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Low-Carbon Europe 2050

Decomposition analysis of long-term projections for the European Union and selected Member States

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Decomposition analysis of long-term projections for the European Union and selected Member States

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Abstract: Low-Carbon Europe 2050

This report presents a thorough analysis of drivers for decarbonization in different scenario studies. Selected baseline and emission reduction scenarios from a range of studies on the EU, including some EU member states, were analysed to generate insights into:

- Which decarbonization strategies exist?
- Which sectors already show a clear decarbonization strategy?
- In which sectors is the decarbonization strategy less obvious or clear as significantly different and mutually excluding strategies are researched?
- Are there sectors where decarbonization is particularly difficult and which are those?
- What issues have not been addressed in the existing scenarios so far?

Besides a generic comparison a decomposition analysis was applied to these scenarios to identify key drivers for changes in emissions in the scenarios.

The studies under consideration include at least one ambitious climate protection scenario, and provide a sufficient level of detail with regard to the quantitative results to allow for applying the framework of the analysis. In addition to an analysis of total energy-related CO_2 emissions, this study analyses major energy-related sectors on the supply and demand side: electricity supply, industry, tertiary, residential and transport (where possible differentiated by passenger and freight). A comparison of findings and a synthesis along with a detailed data appendix complete the report.

Kurzbeschreibung: Model Low-Carbon Europe 2050

Dieser Bericht enthält eine detaillierte Analyse der Treiber für Dekarbonisierung in verschiedenen Szenarienstudien. Ausgewählte Basis- und Emissionsreduktionsszenarien aus einer Reihe von Studien auf EU-Ebene, aber auch auf EU-Mitgliedsstaatenebene wurden ausgewertet in Hinblick auf die folgenden Fragestellungen:

- Welche Dekarbonisierungsstrategien existieren?
- In welchen Sektoren ist bereits eine klare Dekarbonisierungsstrategie erkennbar?
- In welchen Sektoren ist die Dekarbonisierungsstrategie noch unklar, weil verschiedene, sich teilweise gegenseitig ausschließende Strategien gibt?
- Gibt es Sektoren, in denen sich die Dekarbonisierung als besonders schwierig darstellt und welche sind dies?
- Welche Themen wurden in den existierenden Szenarien bisher nicht addressiert?

Neben einer generischen Auswertung und Vergleich der Szenarien wurde eine Dekompositionsanalyse durchgeführt, um die Haupttreiber für Emissionsveränderungen in den Szenarien zu identifizieren.

Alle für den Bericht ausgewerteten Studien enthalten mindestens ein ambitioniertes Klimaschutzszenario und stellen genügend Daten zur Verfügung um die quantitativen Analysen durchführen zu können. Neben einer Analyse der gesamten energie-bedingten CO2-Emissionen wurden auch die wichtigsten energie-relevanten Sektoren auf der Angebots- und Nachfrageseite ausgewertet: Stromerzeugung, Industrie, Dienstleisungssektor, Wohngebäude und Transport (soweit möglich differenziert nach Personen- und Güterverkehr). Ein Vergleich der Studien und eine Synthese sowie ein detaillierter Datenappendix vervollständigen den Bericht.

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List of abbreviations

BECCS	Bio-energy with carbon capture and storage
CCS	Carbon capture and storage
CO_2	Carbon dioxide
DDPP	Deep Decarbonization Pathways Project
DE KSz	German Climate Protection Szenario
EU ER	European Energy Roadmap
GDP	Gross domestic product
GHG	Greenhouse gases
Gtkm	Gross ton kilometers
IEA	International Energy Agency
IT	Italy
KS80	Climate Protection Scenario 80
KS95	Climate Protection Scenario 95
ktoe	Kilo-tonnes oil equivalent
LMDI	Logarithmic Mean Divisia Index
Mtoe	Million-tonnes oil equivalent
N_2O	Nitrous oxide (laughing gas)
NGO	Non-Profit-Organization
OECD	Organisation for Economic Co-operation and Development
PL	Poland
ppm	Parts per million
PtG	Power-to-Gas (any power-based gaseous fuels)
PtL	Power-to-Liquid (any power-based liquid fuels)
PtX	Power-to-X
SE	Sweden
TWh	Terawatt hours
WEO	World Energy Outlook

Summary

This report presents a thorough analysis of drivers for decarbonization in different scenario studies. Selected baseline and emission reduction scenarios from a range of studies on the EU, including some EU member states, were analysed to generate insights into:

- Which decarbonization strategies exist?
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Besides a generic comparison a decomposition analysis was applied to these scenarios to identify key drivers for changes in emissions in the scenarios.

The studies under consideration include at least one ambitious climate protection scenario, and provide a sufficient level of detail with regard to the quantitative results to allow for applying the framework of the analysis. In addition to an analysis of total energy-related CO_2 emissions, this study analyses major energy-related sectors on the supply and demand side: electricity supply, industry, tertiary, residential and transport (where possible differentiated by passenger and freight). A comparison of findings and a synthesis along with a detailed data appendix complete the report.

Key messages:

- Scenarios vary widely with regards to the emission levels reached by 2050, but only three scenarios reach at least 95% reduction below 1990 levels by 2050 ("full decarbonization"): the German KS95, the Advanced energy [r]evolution scenario 2015 and the Vision Scenario for the EU. None of the scenarios reaches zero greenhouse gas (GHG) emissions by 2050 despite our analysis focusing on CO_2 emissions from combustion of fossil fuels and processes only.
- Emission trajectories compatible with the 2°C limit can only be achieved if full decarbonization is achieved by 2050 and the emission reductions from 2010 to 2030 would amount to at least 50% by 2030.
- Most of the scenarios indicate the opportunity of early emission reductions at a significant scale for the electricity sector (50-60% by 2030), while transport and industry show limited reductions in 2030 in almost all scenarios and still have significant emission levels left in the 80% scenarios in 2050. Full decarbonization scenarios for those sectors heavily rely on carbon capture and storage (CCS) or power-to-gas (PtG)/power-to-liquid (PtL) to limit the remaining emissions.
- Different sectors show different key factors for the reduction of emissions: renewables are the key driver in the electricity sector, the tertiary and residential sector heavily rely on

energy efficiency, electricity use and partly renewables, the transport sector uses energy efficiency, renewables, electricity and PtG/PtL. In the industry sector strategies vary significantly including renewables, electricity and heat, CCS or PtG/PtL. Unlike the majority of global scenarios, most of the full decarbonization scenarios do not achieve the additional emission reductions by compensating the residual emissions in net sinks or by CCS based on bio-energy (BECCS).

- The scope of the studies and assumptions made when designing the scenarios heavily impact the decarbonization strategies, e.g. with regards to the availability of CCS or PtG/PtL – which still require significant innovation in the future to become available – or the use of biomass.
- In order to provide resilient input for upcoming debates on long-term climate strategies new long term scenarios should cover all relevant sectors and greenhouse gases and at least try to reach the goal of (nearly) net-zero emissions.

Zusammenfassung

Dieser Bericht enthält eine detaillierte Analyse der Treiber für Dekarbonisierung in verschiedenen Szenarienstudien. Ausgewählte Basis- und Emissionsreduktionsszenarien aus einer Reihe von Studien auf EU-Ebene, aber auch auf EU-Mitgliedsstaatenebene wurden ausgewertet in Hinblick auf die folgenden Fragestellungen:

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- Welche Themen wurden in den existierenden Szenarien bisher nicht addressiert?

Neben einer generischen Auswertung und Vergleich der Szenarien wurde eine Dekompositionsanalyse durchgeführt, um die Haupttreiber für Emissionsveränderungen in den Szenarien zu identifizieren.

Alle für den Bericht ausgewerteten Studien enthalten mindestens ein ambitioniertes Klimaschutzszenario und stellen genügend Daten zur Verfügung um die quantitativen Analysen durchführen zu können. Neben einer Analyse der gesamten energie-bedingten CO2-Emissionen wurden auch die wichtigsten energie-relevanten Sektoren auf der Angebots- und Nachfrageseite ausgewertet: Stromerzeugung, Industrie, Dienstleisungssektor, Wohngebäude und Transport (soweit möglich differenziert nach Personen- und Güterverkehr). Ein Vergleich der Studien und eine Synthese sowie ein detaillierter Datenappendix vervollständigen den Bericht.

Kernaussagen:

- Die untersuchten Szenarien unterschieden sich stark hinsichtlich der bis 2050 realisierten Emissionsminderungen, wobei nur drei Szenarien Emissionsminderungen von 95% gegenüber 1990 und mehr ("volle Dekarbonisierung") erreichen: das deutsche KS95-Szenario, das Advanced energy [r]evolution Szenario von 2015 und das Vision Szenario für die EU. Trotz der Einschränkung auf energie-bedingte CO2-Emissionen erreicht keines der Szenarien ein Emissionsniveau von Null bis 2050.
- Emissionspfade, die mit dem 2°C-Ziel kompatibel sind, erfordern eine volle Dekarbonisierung im oben genannten Sinn bis 2050 und Emissionsminderungen von mindestens 50% bis 2030.
- In der Großzahl der Szenarien werden zeitnahe Emissionsminderungspotenziale insbesondere im Stromsektor gesehen (50-60% Minderung bis 2050). In den Sektoren Transport und Industrie ist dagegen in den meisten Studien nur eine begrenzte Minderung bis 2030 ausgewiesen und beide Sektoren verfügen über deutliche Restemissionen bis 2050 in 80%-Minderungsszenarien. Die Szenarien, die eine "volle Dekarbonisierung" bis 2050

erzielen, setzen zur Minderung der Restemissionen in diesen beiden Sektoren insbesondere auf die Abscheidung und Speicherung von CO2 (CCS) sowie auf die Nutzung von Power-to-Gas/ Power-to-Liquid-Optionen.

