Energy Efficiency
https://doi.org/10.1007/s12053-018-9670-4

RESEARCH ARTICLE

Achievability of the Paris targets in the EU—the role of demand-side-driven mitigation in different types of scenarios

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Received: 21 October 2017 / Accepted: 22 April 2018

Abstract With the Paris target of limiting global warming to well below 2 °C until 2100, at best even 1.5 °C, the question arises what this implies for the EU's mitigation targets and strategies. In this article, the reduction of carbon intensities and energy uses in the most ambitious mitigation scenarios for the EU, France, Germany, Italy, and the UK are compared to those of the EU in global 1.5 and 2 °C scenarios. An index decomposition analysis is applied to energy supply and each end-use sector (industry, buildings, and transport) to identify the main differences. From this, we derive conclusions concerning policies and indicators for an EU mitigation strategy compatible with limiting global warming to 1.5 °C. The index decomposition shows that reducing energy use is a stronger lever in the evaluated national scenarios than in the international scenarios for all end-use sectors. The reasons for that are the lower utilization of CCS, the inclusion of additional technology options, and a detailed consideration of sufficiency in the national scenarios. The results suggest that including more ambitious demand-side mitigation options (sufficiency, energy efficiency, electrification, and fuel switching) can significantly reduce the need for negative emissions that are required in all the existing 1.5 °C-compatible global scenarios. Driving these options requires substantial enhancement of current policies for all end-use sectors. In addition, certain index decomposition approaches are shown to underrate the long-term contributions of demand-side mitigation. Accordingly, demand-side mitigation tends to be under-represented in progress indicators for the Paris Agreement, which calls for improvements.

Keywords Paris Agreement · European Union · Sufficiency · Energy intensity · Carbon intensity · Scenario assessment · Index decomposition analysis

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s12053-018-9670-4) contains supplementary material, which is available to authorized users.

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Introduction

The Paris Agreement includes "pursuing efforts to limit the global temperature rise to 1.5 °C" for the first time and the target of greenhouse gas neutrality during the twenty-first century (UNFCCC 2015). While many global mitigation scenarios limit global warming to well below 2 °C until 2100, only a few scenarios achieve the 1.5 °C limit (Rogelj et al. 2015). The latter require large amounts of negative CO_2 emissions in the second half of the century. However, there is a substantial risk that CO_2 removal technologies may not be able to provide negative emissions to the extent required in these scenarios (Kartha and Dooley 2016).

When assessing the drivers of mitigation, it is common to decompose the CO_2 emissions into the product of an activity variable, the associated energy intensity (energy use per activity) and the associated CO_2 intensity (CO_2 emissions per energy used). According to the

Published online: 10 May 2018

IPCC's 5th assessment report (AR5), it is a consensus in the literature that the reduction of both CO_2 and energy intensities plays a key role in every mitigation scenario that is compatible with limiting global warming to below 2 °C (IPCC 2014). While reducing energy intensities is a main lever in the short to medium term, in particular, this is less clear in the long term. Based on an index decomposition and a comparison with historical trends, Peters et al. (2017) argue that the reductions of CO_2 intensities are larger than the reductions of energy intensities in very ambitious mitigation scenarios in the long term. Lechtenboehmer et al. (2017) provide strong arguments that reducing energy intensity via higher energy efficiency will remain an important lever, not only for those end-uses that cannot be electrified but also for electricity itself. Furthermore, there is evidence that also limiting the activities has to be addressed based on sufficiency considerations, because reducing energy intensities cannot ensure the reduction of energy demand in absolute terms (Mundaca et al. 2013), in particular because of rebound effects (Sorrell 2010).

This article compares the reductions of the carbon intensities and the energy use in different sectors within the European Union (EU) for a set of mitigation scenarios that may comply with the Paris targets and conducts an in-depth analysis of the long-term demand-side mitigation options (sufficiency, energy efficiency, electrification, and fuel switching). This set includes national, European, and global scenarios as well as scenarios based on bottom-up and top-down approaches to modeling end-use sectors. We evaluate bottom-up scenarios for the EU, France, Germany, Italy, and the UK to determine sector-specific mitigation rates and compare them to the EU's pathway in scenarios with a European or global focus. To understand the reasons behind the different evolution of carbon intensities and energy use in the various scenarios, we apply an IDA at the level of sectors (energy supply, industry, buildings, and transport), i.e., we decompose the sectoral evolution of CO_2 emissions. These reasons can be manifold, e.g., the electrification of end-use sectors affects both carbon intensities and energy use. The IDA makes it possible to single out these impacts. From this, we derive conclusions about the indicators and policies for an EU mitigation strategy that is compatible with the 1.5 °C target.

