of biomass. One of the assumptions of greatest doubt is the large role that energy crops are expected to play for bioenergy. One crucial factor that is not sufficiently discussed is the carbon removal rate. Given the strong use of biomass in 1.5TECH and 1.5LIFE, it is important to reflect that carbon is only gradually re-sequestered with a rate depending on land and biomass type.

With regard to the role of **negative emissions,** the only CDR options considered are BECCS and DACCS. Other options such as biochar and enhanced weathering are not considered. The 1.5TECH scenario assumes ambitious carbon removal. The 1.5LIFE scenario assumes much lower carbon capture with marginal BECCS. Carbon capture and negative emissions are almost used interchangeably so that it becomes unclear how carbon is being accounted for in the model: a detailed look reveals that direct air capture is used only in combination with CCU, i.e. as a carbon-neutral option rather than for negative emissions. Compared to studies on the geological storage potential for CO_2 in the EU, the strategic vision relies on a moderate application of underground storage in the scenarios. Costs for CDR technologies are presented in ranges. However, the final values used for the modelling are not clear, which may strongly affect the level of negative emissions.

The assessment of **cross-cutting issues** has covered the topics economic development, just transition, innovation and lifestyle changes, resource needs and circular economy as well as international dimensions including the interaction with SDGs. **Economic development** is considered relative to a baseline that continues current legislation and developments to the year 2050. Following this baseline, GDP increase is expected to reach 68% to +71% relative to 2015. The influence of decarbonisation on this number is rather small (-1.3% to +2.2% depending on the model). Only the sector of mining and extraction will contract strongly. Energy intensive industries and car manufacturing need to transform, which requires substantial investments. Overall, a shift from consumption to investment of roughly 1% in GDP will need to take place, resulting in a substantial increase of the required capital mobilisation. Implications for the multi-annual financial framework of the EU are not assessed in the IDA. Moreover, these results are based on a reduced set of scenarios, including 1.5TECH but not 1.5LIFE, which is a shortcoming for the comparison of the net-zero scenarios. Co-benefits of the transformation like lower air pollution control costs or health benefits are discussed, but not linked back to the economic modelling. Since these aspects are difficult to represent in current tools and measures, the actual benefits of the transition can be expected to be more pronounced.

With respect to a **just transition**, the focus is on labor and related reskilling within the EU. The international dimension is not considered. The actual influence of decarbonisation on labor is small and long-term developments are rather dominated by demographic change, digitalisation and automation. Together with decarbonisation, these trends require a well-managed transition. Regions that are in risk of being left behind are those which depend on contracting or energy intensive economic sectors. A secondary subject of a just transition are the energy prices. The IDA sees energy prices rise to 7.6% of household incomes on average by 2030, before falling below 2005 values (5.6% of income). These average numbers hide a large regional and social spread which will need to be balanced out by adequate measures. Citizen engagement is seen as important, but the required rise in awareness is put off to the civil society, merely supported by labelling and standards.

With regard to **innovation and lifestyle changes**, the EU aims at becoming a global leader in zero-carbon technologies. The IDA sees the need to invest in innovation correspondingly, with special focus on zero-carbon power, electrification, hydrogen technologies and synthetic fuels, but also in zero-carbon production technologies and the bio-economy. Despite this need, the EU LTS identifies a lack in funding, also compared to other economies worldwide. In addition, social innovation is seen to be important as well. In transport, a modal shift is found to be required towards shared mobility and away from aviation. Dietary changes towards less carbon intensive nutrition are touched upon but lack weight in the discussion of lifestyle changes. Again, the IDA does not describe measures to bring about these changes in behaviour. With respect to technological innovations, the documents fall short of describing the necessary diffusion to the market or the increase in scale of certain innovative technologies.

The topic of **resource needs and circular economy** is a recurring theme throughout the IDA with a particular focus in the scenarios CIRC and 1.5LIFE. In a circular economy, the end-of-life of products is incorporated in their design, taking into account reuse, an extension of the lifetime or recycling of the product and the materials used to create it. This concept is accompanied by two major benefits: (1) GHG emissions can be strongly reduced if raw materials are increasingly recycled; (2) the dependency on the respective imports is reduced. The required regulatory framework for a circular economy is not spelled out in the IDA. A possible rebound effect, by which an increased supply through recycling is compensated by an increased use, is also not discussed.