- Unterschiedliche Sektoren weisen unterschiedliche Kerntreiber für die Dekarbonisierung auf: Erneuerbare Energien sind der Haupttreiber im Stromsektor; im Dienstleistungs- und Wohngebäudebereich sind Energieeffizienzverbesserungen, die Nutzung von (CO2-freiem) Strom und teilweise Erneuerbare Energien die Hauptfaktoren; im Transportsektor spielen Energieeffizienz, Erneuerbare Treibstoffe, Stromnutzung und Power-to-Gas/Power-to-Liquid-Optionen eine wichtige Rolle. In der Industrie sind unterschiedliche Strategien in den einzelnen Studien zu finden: Erneuerbare Energien, Strom und Wärme, CCS oder PtG/PtL. Different sectors show different key factors for the reduction of emissions: renewables are the key driver in the electricity sector, the tertiary and residential sector heavily rely on energy efficiency, electricity use and partly renewables, the transport sector uses energy efficiency, renewables, electricity and PtG/PtL. Im Gegensatz zu der Vielzahl der globalen Szenarien, die in den IPCC-Berichten ausgewertet werden, spielt die Kompensation von CO2-Emissionen über Senken (z.B. über die Kombination von Biomasse-basierter Stromerzeugung und CCS (BECCS)) in den untersuchten Szenarien keine Rolle.
- Der Fokus der Studien und die im Rahmen der Szenarioentwicklung getroffenen Annahmen haben wichtigen Einfluss auf die verfügbaren Dekarbonisierungsstrategien, z.B. die Verfügbarkeit von CCS oder Power-to-Gas/Power-to-Liquid-Vermeidungsoptionen - zu deren Realisierung weitere Forschung und Entwicklung notwendig ist - oder zur Nutzung von Biomasse.
- Zukünftige robuste Beiträge in der Dekarbonisierungsdebatte sollten alle relevanten Sektoren und Treibhausgasemissionen berücksichtigen und zumindest versuchen das Ziel von (fast) Null-Emissionen zu erreichen.

1 Introduction

In the process of developing a long-term climate policy vision European policy decision making should build upon or at least reflect carefully the range of already existing scenarios. This in-depth information on existing scenarios provides guidance:

- Which decarbonization strategies exist?
- Which sectors already show a clear decarbonization strategy?
- In which sectors is the decarbonization strategy less obvious or clear as significantly different and mutually excluding strategies are researched?
- Are there sectors where decarbonization is particularly difficult and which are those?
- What issues have not been addressed in the existing scenarios so far?

Against this background, this report presents a thorough analysis of existing emission reduction scenarios. The analysis covers long-term baseline scenarios and long-term emission reduction scenarios for ambitious climate policy targets, both providing a modelling horizon by 2050. The primary focus is set on scenarios and numerical studies for the EU, which allow a more or less direct comparison. In addition to this, energy and CO_2 emission scenarios for selected member states were included that are characterized by a long-term scenario horizon (to 2050) as well as high levels of climate policy ambitions under different circumstances (Germany, Italy, Sweden, Poland). As far as possible, analyses of these scenarios include total CO_2 emissions from energy use, but also analyses of key sectors: energy supply, industry, tertiary, residential and transport.

With a view on the broad range of scenario-specific issues, from input data to modelling approaches, the comparative analysis provided in this report is based on a decomposition analysis, which allows identifying driving forces for emission trends as well as the different abatement levers that determine the results on total or sectoral CO_2 emissions. The decomposition analysis allows for a numerical analysis of different studies and scenarios that allows for an explanation of emission trends at a sufficient level of detail for the different scenarios on the one hand but also creates a framework for highly consistent comparisons between various scenarios and studies not only on an aggregate but also on sectoral levels.

The report is structured as follows: Section 2 provides an overview and brief introduction to the scenarios analysed. Section 3 provides a comparison and synthesis of the analysis of the different scenarios, while Section 4 draws conclusions from the analysis. The detailed study analyses along with an introduction to the methodology applied are provided in the annex.

2 Scenario overview and approach

Scenarios have a key role in providing insights and help policy makers decide and justify policies and targets. Today, several quantitative scenarios with a focus on significantly reducing emissions are available for the EU and for a relevant number of European Union member states. Important ones include:

- EU baseline scenarios
- Scenarios from the Energy Roadmap 2050
- Scenarios from the low-carbon economy roadmap 2050
- Scenarios published each year in the IEA World Energy Outlook
- Greenpeace Energy [r]evolution scenarios for the EU, some of the member states and other regions of the world
- Scenarios from the Deep Decarbonization Pathways Project for the EU, some member states and other regions of the world

Along with national scenarios developed for policymaking or by NGOs as a vision for future development, they provide a good starting point for collecting information on different decarbonization strategies.

Of the modelling exercises available, we selected scenarios based on the following considerations[1]:

- If possible, the scenarios should include all European Union member states.
- The scenarios should reflect a broader range of emission reduction targets to being able to identify differences in strategies for different levels of ambition.
- More recent scenarios were chosen over older scenarios.
- A sufficient level of data should be available for the scenarios included to allow for a meaningful decomposition analysis.

Based on those criteria, 16 scenarios from nine studies were selected that follow different approaches in setting and reaching reduction targets:

- EU Energy Roadmap (2011): The EU Energy Roadmap illustrates different ways of reaching an emission reduction of the EU energy system that is compatible with a GHG reduction target of 80-95% below 1990 levels for the EU. Different strategies for lowering emissions are highlighted in different target scenarios. In addition, a current policy initiatives scenario shows development of emissions without additional efforts to mitigate.
    - Current Policy Initiatives scenario

[1] At the time of analysis, available studies focused on a 2°C target and not the more ambitious targets formulated under the Paris Agreement. Applying more stringent climate targets such as 1.5°C would increase the need for early and very ambitious climate action compared to the studies analyzed in this study.

- High efficiency
- High renewables
- Delayed CCS
- Low Nuclear
- Diversified

▶ PRIMES baseline scenario for the EU: The PRIMES baseline scenario for the EU is updated regularly and used as baseline for different modelling exercises on the EU as well as the MS level. It does not assume reaching specific reduction targets above the level of already implemented policies and EU targets. For this study, the most recent PRIMES baseline scenario from 2016 was analyzed.

▶ Greenpeace Energy [r]evolution 2010/2015: The energy [r]evolution scenario for the EU presents a way towards a 100% renewable energy system for the EU and the European OECD member states, respectively. The analysis includes two scenarios from both studies:

- Energy [r]evolution scenario
- Advanced energy [r]evolution scenario

▶ Vision scenario for the EU (2018): The Vision Scenario for the European Union combines a top-down analysis on a fair share of the EU in a global CO_2 emissions budget that is compatible with the 2°C limit for global warming with a bottom-up analysis on the emission reduction trajectory that fits into such emissions budget for the EU.

▶ IEA World Energy Outlook 2016: The World Energy Outlook presents different scenarios for the development of energy demand and supply along with energy-related emissions. Two scenarios are included, one of which targets at limiting emissions to being compatible with a 2°C target.

- New Policies Scenario
- 450 ppm

▶ Climate Policy Scenario 2050 for Germany: The study presents detailed analysis of contributions of sectors to reducing GHG emissions in Germany. Levels of ambition of the two scenarios included for the analysis vary between 80 and 95% reduction in GHG emissions below 1990 levels.

- KS80
- KS95

▶ Deep Decarbonization Pathway Project for Italy:

- Demand Reduction Scenario

- Energy Scenario 2050 for Sweden
- Low Emissions Scenario for Poland

The modelling exercises that were considered in the comparison reflect different levels of ambition with regard to greenhouse gas emission reductions. The analyzed scenarios can be clustered as follows:

- Full decarbonization scenarios are the scenarios which achieve an emission reduction of 95% or more from 2010 to 2050 (the Advanced energy [r]evolution scenario for Europe, the Vision Scenario for the EU, the KS95 scenario from the Policy Scenarios 2050 project for Germany);
- Deep decarbonization scenarios are the scenarios which model emission reductions of 80 to 90% from 2010 to 2050 (the High Efficiency, High Renewables, Delayed CCS, Low Nuclear and Diversified from the Energy Roadmap 2050 for the EU, the energy [r]evolution scenario for Europe, the 450ppm Scenario from the World Energy Outlook 2016 for the EU, the KS80 scenario from the Policy Scenarios 2050 project for Germany, the Demand Reduction Scenario from the Deep Decarbonization Project for Italy, and the Energy Scenario 2050 for Sweden);
- Low emission scenarios are the scenarios which result in emission reductions in the range of 55 to 65% (the New Policies Scenario from the World Energy Outlook 2016 for the EU, the Low Emissions Scenario for Poland);
- Policy-as-usual scenarios are the scenarios, which are built on the existing policies (the Current Policy Initiatives scenario from the Energy Roadmap 2050 for the EU, the Primes Baseline scenario for the EU).

The emission trajectories of the target-driven scenarios are normative in terms of end-year or interim targets, but they also reflect political considerations as well as considerations on lifetime of capital stocks and/or assumptions on innovation trajectories etc. However, the majority of the scenarios analyzed in the comparison presented not based explicitly on a global temperature limit or a budget approach. The comparison with the Vision Scenario, which is explicitly based on a 2°C-compatible emission budget approach can, however, be used to derive some indication on whether or not the scenarios could be compatible with an overarching climate constraint like the 2°C limit.

The comparative analysis of scenario studies aims on the one hand at identifying reduction contributions of different sectors or levers to the aggregate emission trajectory and on the other hand at an assessment of the underlying driving forces. Against this background, the methodological approach of a decomposition analysis is applied to the broad range of scenarios selected. The starting point for the decomposition analysis is the methodology developed by Kaya (Kaya/Yokobori 1997), on the basis of which the energy-related CO_2 emissions can be described as the product of (1) a driving force described by an activity variable (e.g. gross domestic product), (2) the energy intensity given by the mean energy use per activity, and (3) the sectoral carbon intensity given by the mean carbon emissions per energy used. In a second step, the latter is further decomposed in the shares of the different energy carriers and the fossil carbon intensity (see Annex A1 for detail on the methodology)

The decomposition analysis includes – where possible – an analysis of aggregate results (based on total energy-related CO_2 emissions and primary energy use) along with a detailed analysis of sector results. The sectors included are:

- Electricity sector
- Industry sector
- Residential sector
- Tertiary sector
- Transport, where possible differentiated by freight and passenger transport.

Individual driving forces included in the sector analysis are:

- Aggregate: gross domestic product (GDP) in constant monetary values;
- Electricity sector: electricity generation in terms of energy (in the business as usual trend);
- Industry and tertiary sector: value added in constant monetary values;
- Residential sector: number of households;
- Freight and passenger transport: total freight distance in ton-kilometers and total passenger distance in person-kilometers.

The analysis covers the periods 2010–2030 and 2010–2050. The inclusion of further sectors, other disaggregation of sectors or different driving forces was not possible due to limited data availability in the different studies.