The analysis focuses on the EU because—against the backdrop of the current emissions as well as the economic and political capabilities—the EU can play a pioneering role in demonstrating that the Paris Agreement's goals are indeed achievable. The EU's current target of reducing greenhouse gas (GHG) emissions by 80–95% until 2050 compared to 1990 is based on 2 °C-compatible emission pathways. There is evidence that the EU has some leeway in choosing such a pathway (see, e.g., Wachsmuth et al. 2015), while for the 1.5 °C target, it can only be said that emission reductions at the lower end of the range of 80–95% by the year 2050 are very likely to be insufficient (Schleussner et al. 2016). At the same time, however, many EU member states have developed advanced national decarbonization scenarios.

The remainder of this paper is organized as follows. The next section provides an overview of the relevant literature and identifies gaps that we aim to close. Then, we explain the methodology of our IDA and the main assumptions. We introduce the set of scenarios that are assessed in this article and provide descriptive results on the development of carbon and energy intensities. In the results section, we present and discuss the findings of the IDA at sector level and comment on the methodology. In the concluding section, we relate our findings to gaps in the literature and the EU's policies regarding the 1.5 °C target.

Literature on index decomposition analysis in the context of mitigation scenarios and research gaps

There is a wide literature concerning the application of IDA to decompose the drivers of carbon emissions, with the majority of studies looking at historical emissions. A review can be found in Xu and Ang (2013). Here, we focus on papers that have applied index or structural decompositions in a prospective manner to scenarios for the entire energy system and/or all of the end-use sectors:

- Fortes et al. (2013) compare the development of energy and carbon intensities for all sectors in scenarios from computable general equilibrium (CGE) and techno-economic partial equilibrium models, and point out that the similar overall developments in both models actually result from quite different developments in the sectors.
- In their analyses of European decarbonization scenarios, both Förster et al. (2013) and Capros et al. (2014) find that lowering energy intensities makes

the larger contribution until 2030, while the impact of lower carbon intensities becomes dominant afterwards. Furthermore, after 2030, the lack of technology options in the end-use sector models forces activity reductions according to Förster et al. (2013).
- Marcucci and Fragkos (2015) obtain similar results for global decarbonization scenarios in four world regions (including the EU) until 2100. They emphasize the importance of negative carbon intensities obtained via the extensive use of carbon capture and sequestration (CCS). Here, one should note that, in line with Ang and Liu (2007b), they attribute all savings to carbon intensity once the intensity becomes negative.
- Finally, based on a decomposition of the scenarios in the AR5 scenario database, Peters et al. (2017) argue that negative carbon intensities play a dominant role in very ambitious mitigation scenarios, because their relative deviation from historical trends is larger than that of energy intensities. Consequently, they suggest indicators that focus on the supply side to track progress with regard to the Paris targets.

In the international context, mitigation pathways are usually identified using global integrated assessment models (IAMs), which are based on top-down assumptions concerning the emission dynamics of mostly aggregated end-use sectors. Our analysis at the level of individual national economies follows Fortes et al. (2013) and Förster et al. (2013), whose sectoral results suggest that IAM-based findings should be complemented by an analysis of bottom-up models. We therefore apply an IDA to all EU end-use sectors in global and European mitigation scenarios as well as the most ambitious national scenarios for the four largest emitters in the EU (Germany, France, Italy, and the UK). To the best of our knowledge, an IDA has not yet been applied in a detailed comparison of all end-use sectors of mitigation scenarios compatible with the Paris targets. This makes it possible to check the plausibility of the findings from IAMs and to identify concrete measures based on more detailed statements about the required technologies and structural changes. This is the first main novel contribution of this article.

This research also addresses a methodological issue. The decomposition of carbon emissions into the product of an activity variable, the energy intensity, and the CO_2 intensity assumes the independence of the three factors. It is well known that the activity variable and the energy intensity may not be truly independent due to rebound effects (see, e.g., Sorrell 2010), i.e., lower energy intensity may cause higher activity. Vice versa, decreasing activities may also entail a growth in energy intensity, as it was the case during the economic crisis in 2009 (Jotzo et al. 2012). An additional methodological problem seemingly not yet addressed in the literature is that the independence of carbon and energy intensities assumed in IDA may be weak, in particular in scenarios with emissions close to net zero or even below. With regard to this issue, it is instructive to assume that the reduction of energy intensities in a mitigation scenario reaches historical trends only. Then the same overall emission reductions would require huge amounts of additional non-fossil energy (Lechtenboehmer et al. 2017). Moreover, even to sustain the carbon intensity reduction (and thus the associated emission reductions) would require substantial additional non-fossil energy. The standard IDA approaches are ignorant of this effect. A discussion of this methodological issue and the associated sensitivities of the results are the second novel contribution of this article.