With respect to **international dimensions and interaction with SDGs**, the IDA sees international collaboration as important to tackle global problems, also related to climate change: reducing the threats of conflicts, providing international markets, supporting the global energy system and cooperating on research questions. All these aspects require a certain transparency in their fields. The EU is obliged to comply with WTO regulations and this is seen to provide a level playing field for its partners. A deepened dialogue with countries in financial needs is addressed. The IDA proposes to pursue a dialogue with fossil-fuel exporting nations to diversify their economic portfolio and move towards renewable energies. Overall, climate action is seen to have many co-benefits with other SDGs, especially internationally and considering benefits to health and the eradication of water shortages and poverty.

4.1 Concluding remarks

In **general**, the analytical input provided in the IDA covers the key aspects for building an adequate LTCS and is thus a strong foundation for the Strategic Vision, in spite of certain limitations. The IDA is comprehensive in the way that it covers mitigation pathways for all relevant sectors and GHGs. The IDA serves as a basis for the discussion of a long-term GHG development strategy only for the EU. Nevertheless, its extensive efforts on assessing the feasibility of net-zero GHG emissions may be helpful to a lot of other countries as well. It is also positive that the two net-zero scenarios show the trade-off between behavioural changes and higher negative emissions rather explicitly. However, there is almost no discussion of its political implications, in particular no prioritisation of measures required in any case or to avoid a lock-in at a lower level of ambition. This will be very important to arrive at a meaningful LTCS. Furthermore, while the set of scenarios with an 80% GHG reduction in 2050 explore many different options, the set of only two net-zero scenarios is rather limited. For instance, it is unclear why a scenario which maximises the use of RES in order to fully substitute fossil fuels has not been explored. Moreover, the analysis is not fully transparent because important input data such as discount rates and fuel prices are not provided for all scenarios. The output data is also limited and thus difficult to assess. An increase of transparency will be important to foster the acceptability of an LTCS based on the IDA by the relevant stakeholders.

The IDA also contains detailed considerations of economic and social implications, which shows that the EC is strongly aware of these important issues. In particular, there is a quantitative assessment of implications for the economic development and employment. The variety of models used provides evidence for the robustness of certain findings, in particular the economic feasibility of a transformation to net-zero GHG emissions. However, the macro-economic models have been run for a restricted set of scenarios only, including 1.5TECH but not 1.5LIFE. This is a shortcoming with regard to the comparison of the scenarios and the general robustness of the findings, which is a drawback for strategic considerations. Other important cross-cutting issues are discussed qualitatively and to a varying extent. There is detailed information on the role of technical and also social innovation, including the current status of the EU's innovation framework, but the future requirements remain vague. The role of lifestyle changes is also only touched upon and possibly disruptive transitions are not addressed. While resource efficiency is considered throughout the IDA, a section dedicated to this important issue is missing so that its implications do not become clear. International cooperation is seen both as having multiple benefits and as being key for fostering the trans-formation to net-zero GHG emissions, which should be reflected in the derivation of an LTCS.

Finally, although the extensive material covered by the IDA is an important step forward in a comprehensive assessment of how to achieve net-zero GHG emissions in the EU, there are some **aspects of the sectoral pathways not fully covered in the IDA** that can provide important additional insights. Energy-related aspects that call for further inquiry are the role of infrastructures, in particular in energy supply and transport, regional differences of the building sector as well as a more detailed consideration of material efficiency and circular economy approaches in industry. For agriculture, the role of crop rotations and dietary changes would benefit from a more detailed consideration. With regard to land use, the trade-off between bioenergy and land carbon sinks requires attention, in particular in view of delayed carbon sequestration by forests. Another topic explored little are the use of CDR options other than CCS, e.g. biochar. A cross-sectoral theme not explored in the IDA is the use of sectoral targets and carbon budgets as well as the role of the EU Emission Trading System in this regard.

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