For each of the abatement levers, the figures show their contribution to the total emission reduction relative to 2010, according to the concrete approach to the index decomposition described in Annex A1. The individual levers are:

- Driving force and demand reduction: change of the chosen driving force in a baseline scenario and in the evaluated scenario relative to the baseline;
- Energy efficiency: change of the energy used per activity level of the driving force;
- Electricity/heat/renewables/power-to-gas (PtG)/power-to-liquids (PtL)/nuclear: change of the energy carrier's share in the energy mix;
- CO_2 intensity and CCS: change of the carbon emitted per fossil energy due to fuel switch and application of CCS respectively.

3 Comparison and synthesis

This section provides a comparison and synthesis for the different scenarios analysed. Detailed analyses of the individual studies can be found in the Annex.

3.1 Aggregate and sectoral emission trajectories

The analysis of the trajectories of aggregate energy-related CO_2 emissions with a view to the changes during the first 20 years from 2010 to 2030 compared to the 40 years from 2010 to 2050 indicates some similarities as well as some differences:

- Most of the target-driven scenarios (all full and deep decarbonization scenarios except those from the EU Energy Roadmap 2050), with emission reductions of 70% and more by 2050 (compared to 2010), achieve 50% to 60% of the total emission reductions from 2010 to 2030. These scenarios thus achieve a more than proportional share of emission reductions in the first half of the 40 years period.
- The only outliers in this regard are the scenarios from the EU Energy Roadmap 2050. In these scenarios typically 40% of the total emission reduction effort for the phase from 2010 to 2050 materializes by 2030 and thus the smaller part.
- The low-emission scenario for Poland (total emission reduction by 2050 of 57%) indicates a comparatively low emission reduction during the phase from 2010 to 2030 of only 22%.
- For the EU-wide policy-as-usual scenarios (with total emission reductions from 2010 to 2050 ranging from 35 to 57%) between 58% and 64% of the emission reductions are achieved from 2010 to 2030.

Most of the modelling exercises for the EU and the deep decarbonization scenarios without emission budget constraints show disproportionately high emission reduction efforts in the first half of the scenario period. However, only a narrow range of scenarios can be assessed as compatible to the global 2°C limit. Typically these scenarios reach a full decarbonization by 2050, and deliver at the same time CO_2 emission reductions of 50% or more from 2010 to 2030.

A closer look to the sectoral emission trends discloses additional valuable insights into particular sector specifics:

- The emission reductions achieved in the electricity sector are typically 8 to 15 percentage points higher than for the overall reduction efforts from 2010 to 2050. The only exceptions here are the full decarbonization scenarios where all sectors need to be fully decarbonized by 2050 and thus almost no differences between the sectors can remain. For the period from 2010 to 2030 the emission reductions from the electricity sector are consistently significantly higher than for the overall emission trends (between 10 and 25 percentage points).
- For most deep decarbonization scenarios, the emission reductions from industry are disproportionally low, typically between 10 and 20 percentage points below the aggregate emission trends for both phases, from 2010 to 2030 and 2010 to 2050. The only exception here is the full decarbonization scenario for Germany, which considers CCS for CO_2

emissions from industry. As a consequence, the emission reduction from industry for the period from 2010 to 2030 is disproportionally low compared to the emission mitigation during the subsequent two decades.

- The emission reduction trajectories for the tertiary sector are generally in line with the aggregate emission trends during the course of the period from 2010 to 2030 and from 2010 to 2050.
- The trajectories for emissions and emission reductions for the residential sector are mixed. In the EU Energy Roadmap 2050 scenarios, the emissions from the residential sector follow more or less the same patterns than the aggregate emissions. The country scenarios for Germany and Italy show higher than total emission reductions by 2030 and 2050 (again with the exception of the full decarbonization scenario for Germany).
- The emission trajectories for the transport sector show in nearly all scenarios disproportional emission reductions compared to the aggregate emission trends. Furthermore, most scenarios indicate lower shares of emission reductions from 2010 to 2030 than for 2030 to 2050. Only the Greenpeace scenarios result in approximately the same reduction effort from 2010 to 2030 and 2030 to 2050.

In summary most of the scenarios indicate the opportunity of early emission reductions at a significant scale for the electricity sector, long innovation lead-times for transformative emission reductions in the transport sectors and very heterogeneous emission reduction trajectories for the industry and the residential sectors.

3.2 Sectoral contributions

The analysis of the sectoral contributions to the overall emission reductions shows strong similarities for the EU-wide scenarios:[2]

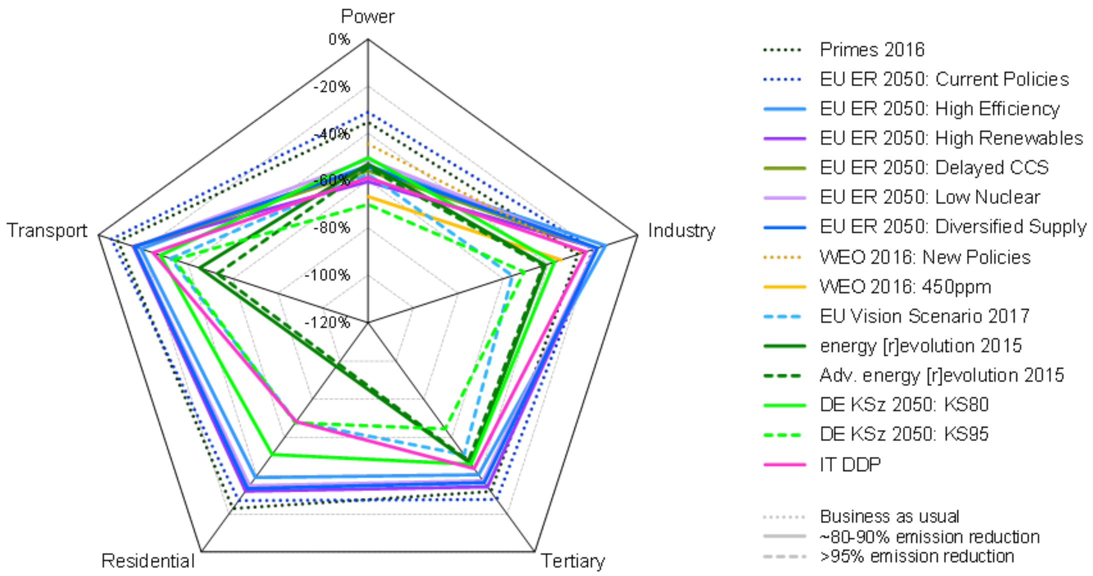
- For the period from 2010 to 2030 (**Fehler! Verweisquelle konnte nicht gefunden werden.**)[3]
  - the emission reductions from the electricity sector range from 50 to 60%;
  - the emission reductions from the industry range from 15 to 25% and differ not that much from the policy-as-usual trajectories;
  - the emission reductions from the tertiary sectors range from 30 to 40%;
  - the emission reductions from the residential sector range from 30 to 40%;
  - the emission reductions from the transport sectors range from 15 to 25%.
- For the period from 2010 to 2050 (Figure 2)

[2] The decomposition analysis presented in this study is based on emission trends starting in 2010 and not in 1990 due to the availability of consistent historical data.

[3] The figure shows the full sample of scenarios to allow the identification of robust corridors for the emission reduction contributions from different sectors. The dotted lines mark scenarios that can be characterized as business as usual, the continuous lines mark scenarios from the cluster of deep decarbonization scenarios and the broken lines mark full decarbonization scenarios.

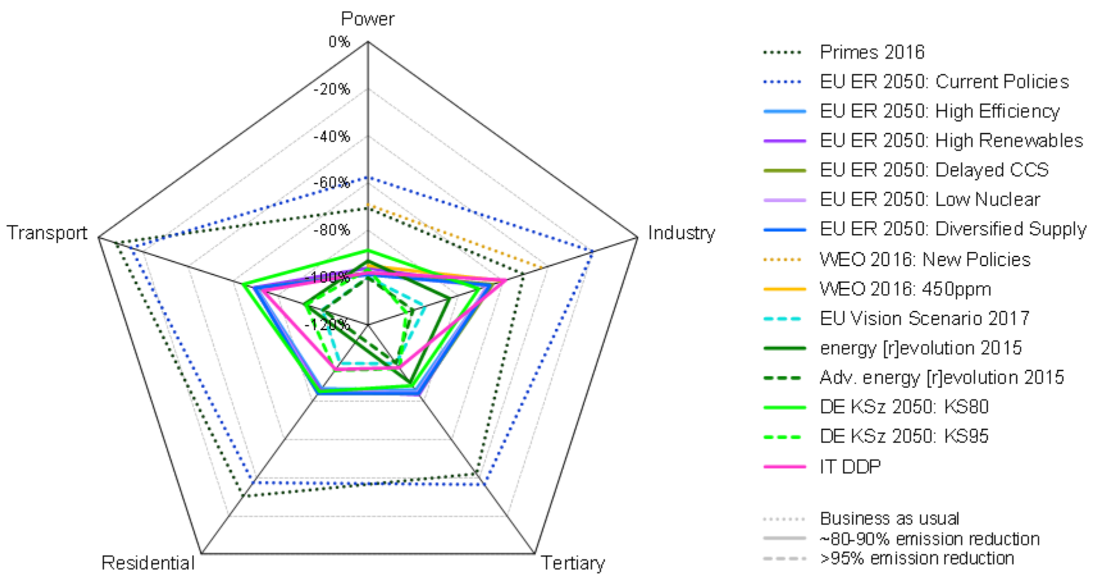
- the emission reductions from the electricity sector amount to 90% and more;
- the emission reductions from the industry range from 60 to 70%;
- the emission reductions from the tertiary sectors range from 80 to 90%;
- the emission reductions from the residential sector range around 85%;
- the emission reductions from the transport sectors range from 60 to 90%.

Figure 1: Sectoral contributions to total emission reductions, 2010–2030



Source: Calculations by Öko-Institut

Figure 2: Sectoral contributions to total emission reductions, 2010–2050



Source: Calculations by Öko-Institut

For scenarios with a focus on national emission trajectories and partly deeper emission reductions, some specifics should be noted:

- For the scenario on Italy, the deep emission cuts in the residential sector for the period from 2010 to 2030 are remarkable, also the disproportionally low emission reductions in the transport and the industry sectors for the period from 2010 to 2050;
- The full decarbonization scenario for Germany is characterized by more than proportional emission reductions in the transport and the industry sectors compared to the KS80 scenario (emission reduction of 80%).