Methodology of the index decomposition analysis

To identify the main levers for the reduction of carbon emissions in the evaluation of national and international mitigation scenarios, we separate the impacts of demographic and economic development from the reductions of carbon and energy intensities using an index decomposition analysis of the energy-related carbon emissions (cf. Capros et al. 2014).

As Fortes et al. (2013) and Förster et al. (2013) pointed out the importance of sectoral details, we consider the disaggregation of carbon emissions both for the energy system as a whole and for the end-use sectors separately. Given the different levels of disaggregation in the various scenarios, we decided to look at industry as a whole and subsume freight and passenger transport under "transport" as well as the residential and service sector under "buildings." This leaves us with three end-use sectors: industry, buildings, and transport (see Fig. 7 in the annex).

In the transport sector, we include aviation and domestic shipping but exclude international shipping because there is no uniform approach to its coverage in the evaluated scenarios. In the industry sector, we look at energy-related emissions only and only include the energy-related share of industrial CCS.

Electrification means that an important share of emissions is shifted from the end-use sectors to the energy supply sector. We therefore also carry out a complementary IDA for the energy supply side. Here, we focus on the gross electricity demand including combined heat and power (CHP) generation and transmission losses. We do not look at the centralized generation of district heat because it plays only a minor role in the scenarios.

Since our focus is on end-use sectors, we present the methodology for them in detail here. It is relatively straightforward to adapt this to the energy supply sector. In general, index decompositions can be carried out with regard to different metrics, in particular primary energy and final energy, but also more sophisticated metrics such as exergy. We choose final energy for the following reasons. Due to the statistical conventions for the primary energy of solar, wind, and hydropower, a naive approach to primary energy would result in mixing the impacts of renewable energy sources (RES) and energy efficiency. The so-called substitution approach to primary energy supply makes it possible to circumvent this issue. Still, the substitution approach cannot single out the important contributions of electrification and synthetic fuels, as neither shows up on the level of primary energy demand. We cannot apply an exergy-based approach because most of the scenarios lack a sufficient level of detail. A caveat of this is that there is no account of exergy losses due to the conversion of higher-value to lower-value energy carriers, e.g., the application of power-to-heat technologies.

The general methodology of an IDA of carbon emissions and in particular the commonly used logarithmic mean Divisia index (LMDI) approach are described in Xu and Ang (2013). LMDI has the advantage that the decomposition yields no residual term. In the context of scenarios with CCS, the problem arises of how to deal with zero and negative values of CO_2 intensities (Ang and Liu 2007a, b). The solution for negative values provided by Ang and Liu (2007b) results in allocating all emission reductions to CCS. In this article, we single out the impact of the use of CCS and instead look at the gross CO_2 emissions $C_{i,t}$ of sector i at time t instead of the net CO_2 emissions:

$$C_{i,t} = \mathrm{Net}\, C_{i,t} + CCS_{i,t} \tag{1}$$

where $\mathrm{CCS}_{i,t}$ is the amount of sectoral carbon emissions avoided by CCS.[1] Applying the commonly used Kaya identities, we decompose the net carbon emissions of sector i at time t as

$$C_{i,t} = Population_t \cdot \frac{Activity_{i,t}}{Population_t} \cdot \frac{FED_{i,t}}{Activity_{i,t}} \cdot \frac{C_{i,t}}{FED_{i,t}} \tag{2}$$

$$= Population_t \cdot AI_{i,t} \cdot EI_{i,t} \cdot CI_{i,t} \tag{3}$$

where $\mathrm{FED}_{i,t}$ is the sectoral final energy demand and $AI_{i,t}$, $EI_{i,t}$, $CI_{i,t}$ are the sectoral activity, energy, and carbon intensity at time t. We note that in the decomposition applied here, CCS does not affect the carbon intensity of either electricity or fossil fuels because it is treated separately. This avoids negative carbon intensities and thus the drawback of approaches like the one followed by Ang and Liu (2007b), where no account is taken of changes in the non-negative drivers at the point in time when carbon intensities become negative.

Since the carbon emissions of electricity and heat supply are accounted for in the IDA of the energy supply sector, we do not cover indirect emissions in the end-use sectors and set the carbon intensity of electricity and heat to zero. Moreover, we assume that no carbon emissions are associated with the use of renewable fuels and hydrogen. Then the carbon intensity can be further decomposed as

$$CI_{i,t} = CI_{i,t}^{foss} \cdot \left(1 - s_{i,t}^{elec} - s_{i,t}^{heat} - s_{i,t}^{H2} - s_{i,t}^{RES}\right) \tag{4}$$

where $CI_{i,t}^{\mathrm{foss}}$ is the sectoral carbon intensity of the fossil fuels used and $s_{i,t}^{j}$ are the sectoral shares of the energy source j (electricity, district heat, hydrogen, and renewable fuels + heat (ambient heat, biomass, and synfuels)) at time t.