3.3 Contribution of emission reduction levers

The decomposition analysis provides also the possibility to compare the different emission reduction levers between the scenarios. For this purpose, the results of the single decomposition analysis exercises were normalized to the driving forces to enable a robust inter-scenario comparison[4], presented here from both an aggregate and a sectoral perspective.

Aggregate perspective

Figure 3 and Figure 4 indicate the contributions of the different emission reduction levers to the total emission reduction from 2010 to 2030 and 2010 to 2050:

- The comparison shows the significant differences with regard to the driving forces, i.e. the growth of gross domestic product. The driving forces range from 10 to 6035% for the period 2010 to 2030 and 10 to 60% for the period from 2010 to 2050. The scenarios with the lower driving forces are essentially the country scenarios for Germany and Italy.
- Typically, the contribution of primary energy productivity is the stronger the stronger the driving forces are. This is due to the enhanced potential for energy efficiency in a system with higher activity. This might be a key explanation for the broad diversity of its contributions to the total emission reductions.
- The strongest diversity can be observed for the emission reduction contributions from renewable energies. Renewables can therefore be seen as a reliable marker for differences between the scenarios.
- The contributions from a transition to fossil fuels with lower CO_2 emissions is significant in 2030 as well as in 2050. In the full decarbonization scenarios, the emission increasing lever results essentially from the fact that the remaining CO_2 emissions (at very low levels) result from fuel oil use in the sectors where some fossil fuel use remains (inland navigation etc.).
- CO_2 capture and storage (CCS) plays a role only in a few scenarios. Even in the respective scenarios there is no significant emission reduction contribution for the period from 2010 to

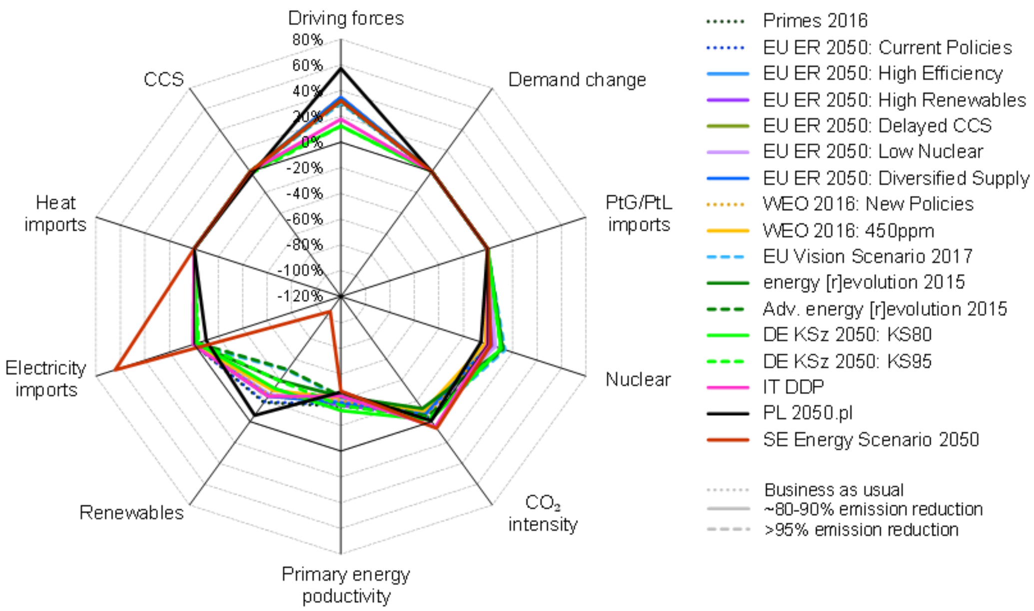
[4] See section A 1 for the detailed methodology and its implications for the comparison of different driving forces and emission abatement levers.

2030 and only a range of contributions that is 20% or less of total the reduction effort between 2010 and 2050.

- In nearly all scenarios, the role of nuclear energy decreases and constitutes a lever that drives emissions and needs to be compensated by other emission abatement levers. In the most ambitious nuclear scenarios, nuclear energy maintains its contribution to the emission reduction efforts, in most of the other scenarios nuclear phase out is a driving force of up to 20% of the base year emissions.

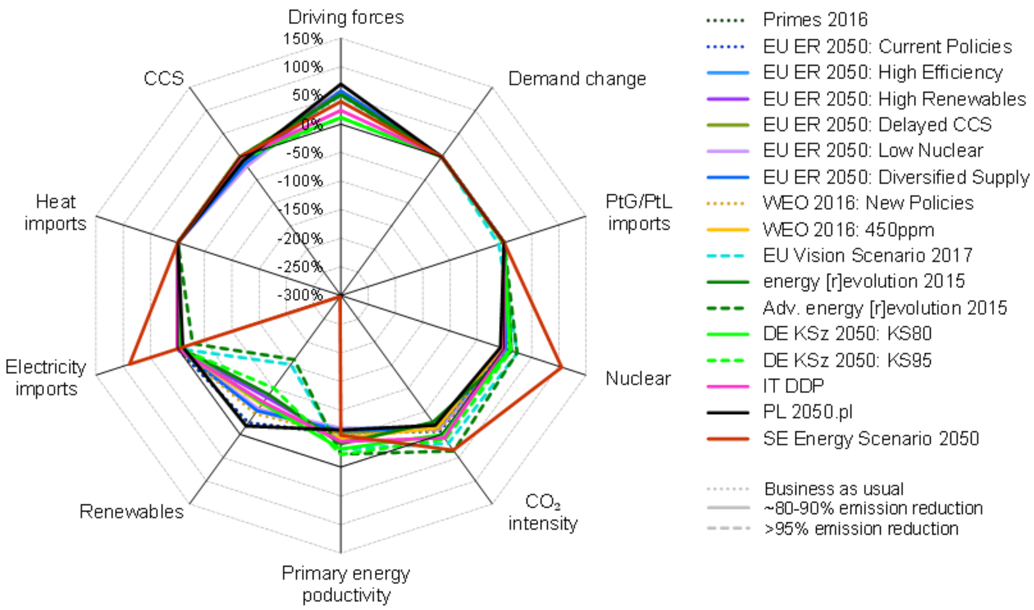
Last but not least it should be mentioned that the profile of emission abatement levers for the Swedish scenario is characterized by the specific starting point of the country (high share of imports, significant shares of hydro and nuclear energy) and its general trends towards significantly less electricity generation from nuclear and much less electricity imports. The specifics of the scenario for Poland result from the significantly higher economic growth (which is the key driving force for emissions) and the lower ambition on the use of renewable energy sources.

Figure 3: Contributions of the different emission levers to the total emission reductions, 2010–2030



Source: Calculations by Öko-Institut

Figure 4: Contributions of the different emission levers to the total emission reductions, 2010–2050



Source: Calculations by Öko-Institut

Electricity sector

The electricity sector as the most significant single CO_2 emission source for most of the jurisdictions mirrors most of the emission levers at the aggregate emission levels.

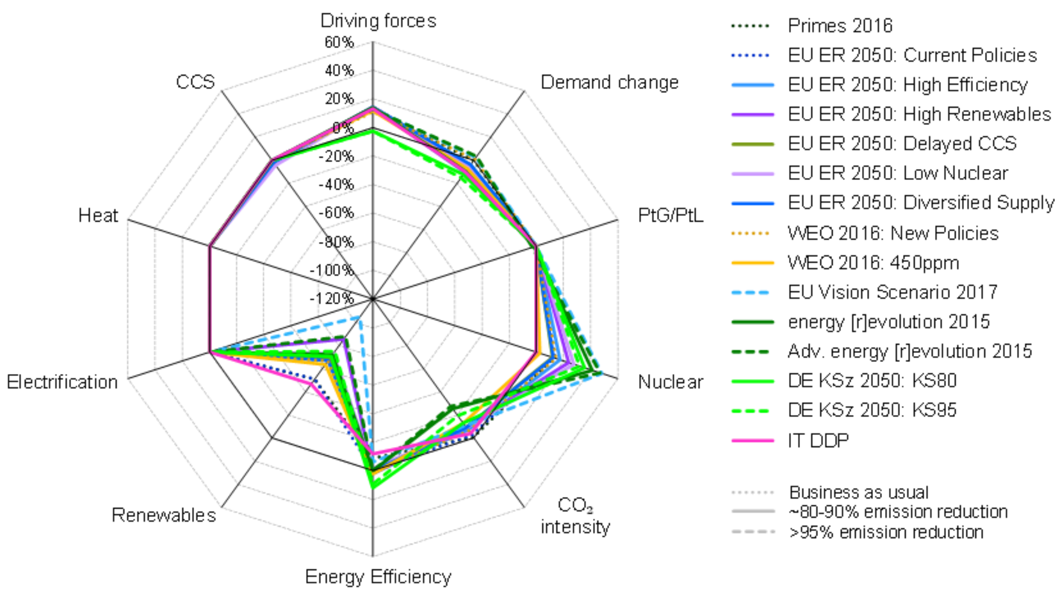
Figure 5 and Figure 6**Fehler! Verweisquelle konnte nicht gefunden werden.** show the emission lever contributions to the total emission reductions for the electricity sector.

- For most of the scenarios the driving forces for the electricity sector, i.e. electricity consumption before additional electricity savings but also before the effects from additional electrification, are more moderate and amount at the maximum to 20% in 2030 and 30% in 2050.
- For the time horizon 2030, electricity savings (“energy efficiency”) contribute significantly to emission reductions (up to 20% of base year emissions) but turn back to be no longer an emission abatement lever by 2050. This is due to the increasing role of electrification in other sectors in later years. In 2050, the demand change is a more neutral lever compared to the base year emissions, i.e. additional electricity savings are compensated by the additional demand from stronger electrification efforts.
- The switch to low-CO_2 fossil fuels (“CO_2 intensity”) contributes with up to 20% in 2030, ranging from 0% to 20%. For 2050 this range does not narrow significantly, the median is, however, shifted a bit more to the 0% level.
- The biggest range of emission reduction contributions can be found for renewables, which carry between half and almost the full emission reduction in the electricity sector. Against the reverse contributions of increasing demand and less use of nuclear, the contribution of

renewables to the emission reduction effort can amount to more than 80% of the base year emissions in the high-renewables scenarios.

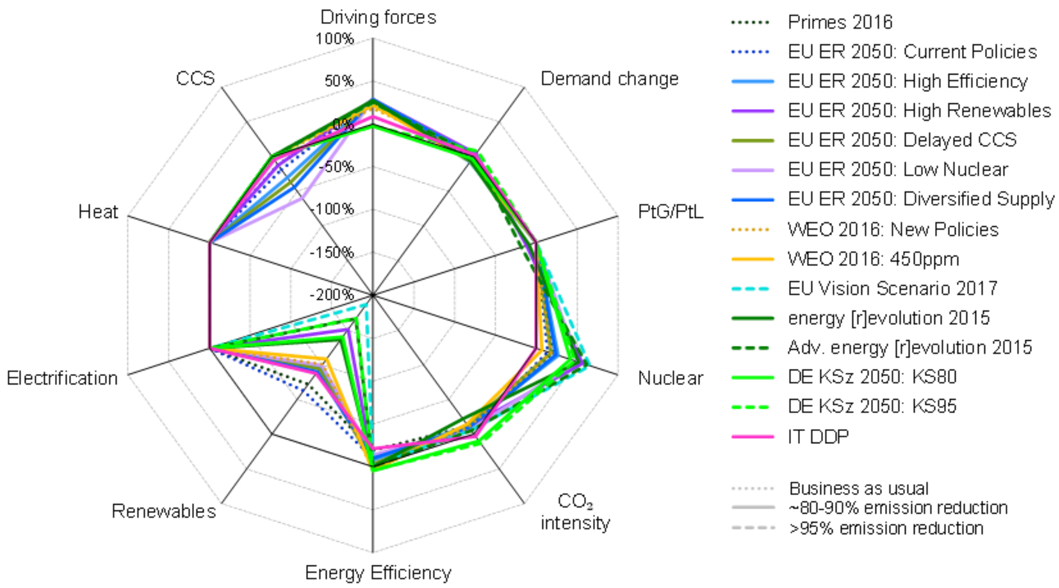
- CCS in the electricity sector is only an option in a few scenarios and plays almost no role for the period from 2010 to 2030. For 2050, the reduction effort amounts to 50% of the total emission efforts at the upper part of the scenario range. For scenarios that allow for CCS in the electricity sector but set no special focus on this emission reduction lever, the abatement contributions are around 25% of base year emissions.
- The use of nuclear energy is neutral with regard to additional emission abatement only in the "high-nuclear" scenario (titled "Delayed CCS"). In all other scenarios, the decreasing role of nuclear drives the emission levels and other emission abatement levers (renewables or CCS) fill the gap.

Figure 5: Contributions of the different emission levers to the emission reductions in the electricity sector, 2010–2030



Source: Calculations by Öko-Institut

Figure 6: Contributions of the different emission levers to the emission reductions in the electricity sector, 2010–2050



Source: Calculations by Öko-Institut

- ► Electricity imports or electricity generation based on imported synthetic fuels (PtG/PtL) play nor or only minor roles for emission abatement in the electricity sector for both time frames.

Industry sector

The patterns of levers that reduce emissions and levers that drive emissions are much more diverse for the industry sectors in the different scenarios for the EU or single member states.

Figure 7 and Figure 8 highlight the different emission levers to emission reductions in the industrial sectors:

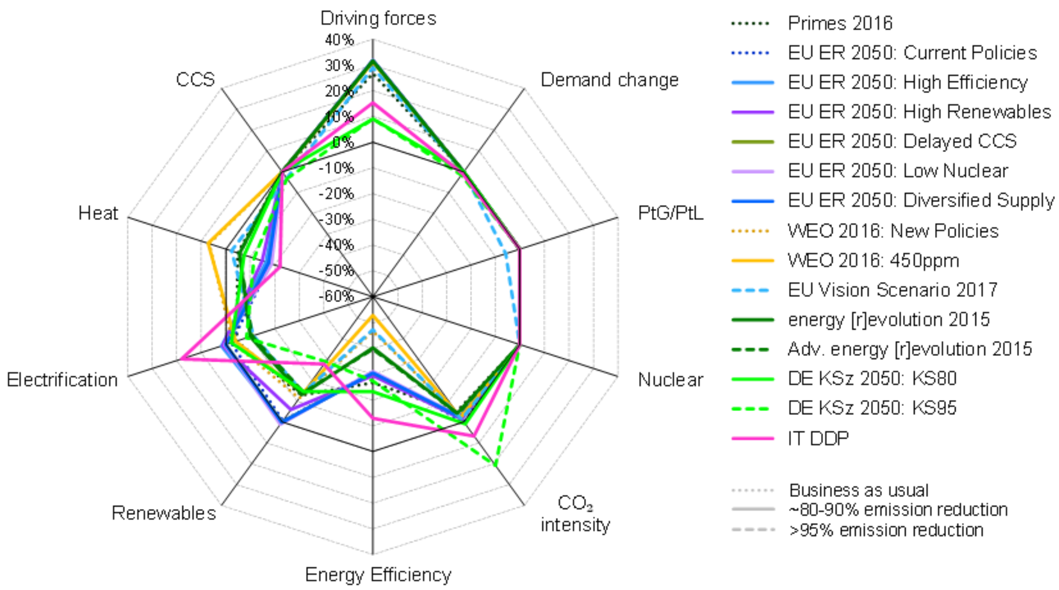
- ► There are major differences between the different scenarios with regard to the assumptions on how the industrial sectors grow from 2010 to 2030 and the subsequent two decades. The highest assumptions on economic growth in the industrial sectors here can be observed for the EU-wide projections whereas the driving forces in the projections for Germany and Italy differ significantly from these levels.[5] Overall, the economic growth in industry represents an increasing contribution to industrial emissions (if all other factors would not change) between approx. 10 and 30% in the period from 2010 to 2030 and 10 to 60% from 2010 to 2050.
- ► The contribution of energy efficiency in the industrial sectors depends on the one hand again on the assumptions on economic growth. The contribution to CO_2 mitigation differs, however, significantly for scenarios with almost identical assumptions on industrial growth

[5] This situation results for some scenarios from specific issues of data availability. In the scenarios for Germany and Italy, changes occur in terms of production volumes but there is no recalculation into value added terms, which are used as the basis in the decomposition analysis.

and range here from 60 to 80% of the base year emissions. The highest ambition with regard to industrial energy efficiency can be observed for the two IEA scenarios.

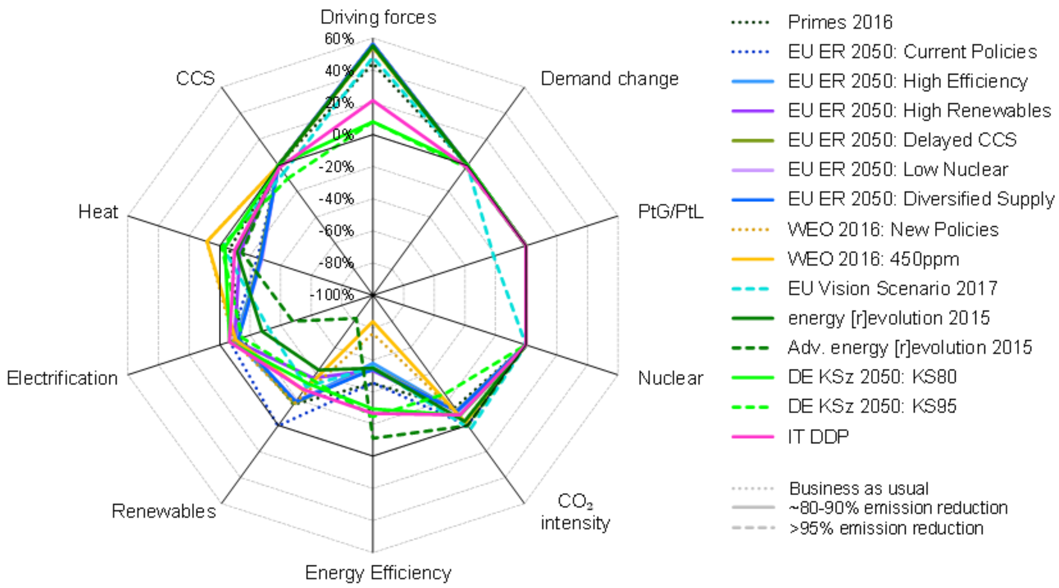
- The switch to less CO_2-intensive fossil fuels plays a limited role by 2030 but represents emission levers of 0 to 20% for the period from 2010 to 2050. For most scenarios, this lever arrives at a level of approx. 10% in 2050.

Figure 7: Contributions of the different emission levers to the emission reductions in the industry sectors, 2010–2030



Source: Calculations by Öko-Institut

Figure 8: Contributions of the different emission levers to the emission reductions in the industry sectors, 2010–2050



Source: Calculations by Öko-Institut

- The most significant variations result again for the direct use of renewables in the industrial sectors. In most scenarios beyond the policy-as-usual projections renewables deliver an emission reduction effort of up to 30% (of base year emissions) in 2030 and up to 40% by 2050, with a main cluster of 10% in 2030 and 30% in 2050. The advanced energy [r]evolution scenario is an outlier here, because the emission abatement lever of direct use of renewables reaches 80% of base year emissions in the period from 2010 to 2050.

- The contribution of electrification is in the range of 0 to 10% in 2030 (apart from the outlier in the decarbonization scenario for Italy) and around 30% in full decarbonization scenarios by 2050 i.e. the KS95 scenario for Germany, the Vision Scenario for the EU and the advanced energy [r]evolution scenario, with the remaining scenarios reaching a contribution of around 10% in 2050.

- Electricity-based fuels (i.e. hydrogen) play only a significant role in the Vision Scenarios beyond 2030 (emission abatement lever of 20%) due to its full decarbonization approach and the assumption on a very limited availability of sustainable biomass.

- A broad variety of emission levers results for the use of heat which ranges from +10% to -20% in 2030 and from +10% to -20% in 2050.

- CCS only plays a minor role in the full decarbonization scenario for Germany in 2050.