Löfgren and Muller (2010) have contributed several important methodological remarks: For instance, they point out that monetary activity variables can at best be proxies for real sectoral activity. In addition, they underline the sensitivity of an IDA to the level of aggregation of both sectors and time steps, something that has been stressed in the literature several times. They conclude that an IDA should avoid monetary variables like value added and disaggregate sectors and time steps if possible. Following Löfgren and Muller (2010), we use

[1] For industrial CCS, we assume that one fourth of the emission reduction concerns energy-related emissions (the rest are process emissions) if no splitting is available. This weighting factor is based on the results in Repenning et al. (2015).

the highest time disaggregation possible in order to justify the approximation via an index decomposition that assumes independence of the factors. In our case, we have intermediate time steps of 10 years available for all the evaluated scenarios. The changes in carbon emissions are therefore disaggregated as

$$\Delta C_{i,2050,2010} = \sum_{t=2020}^{2050} \Delta C_{i,t,t-10} \tag{5}$$

where $\Delta C_{i,\ t1,\ t2}$ is the change in carbon emissions from time $t2$ to $t1$. In order to avoid a residual, we apply the LMDI approach mainly developed by Ang and co-authors (see, e.g., Xu and Ang 2013). The LMDI formula for the contribution of the intensity variables in sector i reads

$$\Delta C_{i,t}^{X} = \mathrm{L}\left(C_{i,t}, C_{i,t-10}\right) \cdot \ln\left(X_{i,t}/X_{i,t-10}\right) \tag{6}$$

where $\mathrm{L}(y,z) = \frac{y-z}{\ln(y)-\ln(z)}$ is the logarithmic mean of y and z, and X is either the activity, the energy, or the fossil carbon intensity. The LMDI formula for the contributions of changes in the final energy mix is

$$\Delta C_{i,t}^{mix} = \sum_{j} \mathrm{L}\left(C_{i,t}, C_{i,t-10}\right) \cdot \ln\left(s_{i,t}^{j}, s_{i,t-10}^{j}\right) \tag{7}$$

To understand the impact of introducing time steps, consider the following stylized but insightful example: a reduction of emissions by 100% can be achieved by reducing energy intensity by 50% and reducing carbon intensity to zero. The relevant question is now how much of the emission reduction should be allocated to the reduction of energy intensity. If one thinks of the reduction of carbon and energy intensity as happening one after the other, the order is crucial:

- Variant A: If carbon intensity is reduced to zero first, the time-step approach attributes 100% of the emission reduction to the carbon intensity, as any later reduction of energy intensity has no effect given the already vanishing emissions.
- Variant B: If energy intensity is reduced first, the time-step approach attributes 50% to energy intensity and the other 50% to carbon intensity.

An index decomposition without time steps cannot distinguish between Variant A and B. In both cases, the LMDI approach attributes roughly 85% to carbon intensity, thereby assuming that decreasing carbon intensity makes it less and less useful to reduce energy intensity. Given the transportability and the vanishing marginal costs of non-biomass RES, however, it seems likely that the reduction of energy intensities will reduce the use of RES only to a limited extent. When the supply with non-fossil energy approaches final energy demand in the long run of a decarbonization scenario, one might even expect that the amount of non-fossil fuels supplied is expanded only until the remaining demand is met. Building up RES overcapacities beyond necessary levels of redundancy is even more unlikely because it will be ambitious to establish a full supply with non-fossil fuels even for the reduced levels of demand due to limitations because of land use and acceptance issues.

Another critical point in index decompositions is the choice of the activity variable. As Löfgren and Muller (2010) argue, monetary variables can lead to inconvenient sensitivities. These can be with respect to exchange rates but also to impacts of the intensity changes on the monetary variables like the value added by the energy sector. Since some of the scenarios evaluated here are not based on monetary variables at all and we want to avoid such sensitive assumptions, we look at the energy use per capita instead of considering the energy intensity relative to an economic activity for the overall analysis. On the sectoral level, various other activity variables are applied in the literature:

- The total floor area is a possible activity variable for buildings (the combination of the residential and the service sector). However, this is only available for some of the evaluated scenarios. Therefore, we use population and energy use per capita for the buildings sector, too.
- In the transport sector, we combine the passenger kilometers traveled and the tonne-kilometers of transported freight into a single activity variable by adding them with a weighting factor of 1 to 10, which is the conventional way to account for the difference between the weights of freight and passengers.[2]
- For the industry sector, the gross value added or the subsector levels of production are often used as activity variables. Given the large variety in the data available for the scenarios, we stick to energy use

[2] The passenger and freight transport distances are available for all but the IMAGE scenario. For the latter, we estimate distances based on the given GDP and population development.

per capita here instead of singling out an activity and looking at the relative energy intensity.

In summary, the consistent use of population size for all the sectors enables a clear comparison between them. Due to the lack of individual activity variables, however, the impact of limiting activity is an implicit part of the energy use per capita in the buildings and industry sector, while it is explicitly separated in the transport sector. For the other sectors, this means it is not possible to separate the contributions of energy efficiency from those due to sufficiency in a quantitative way. We therefore discuss this qualitatively for the national scenarios.

Selection and description of the assessed mitigation scenarios

Given the limited availability of global scenarios compatible with the Paris target and the remaining ambiguity on the European level, we start with scenarios that have more than two thirds likelihood of keeping the temperature rise below 2 °C during the whole of the twenty-first century (no overshoot of the 2 °C target). The European scenarios selected apply a fixed cumulative emission budget for 2010 to 2050 that is compatible with the majority of global 2 °C scenarios.

The evaluated scenarios are required to provide specific data for the EU as well as on a sectoral level. They also have to cover at least all energy-related carbon emissions. Sources that provided sufficiently detailed information and were therefore included are as follows:

- EU data of global mitigation scenarios from the databases of the projects AME, AMPERE, and LIMITS (accessible via the AR5 scenario database[3]);
- European mitigation scenarios from the database of the AMPERE project.

For the national scenarios, we focused on the most ambitious scenarios available for the four largest emitters in the EU, namely

- the French "Scenario négaWatt 2050" (négaWatt Association 2014),
- the German "Climate protection scenario 2050," KS95 run (Repenning et al. 2015),
- the "Pathways to deep decarbonization in Italy," demand reduction scenario (Virdis et al. 2015), and
- the UK scenario "Zero Carbon Britain 2030" (Allen et al. 2013).

All the national scenarios reduce carbon emissions by at least 80% from 1990 to 2050. However, they differ significantly in their level of ambition, with a reduction of energy-related carbon emissions by 83% for Italy, by 93% for France, by 97% for Germany and by 100% for the UK from 2010 to 2050.[4] The evaluated national scenarios are target-oriented normative scenarios, but they all consider only mitigation options that are either already mature or at least close to technological maturity. In addition, the German and Italian scenarios are based on the techno-economic modeling of climate policies. All the national scenarios rule out the construction of any new nuclear plants and thus result in a phase-out of nuclear. The French and UK scenarios determine energy demand based on sufficiency and look at technical feasibility as well as impacts on job creation, while the German and Italian scenarios limit sufficiency considerations and apply cost-optimization models that achieve the desired level of decarbonization via an increasing carbon price. In 2015, the four countries considered accounted for approximately 53% of both the EU's population and its GHG emissions.

The EU's energy use per capita and the related carbon intensity span a wide range in the evaluated global and European mitigation scenarios. For the national mitigation scenarios, the energy uses and carbon intensities start out at differing values depending on the individual countries' circumstances. For example, carbon intensities are lower in France because of its high share of nuclear in the electricity mix. With regard to emission intensities, the differences reflect the varying levels of

[3] Link to the AR 5 database (accessed 19 October 2017): https://secure.iiasa.ac.at/web-apps/ene/AR5DB/dsd?Action=htmlpage&page=about.

[4] We note that the national scenarios do not originate from peer-reviewed research but were commissioned by governments or NGOs. Still, our detailed analysis has shown that they reflect the main technical and economic constraints. Solely for the UK scenario, we also assume that the reduction of GHG emissions by 100% is reached in 2050 and not already in 2030 as in the original scenario. This assumption produces sectoral mitigation rates that are more in agreement with similar scenarios and historical values. The underlying reasons are that several sectoral targets in the study were taken from another scenario for 2050 and moved to 2030 for normative reasons. For the IDA, the shift of the target year from 2030 to 2050 results in the sole difference that we evaluate not one intermediate time step but three as for the other scenarios.

ambition of the national mitigation scenarios. Conversely, energy uses converge to a similar level in all the evaluated national mitigation scenarios in the long run (see Fig. 1).

Comparing the carbon intensities for the EU between scenarios based on global and those based on European models does not reveal any significant difference between the two groups. The development depends mainly on the scenario assumptions and less on the type of model used. In the European models, the carbon intensities of final energy fall by 61 to 83% by 2050, which is well within the range of the global models of 41 to 96%. In all scenarios, carbon intensities decrease rapidly and approach zero or even become negative in the second half of the twenty-first century. The difference here is mainly due to different technology assumptions in the scenarios, in particular, the availability of CCS. The carbon intensities in the national scenarios show a decrease ranging from 70 to 100%, with a gradual convergence of the existing national differences.