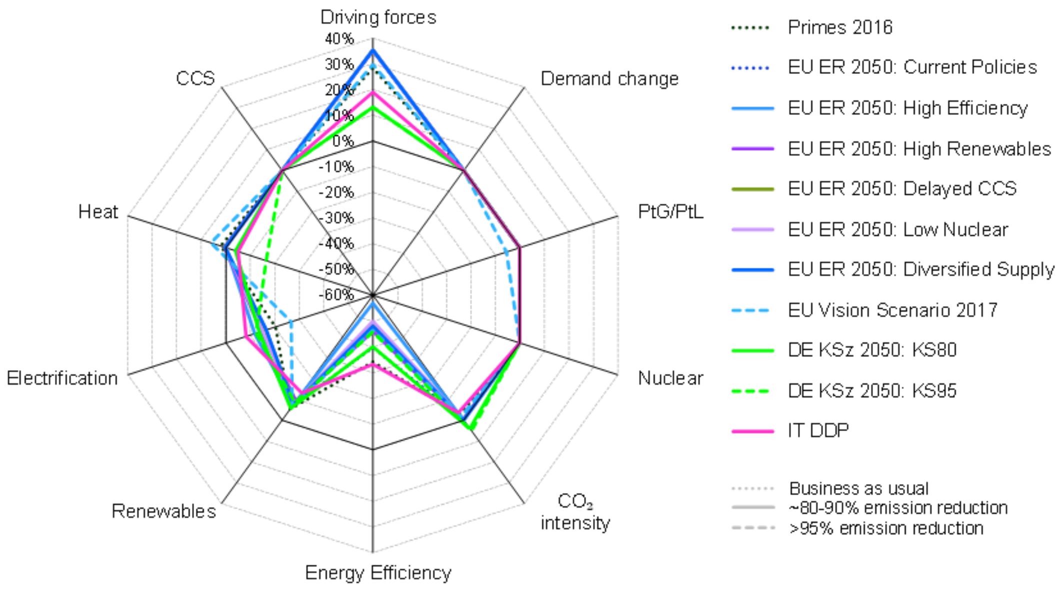
Different to the industrial sector, the patterns of determinants for CO_2 emission trends for the tertiary sector from 2010 to 2030 as well as from 2010 to 2050 differ much less but show significant differences for single emission levers.

Figure 9 and Figure 10**Fehler! Verweisquelle konnte nicht gefunden werden.** indicate the variety of emission reduction contributions for the tertiary sector[6]:

- The range of driving forces for the tertiary sector in the different scenarios is significant. The key differences occur between the EU-wide scenarios and the country-specific projections for Germany and Italy. Whereas the economic growth in the tertiary sectors represents a driver for emissions growth of about 35% from 2010 to 2030 it represents a contribution of almost 60% from 2010 to 2050. For Germany and Italy, the contribution of economic growth in the tertiary sectors ranges from 10 to 20% in the period from 2010 to 2030 and from 2010 to 2050.
- The contribution of increased energy efficiency in the tertiary sector mirrors again the assumptions on economic growth on the one hand. On the other hand, it differs (slightly) among the EU-wide scenarios as well as the two scenarios for Germany. In all scenarios, the energy efficiency lever at least offsets the contribution from economic growth.
- With regard to the emission reduction contributions from the direct use of renewables the range between the scenarios is comparatively small for the period from 2010 to 2030. The lever here presents an emission reduction contribution of approx. 10% of the base year emissions. For 2050, two clusters can be identified: one group of scenarios sees emission reduction contributions around 20% of base year emission and another group sees significantly higher contributions that amounts to approx. 40%.
- A part of the differences with regard to direct use of renewables can explained by the different results on the emission reduction contributions from electrification. For 2030, the range here is from 10 to 20% of base year emissions and for 2050 from 15 to 45%. Typically, the scenarios with lower emission reduction contributions from direct use of renewables envisage higher contributions from electrification. The only exemptions here are the deep decarbonization scenario for Italy and the full decarbonization scenario for Europe as outlined in the Vision Scenario. Electrification represents an emission abatement lever of about 70% by 2050.
- Quite similar patterns can be observed for the contributions from heat supplies to the tertiary sectors.
- As for the industrial sectors the Vision Scenario for the EU shows as the only scenario very significant contributions from hydrogen as a form of PtG (emission abatement lever of more than 50%).

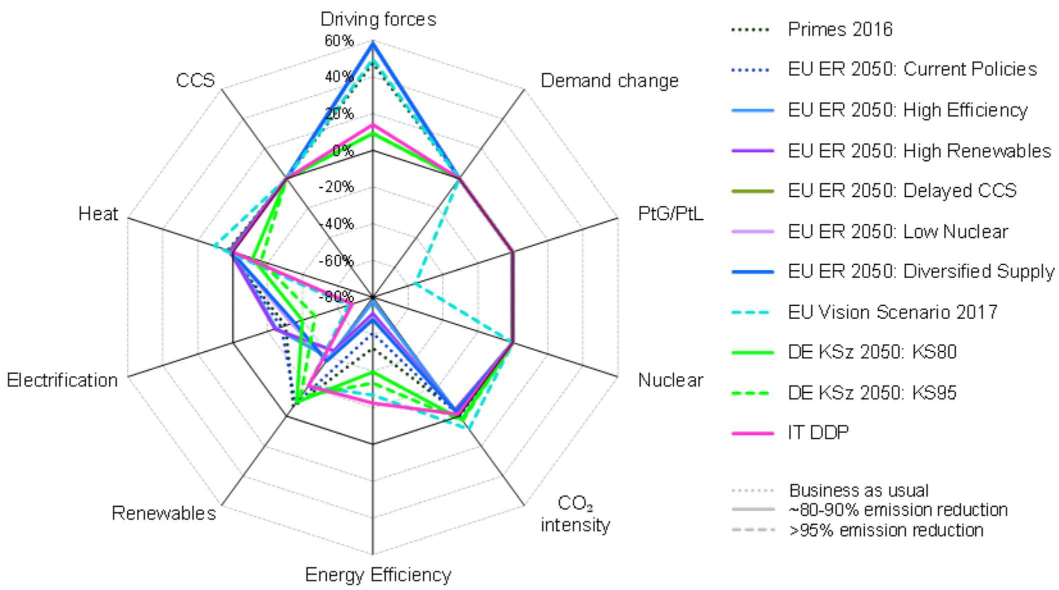
[6] The Advanced energy [r]evolution scenario, the energy [r]evolution scenario as well as the WEO 2016 scenarios do not provide disaggregated data for the tertiary and the residential sectors.

Figure 9: Contributions of the different emission levers to the emission reductions in the tertiary sectors, 2010–2030



Source: Calculations by Öko-Institut

Figure 10: Contributions of the different emission levers to the emission reductions in the tertiary sectors, 2010–2050



Source: Calculations by Öko-Institut

- The other levers (CCS, synthetic fuels, nuclear) play no role for the tertiary sectors.

Residential sector

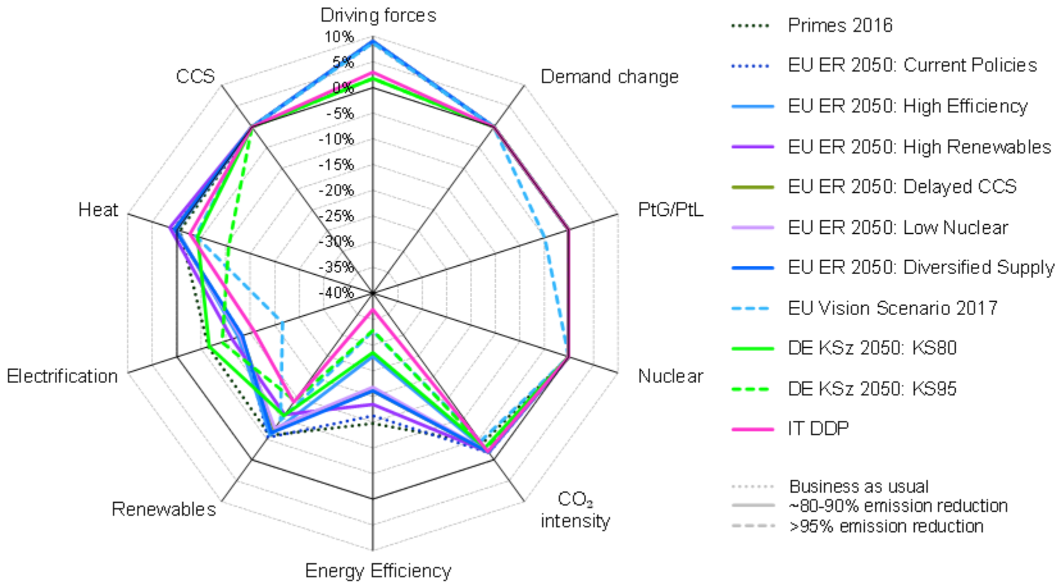
The differences with regard to the different emission abatement levers for the residential sector are clearly visible for the period from 2010 to 2030 and even more significant for the time span from 2010 to 2050.

Figure 11**Fehler! Verweisquelle konnte nicht gefunden werden.** and Figure 12 show the different contributions to emission increases and emission reductions for the periods from 2010 to 2030 and 2010 to 2050[7]:

- Different to the industrial and the tertiary sectors, the underlying growth trends play a much less significant role for the residential sector. The driving force is here essentially the increase of living space. Again, the driving force for the EU-wide projections (around 10%) is significantly higher than for the country scenarios for Italy and Germany (almost constant).
- The role of energy efficiency is significant in all scenarios and ranges from 20 to 35% for the period from 2010 to 2030 and from 25 to 35%, mainly around 30%, from 2010 to 2050. The interrelations between the emission reduction contributions from energy efficiency and direct use of renewable energy sources or electrification are significantly lower than for the tertiary sector.
- The emission reduction contributions from direct use of renewables differ significantly between the two time horizons on the one hand and for the different jurisdictions. For the period from 2010 to 2030, three clusters exist. A subset of the EU-wide scenarios show an emission reduction contribution of 5% for the time span from 2010 to 2030. Other EU-wide scenarios and the 80% reduction scenario for Germany show a 10% contribution and the deep decarbonization scenario for Italy as well as the 95% reduction scenario for Germany show a 15% contribution. For 2050, the patterns differ much more significantly. The High Renewables Scenario shows an emission reduction of 40%, the other EU-wide scenarios and the projection for Italy show a contribution of 30% and the two scenarios for Germany show a contribution of approx. 15% emission reduction.