The differences are more pronounced for the energy use per capita: In the scenarios based on global models, the development of the energy use per capita ranges widely from an increase by 5% to a decrease by 47% until 2050. The European scenarios are all within the bottom half of this range (25–38%). The national scenarios show a similar decrease of 26 to 36% until 2030 and end up between 46 and 62% in 2050. In particular, the least ambitious national scenario has a similar level of reduction as the most ambitious supra-national scenario. We recall that the energy use covers both the impacts of sufficiency-driven activity reductions and efficiency-driven intensity reductions. Both with regard to sufficiency and efficiency, we emphasize that there may be various reasons for the higher ambition of national scenarios, e.g., additional technology options, different demand and activity constraints as well as varying cost and diffusion assumptions. To identify the reasons for the differences, it is necessary to take a closer look at the end-use sectors (see the next section). After 2050, the range of reductions in the global models widens even more with reductions of more than 60% that are not realized before 2080.

To contextualize the reductions of energy uses and carbon intensities in the scenarios, we discuss them with respect to historical trends and the most relevant literature. Mundaca and Markandya (2016) assessed the progress made in decarbonizing energy systems on the level of world regions between 1972 and 2012. Globally, they find that the reduction of carbon and energy intensities has not been able to compensate fully for the growth in population and economic activity. In particular, no absolute reductions of energy demand have been achieved. OECD Europe is the only region that has made progress after 2005 in this respect. Nevertheless, Mundaca and Markandya (2016) find that the simple continuation of historical trends until 2050 would fail to reach the target of an 80% reduction of CO_2 emissions in OECD Europe by between 3 and 21 percentage points (depending on the development of activities). The latter suggests that limiting the growth of activities can also provide an important contribution. Spencer et al. (2017) compared the reduction of sectoral carbon and energy intensities in a set of mitigation of

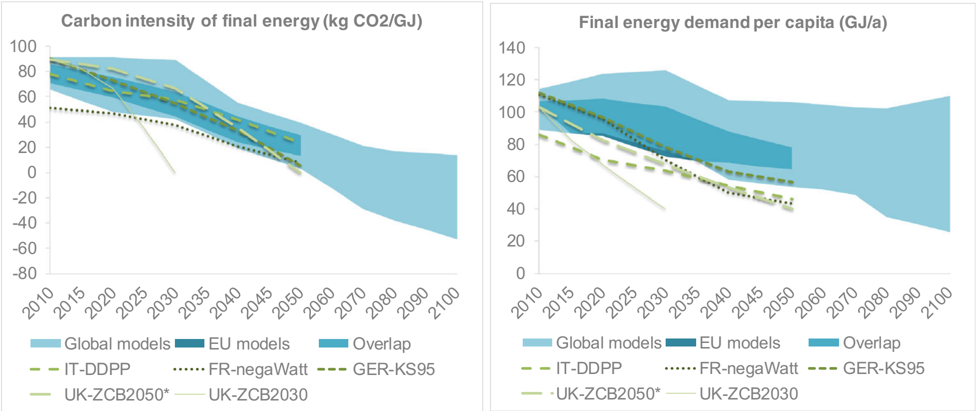

Fig. 1 Comparison of the developments of carbon intensities (left figure) and final energy demand per capita (right figure) in national scenarios with the ranges for the EU scenarios based on global and European models. *Modified Zero-Carbon Britain 2030 assumes the target year of 2050 instead of 2030

scenarios to the historical trends for the same countries considered here. While the mean annual reductions of sectoral energy intensities and the carbon intensity of electricity since 2000 range from 0.5 to 1.8%, the sectoral carbon intensities have only reduced by 0.3 to 0.6% on average per year (Spencer et al. 2017). When comparing these sectoral trends to the required rates in 2020–2030, they find substantial gaps with regard to the median intensities in the end-use sectors, with the biggest gap of 2.3 percentage points per year for the carbon intensity of residential buildings. The gap for the carbon intensity of electricity supply is even higher at almost 4 percentage points. When we carry out the same comparison for the national scenarios considered here, we find similar but on average slightly larger gaps, with the maximum gap between annual reductions of 2.7 percentage points for the end-use sectors and a gap of 4.4 percentage points for electricity supply. The differences reflect that the overall reduction of carbon emissions is only slightly higher than 80% in the scenarios in Spencer et al. (2017). In all cases, the gaps between current trends and required rates show how challenging it is to realize the corresponding mitigation pathways. However, it is important to note that the required ranges of intensity reductions have been observed in the recent past, at least for some years in certain EU countries (Spencer et al. 2017).