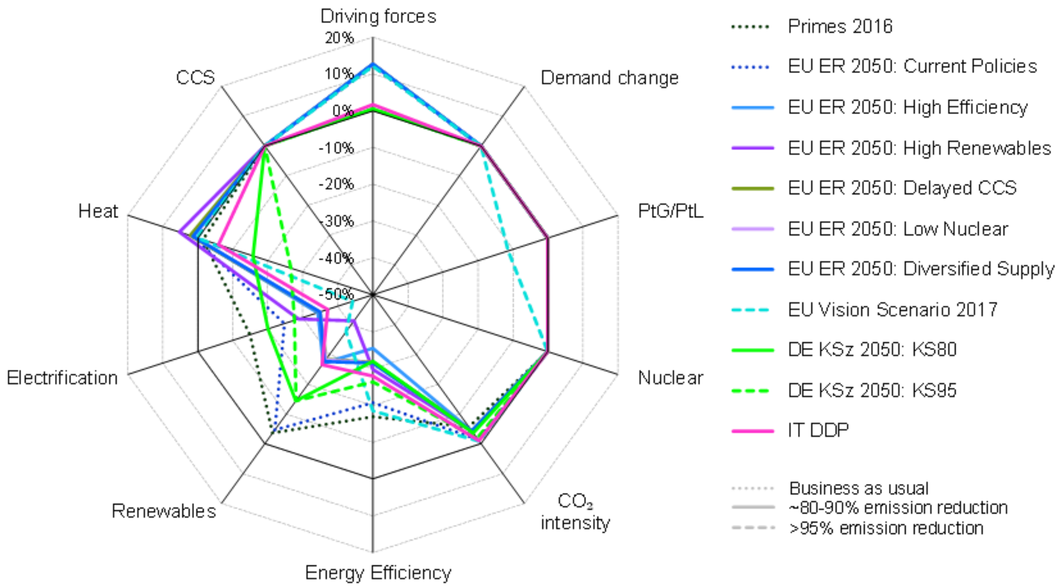
[7] The Advanced energy [r]evolution scenario, the Energy [r]evolution scenario as well as the WEO 2016 scenarios do not provide disaggregated data for the tertiary and the residential sectors.

Figure 11: Contributions of the different emission levers to the emission reductions in the residential sector, 2010–2030



Source: Calculations by Öko-Institut

Figure 12: Contributions of the different emission levers to the emission reductions in the residential sector, 2010–2050



Source: Calculations by Öko-Institut

- The contributions from electrification in the residential sector in most of the EU-wide projections, the scenario for Italy and the 95% reduction scenario for Germany range from 30 to 35%. In the 80% reduction scenario for Germany, this contribution is much lower and amounts to approx. 20%. Only for the Vision Scenario for the EU electrification represents a higher emissions abatement lever of more than 20% by 2030 and more than 40% by 2050.

- The range of contributions from heat supplies to the residential sector is significant but interferes partly with the contributions from electrification. In the EU-wide scenarios and the projection for Italy, the role of heat supplies is very low, but it is significant for the scenarios for Germany (15 to 25%) at least for 2050.
- A more than marginal contribution from hydrogen (PtG) is only modelled in the Vision Scenario for the EU with an emission abatement lever of approx. 5% by 2030 and 10% by 2050.

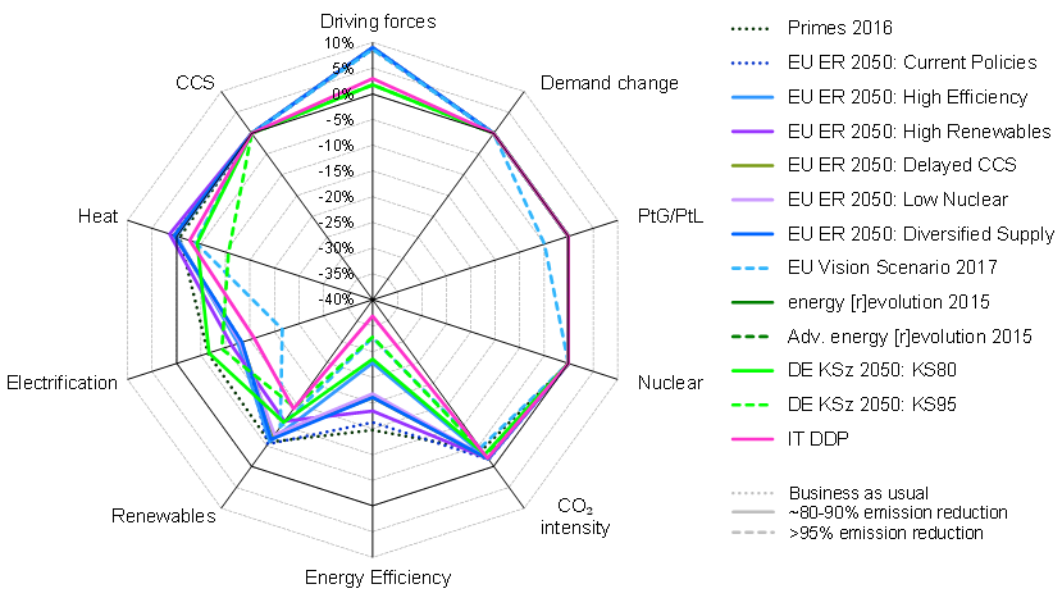
Transport sector

The transport sector is the sector with the most homogenous starting position. Energy consumption and carbon emissions are currently dominated by petroleum products. The range of future trajectories might be very different in terms of technology and also might differ significantly for the passenger transport on the one hand and freight transport on the other hand.

Figure 13 and Figure 14 highlight the different patterns in the scenarios and their evolution over time[8]:

- The driving forces differ again significantly for the EU-wide scenarios on the one hand and the projections for Italy and Germany on the other hand. The growth of transport activity (before transport avoidance) amounts to more than 25% for the EU-wide scenarios and levels around 15% for Germany and Italy from 2010 to 2030. From 2010 to 2050, the increasing transport activities grow by almost 40% for the EU-wide scenarios and by 10 to 15% for Germany and Italy.

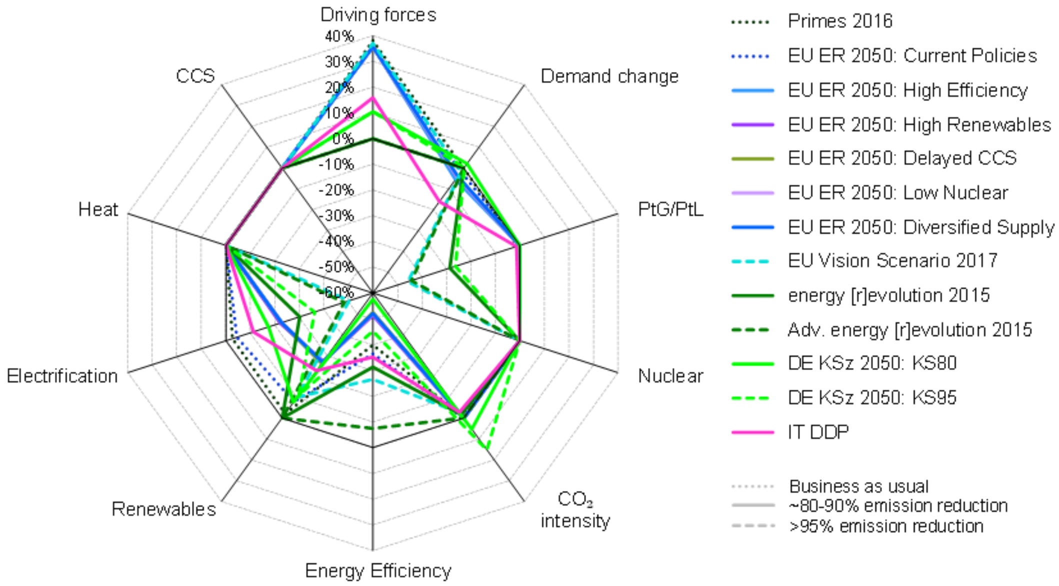
Figure 13: Contributions of the different emission levers to the emission reductions in the transport sectors, 2010–2030



[8] The WEO 2016 scenarios do not provide disaggregated data for the transport sector.

Source: Calculations by Öko-Institut

Figure 14: Contributions of the different emission levers to the emission reductions in the transport sectors, 2010–2050



Source: Calculations by Öko-Institut

- Demand change (avoidance of transport) plays a significant role only for Italy (emission reduction contribution of 15%) and there especially in the long term.
- The contributions of energy efficiency again mirrors the growth of transport activity and ranges from 30 to 50% for the period from 2010 to 2030 and 30% to 60% for the period from 2010 to 2050. These reductions contain the efficiency gains due to the switch from vehicles with combustion engines to electric vehicles, while only the fuel switch itself is accounted for under electrification.
- The contributions from the direct use of renewables in the transport sectors is very low in all scenarios from 2010 to 2030 (5% or less). For the period from 2010 to 2050, the EU-wide scenarios and the scenario for Italy rely on significant contributions (20 to 25%) from direct use of renewables (mainly biofuels). The contribution of this lever to emission reductions is very low in the projection for Germany.
- A comparison between the different projections shows that the lower the contribution from biomass (i.e. the direct use of renewable energy sources) and the higher the emission reduction level is the higher the emission reductions attributable to electrification are. For the three full decarbonization scenarios (Advanced energy [r]evolution, Vision Scenario and KS95 for Germany), electric mobility provides emission abatement levers between 30 and 60% of base year emissions. For the other scenarios, electrification provides emission reductions contributions of 10 to 20%.

- A unique feature of the transport sector among the scenarios analysed here is the role of electricity-based fuels (PtG/PtL: synthetic fuels, hydrogen etc.). For the three full decarbonization scenarios, these new fuels represent emission reduction contributions that amount to 30 to 45%. They become relevant only after 2030.

4 Conclusions and lessons learned

Being part of the project "Model low-carbon Europe 2050" the analysis serves to identify important aspects for the development of the scenario "Low-carbon Europe 2050" and to provide the context of the scenario developed within this project compared to other already existing scenarios. This is the focus of this section, which is organized around some guiding questions.

1. What emission levels are reached in the different studies and how do they relate to the EU's target of an 80-95% reduction below 1990 levels in 2050 and to the Paris Agreement's targets of limiting temperature increase to well below 2°C, aiming at 1.5°C and reaching net-zero emissions in the second half of the 21st century?