In the remainder of this paper, we apply an IDA to explore in more detail the factors underlying the relatively similar decrease of carbon intensities, and the faster decrease of energy use per capita. As this requires more detailed consideration of the sector and variable definitions in the models, we select one global and one European scenario: namely, the IMAGE model run for the AMPERE2-450-NucOff-OPT scenario and the PRIMES model run for the AMPERE5-HiEffHiRES scenario (see Table 1 for an overview of all scenarios included in the analysis). This focus on two specific scenarios also allows a detailed discussion of the similarities and differences in the results. These two scenario runs were selected based on the following hierarchical criteria:

- sectoral detail of available data is sufficient for a meaningful decomposition (sectoral carbon emissions and final energy shares by energy carrier required),
- deployment of nuclear energy is limited,
- most ambitious level of GHG emission reduction in the EU until 2050.

The latter two criteria ensure that the scenarios are as similar as possible to the national scenarios. Consequently, the differences between the national bottom-up models and the more aggregated models can be identified more clearly.

Results and discussion of the index decomposition analysis

Table 2 summarizes the definitions of all the variables used in the index decompositions as well as any

Table 1 Characteristics of the scenarios evaluated in the index decomposition analysis

Country/region	Scenario/model run	Sectors/gases	Mitigation options excluded	Type of model	Energy-related CO_2 emissions 2010–2050
EU	AMPERE2 450-NucOff-OPT, IMAGE run	All sectors/all gases	No nuclear	Techno-economic IAM	− 89%
EU	AMPERE3 HiEffHiRes, PRIMES run	Energy-rel./CO_2	Limited CCS and nuclear	Techno-economic bottom-up	− 83%
France	Scenario négaWatt 2050, 2011–2014	All sectors/CO_2, partly CH_4 and N_2O	No CCS and no nuclear	Socio-technical bottom-up	− 93%
Germany	Climate protection scenario 2050, KS95 run, 2015	All sectors/all gases	Industrial CCS only, no nuclear	Techno-economic bottom-up	− 96%
Italy	Pathways to deep decarbonization in Italy, DMD_RED run, 2015	Energy-rel./CO_2	No nuclear	Techno-economic bottom-up	− 83%
UK	Zero Carbon Britain 2030, 2014	All sectors/all gases	No CCS and no nuclear	Socio-technical bottom-up	− 100% (by 2030)

CCS carbon capture and sequestration, *IAM* integrated assessment model

Table 2 Variables used in the index decompositions and necessary data adjustments

Variable	Definition	Sectors	Data manipulation*
Population	Size of population	All sectors	UK (applies to all variables): 2010–2030 stretched to 2010–2050
Transport activity	Passenger-kilometers + 10 times freight-tonne-kilometers per capita	Transport	IMAGE: estimated by GDP, population, and current values
Electricity/energy use per capita	Gross electricity/final energy demand of a sector per capita	All sectors but transport	–
Energy intensity	Final energy demand of a sector per activity	Transport	–
Electrification	Share of electricity in final energy demand of a sector	All sectors	–
District heat	Share of district heat in final energy demand of a sector	buildings, industry	–
RES fuels + heat	Share of renewable heat and fuels in final energy demand of a sector	All sectors	–
Hydrogen	Share of hydrogen in final energy demand of a sector	Transport	–
Nuclear	Share of nuclear in gross electricity demand	Energy supply sector	
Import	Share of electricity imports in gross electricity demand	Energy supply sector	All: exports are considered as negative shares
Carbon intensity fossil fuels	Direct CO_2 emissions of a sector per use of fossil fuels	All sectors	France: derived from energy demand by fuel + CO_2 factors
Carbon capture and sequestration	Energy-related CO_2 emissions mitigated by the use of CCS	Overall, industry	All: energy-related CCS share based on German splitting

*Data sources: AMPERE database, Allen et al. 2013; Association négaWatt 2014; Repenning et al. 2015; Virdis et al. 2015, and private communication with the authors of the national scenario studies

necessary data adjustments. Note that the definitions imply that any efficiency gains due to electrification are accounted for in the energy use per capita. Accordingly, the share of electricity (in the following "electrification") only accounts for the related change in carbon intensity. For heat pumps, we take into account the ambient heat delivered, so that their main contribution occurs under "renewable fuels + heat."

Energy supply sector

Before we turn to the results of the IDA for the end-use sectors, we start with a short overview of the results for the energy supply sector. This is included to complete the overall picture because indirect carbon emissions are excluded in the end-use sectors. Since mitigation scenarios for the energy supply sector have been analyzed extensively in the literature, we refer the reader to van Sluisveld et al. (2015) for a more comprehensive discussion.

For the energy supply sector, the reduction of carbon emissions is close to 100% in all but the IMAGE scenario. The latter even achieves substantial negative emissions via extensive use of bioenergy-based CCS, which partly compensates for the lower levels of emission reductions in end-use sectors. This also applies to the PRIMES scenario to a lesser extent. However, for the national scenarios, CCS plays hardly any role in this sector (see Fig. 2).