The scenarios analyzed vary widely with regards to the emission levels reached by 2050. The studies commissioned by the European Commission, except for the Primes Baseline scenario and the current policy initiatives scenario from the EU Energy Roadmap aim at a reduction of 80% below 1990 levels by 2050 and hence the lower end of the reduction range set by the EU. Scenarios with similar targets can also be found for Germany, Italy, and Sweden as well as in the World Energy Outlook 2016 (450 ppm scenario) and to some extent the Energy **[r]evolution scenario 2015**. Lower reductions are reached in the policy-as-usual scenarios (current policy initiatives scenario from the Energy Roadmap 2050, Primes Baseline scenario), but also in the study for Poland and the new policies scenario from the World Energy Outlook 2016. **Full decarbonization scenarios (i.e. at least 95% reduction below 1990 levels by 2050) are only represented by three scenarios: the German KS95, the Advanced energy [r]evolution scenario 2015 and the Vision Scenario for the EU.**

Most of the climate target scenarios reach the EU's reduction range for 2050, however, none of the scenarios under consideration reaches zero GHG emissions by 2050. Since our analysis focuses on CO_2 emissions from combustion of fossil fuels and processes only, it is unlikely that this reduction level is sufficient to meet the Paris Agreement's target of net-zero emissions because a significant share of the non-CO_2 emissions will remain and therefore will require a complete phase-out of fossil fuels. However, strategies and technologies to move to net-zero, such as CCS or the use of power-to-gas/power-to-liquid (PtG/PtL), have been integrated in more recent full decarbonization scenarios. Increasing their share could make an additional contribution to reach zero CO_2 emissions. But, options to create net CO_2 sinks will probably still be needed to achieve net-zero CO_2 emissions by 2050 and potentially net negative CO_2 emissions for the decades beyond 2050.

If full decarbonization (i.e. at least 95% reduction below 1990 levels by 2050) is achieved by 2050, the emission reductions from 2010 to 2030 would amount to at least 50% by 2030. Except for the EU Vision Scenario, none of the scenarios is explicitly based on a carbon budget approach. Hence, the compatibility with reaching the temperature goal(s) of the Paris Agreement was only possible on the basis of very approximate comparisons. According to the Vision Scenario emission trajectories in this range are compatible with the 2°C limit. For reaching a 1.5°C target, the requirements for early and ambitious emission reductions are even more pronounced.

Finally, the decomposition analysis showed that except for the EU Energy Roadmap scenarios, the scenarios aiming at a reduction of 80% and more already show a significant amount of reductions between 2010 and 2030, which has a positive effect on cumulative emission levels. In contrast, in the scenarios of the EU Energy Roadmap 2050 only 40% of emission reductions are achieved between 2010 and 2030, resulting in higher cumulative emissions. Scenarios with lower emission reductions than 80% by 2050 result in higher cumulative emissions (scaled to EU levels) and are hence more unlikely to meet the temperature targets.

2. What sectors are the remaining emissions located in? What sectors appear to hold significant challenges for decarbonization?

While in the full decarbonization scenarios the remaining emissions are strongly limited, both, their figures for 2030 and the figures for 2050 in the deep decarbonization scenarios aiming at 80% give an indication of which sectors are particularly difficult to decarbonize.

The comparison of the different scenarios shows that **emission reductions in the electricity sector are significant; by 2050 emission reductions of 90% and more are reached in most of the target scenarios**. At the same time, electricity sector emission reductions by 2030 are already quite significant (50–60%).

In contrast, **transport and industry show limited reductions in 2030 in almost all scenarios and still have significant emission levels left in the 80% scenarios in 2050**. In the full decarbonization scenarios, CCS or PtG/PtL are used to limit the remaining emissions in these sectors.

Finally, it should be noted that greenhouse gas emission reductions in the agriculture sector are constraint significantly on the one hand (e.g. for methane and nitrous oxide). On the other hand, ambitious climate policy strategies also need to consider the potentials of agriculture and forestry to create net CO_2 sinks, which were not reflected in the analysis carried out in this study on energy-related CO_2 emissions.

3. What reduction levers are used in the different scenarios?

When analyzing overall emission reductions by decomposition analysis, the impact from driving forces (i.e. demographic trends or economic activities that usually drive emissions up) get obvious. Primary energy productivity, renewables, partly nuclear, CCS and imports of carbon-free fuels drive emission levels down. In the electricity sector, the use of renewables is the key driver, with nuclear having an increasing effect in those scenarios where its share is reduced or even phased-out. CCS use in the electricity sector is very limited in the scenarios, having a strong decreasing effect on emissions only in those scenarios from the EU Energy Roadmap 2050 where CCS use is not excluded or tightly restricted.

In the industry sector, the development of emissions in the different scenarios is driven by development of the economic activity, energy efficiency, use of renewables, electricity and heat. Along with differences in remaining emission levels, strategies for reducing emissions vary significantly between scenarios. While energy efficiency improvements are important in all scenarios, but with varying contributions, the impact of renewables, electricity and heat are more heterogeneous. Among the full decarbonization scenarios, the KS95 uses a significant amount of renewables (in particular biomass) along with contributions from electricity and heat and a small amount of CCS for reducing emissions down to almost zero. In contrast, the Energy [r]evolution scenario assumes even more contributions from energy efficiency and a less significant contribution from direct use of renewables. In addition to this, the Vision Scenario considers significant contributions from electricity-based fuels (PtG/PtL), essentially hydrogen from domestic production and synthetic or other ("novel") motor fuels that are imported to Europe.

In the tertiary and the residential sector, the activities along with energy efficiency, electricity use and partly renewables are the main factors for the development of emissions. While energy efficiency in these sectors is important in all scenarios, the impact of renewables and electricity differs. For the tertiary sector, there is a tendency to use electricity for decarbonization of heat supply instead of renewables. For the residential sector, similar effects can be found, however, renewables play a more important role compared to the tertiary sector.

For the transport sector, its activity, energy efficiency, renewables, electricity and – newly – PtG/PtL (including hydrogen) are important drivers for the development of emissions. The use of electricity varies in accordance with the reduction level and the demand for transport. In addition, those scenarios that reach emission reduction levels of 95% and more also use a significant share of power-to-gas/power-to-liquid to decarbonize the transport sector (German KS95; the advanced energy [r]evolution 2015; and the Energy [r]evolution 2015 scenario). In contrast, the 80% scenarios from the Energy Roadmap 2050 use a significant amount of biofuels to reduce emissions in the transport sector.

In summary, unlike the majority of global scenarios, most of the full decarbonization scenarios (as defined in this report) do not achieve the additional emission reductions by compensating the residual emissions in net sinks (i.e. additional efforts in agriculture or forestry) or by CCS based on bio-energy (BECCS). Instead, the full decarbonization scenarios use additional mitigation options in energy end-use sectors (energy efficiency, electrification, PtG/PtL). The availability of these levers is of crucial importance and necessary for the design of a long-term strategy for achieving net-zero emissions in the EU but probably not sufficient. Additional levers that create net CO_2 sinks are an essential element of strategies that target net-zero emissions.

4. How much do assumptions on emission abatement levers determine the outcome of the scenarios and what role play system boundaries?

Target emission levels are not the only parameter that determines the scenario outcome. Another important factor is the scope of the scenarios. The emissions (i.e. industrial process emissions along with energy-related emissions) as well as the sectors (international and domestic aviation and maritime shipping) included determine to a large extent the reduction potential available. The reduction of process emissions requires either changes in consumption patterns and materials used or the use of technologies such as CCS. Aviation and maritime shipping are growing sectors where direct use of electricity as mitigation option is limited, thus other mitigation options such as PtG/PtL need to be considered. With regard to PtL it should be noted that the needed climate-neutral fuels could be electricity-based but also could result from not yet foreseeable breakthroughs with regard to completely new generations of sustainable biofuels. As the share of these “novel fuels” (from whatever sources) will be required significantly beyond 2030, “novel fuels” should be considered as a wildcard for highly innovative fuels that still do require a broad range of innovation efforts.

Along with the scope of the respective studies, the assumptions made when designing the scenarios are the most important factors for the results. A good example is CCS, which is allowed in the KS95 scenario and hence applied to reduce process emissions in the German industry sector, while this option does not feature in the KS80 scenario and hence emission levels in the industry sector remain significantly above zero. A similar example is the use of nuclear for electricity generation, which can contribute to emission reductions but the application of this technology is highly depending on political targets (e.g. KS80/KS95, Energy Roadmap 2050 low nuclear, Energy Roadmap 2050 high renewables). Similarly, the use of biomass can be restricted due to political reasons, resulting in other mitigation options being required for the transport or industry sector.

5. What can be learned from the results of the analysis for the development of a scenario “Low-carbon Europe 2050”?

The Low-carbon Europe 2050 scenario should at least try to reach the **goal** of (nearly) **net-zero emissions**. Such a scenario would provide further insights compared to the scenarios already out there for the EU. This is particularly relevant for the partially unavoidable non-energy-related emission sources in agriculture, waste and possible emission sinks in the land use sector[9], but also for the transport and industry sector, where the majority of scenarios does not reach a complete decarbonization.

To provide a relevant assessment reference for the discussions under the Paris Agreement, i.e. aiming at net-zero emissions around mid-century the scenario needs to **cover all relevant sectors and greenhouse gases**. That includes in particular methane and N_2O from agriculture, where technological emission reduction options are limited and a significant amount of emissions will remain. It further includes the aviation and shipping sector, for which direct use of electricity is a mitigation option only to a limited extent and other options are needed such as climate-neutral synthetic fuels (PtG/PtL) or biofuels. Also waste treatment is important to address – due to the persistence of the emission source – though emission levels are significantly lower compared to other sectors. On the other hand, it includes an assessment of sinks from the land-use, land-use change and forestry.

While the strategy for decarbonization seems to be rather clear for some sectors, e.g. the electricity and transport sector, scenarios for other sectors, i.e. industry, still vary significantly, which indicates that different decarbonization strategies may be possible. **Focusing on these sectors with yet undecided decarbonization strategies and assessing the different key strategies** during the scenario development, taking into account interlinkages between sectors along with the European perspective can be a key contribution of the scenario "Low-carbon Europe 2050".

The assumptions made in the modelling process determine to a large extent the solution space and the scenario derived. **Assumptions** (e.g. use of CCS/exclusion of CCS, use of biomass, assumptions on main drivers such as GDP, production, …) made should therefore be **transparent and well-argued.**

The use of PtG/PtL in the transport and other sectors depends strongly on supply options of synthetic fuels (PtG/PtL). In contrast to the direct use of electricity, PtG/PtL production requires besides significantly higher electricity supplies climate-neutral carbon sources if it goes beyond the use of hydrogen. These challenges need to be addressed transparently.

[9] These sectors were not included in this analysis as not all studies analyzed cover those sectors

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