RES expansion is by far the most important lever for emission reduction in the energy supply sector in all the scenarios. Since all but the Italian scenario start out with a relevant share of nuclear energy that is then reduced substantially, changes in the nuclear share have the effect of virtually increasing carbon emissions in those scenarios. This is particularly noticeable in the French scenario because the phase-out of nuclear, which has a high share in the beginning, results in a particularly high increase of carbon emissions. This is compensated by a correspondingly higher contribution of RES to emission reduction.

The reduction of the fossil carbon intensity by switching from coal to gas is an important lever in all scenarios except the IMAGE scenario. Here, it is not important due to the large-scale application of CCS, which minimizes the carbon intensity of fossil power

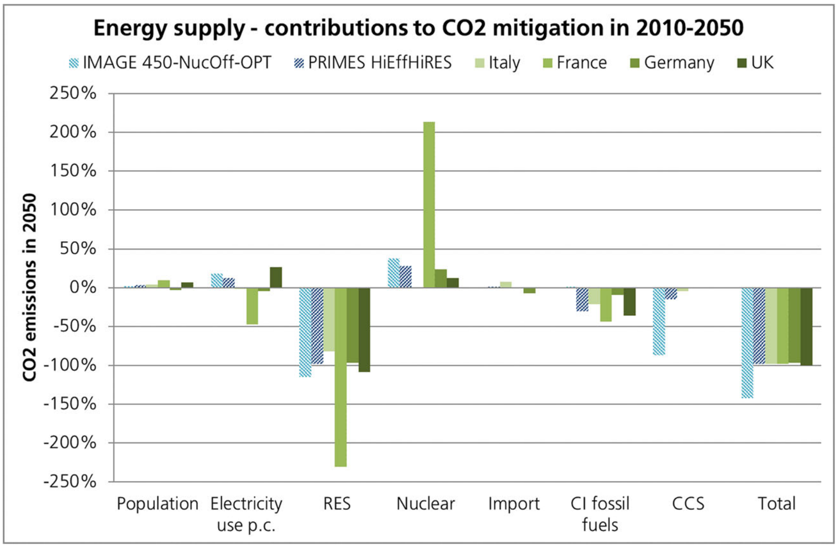

Fig. 2 Results of the index decomposition of the change in carbon emissions in the energy supply sector from 2010 to 2050 (with time steps). *CCS* carbon capture and sequestration, *CI* CO_2 intensity, *p.c.* per capita, *RES* renewable energy source

generation. For the French scenario, the reduction of energy use per capita is important, too, because France starts from a high level of electric heating, which is then replaced by more efficient heating technologies. This has the effect of reducing the total electricity demand in spite of the increased demand from industry and transport. In contrast, the electricity use per capita increases in the UK scenario, as this relies heavily on electrification and electricity-based hydrogen production.

We now turn to the IDA for the individual end-use sectors. An IDA for the aggregation of all end-use sectors can be found in the annex.

Buildings

For the buildings sector, the national scenarios reduce carbon emissions by 94–100%, which is much more ambitious than the IMAGE scenario (46%) and moderately more ambitious than the PRIMES scenario (85%). The index decomposition reveals that the main reasons for the lower reduction in the IMAGE scenario are the much lower contribution of reducing energy use per capita (only 12% compared to 35–41%) and the opposing contributions of RES fuels and heat (see Fig. 3). The latter is due to a lower use of biomass in the IMAGE scenario, while the national scenarios make extensive use of heat pumps and some also of solar heat grids—a technology option not covered in the IAM scenario. The lower energy use per capita in the national scenarios in some cases results from moderate lifestyle changes like a slower increase in housing sizes, but mainly from much higher energy efficiency levels. Electrification is a strong lever (> 20%) in all six scenarios except the French scenario, where the share of electricity for heating buildings is already high today. The reduction of fossil carbon intensity via a shift to natural gas has the strongest impact in the IMAGE and the Italian scenarios. Changes in population size and the share of district heat are of minor importance.

The IPCC's AR 5 already found that sectoral bottom-up models cover mitigation options in the buildings sector in more detail and thereby achieve higher mitigation rates than IAMs (Lucon et al. 2014). In turn, the physics-based bottom-up assessment of energy demand in buildings has attracted growing attention recently leading to the emergence of the field of urban building energy modeling (see the review by Reinhart and Cerezo Davila 2016). Güneralp et al. (2017) point out that it may even be advantageous to partly delay a renovation of the building stock until the most-efficient thermal insulation technologies are ready for large-scale roll-out. In the analyzed national scenarios, however, the high reductions are enforced by the assumption that both new buildings and renovations of the building stock have to satisfy the highest available thermal energy standards based on existing and almost mature insulation options. This is necessary to avoid a lock-in of emissions given that no additional retrofits of a new or renovated building can be expected before 2050. Even if standards are sufficiently strict, the rate of renovations still has to be increased although for a limited period only. In the French scenario, for example,

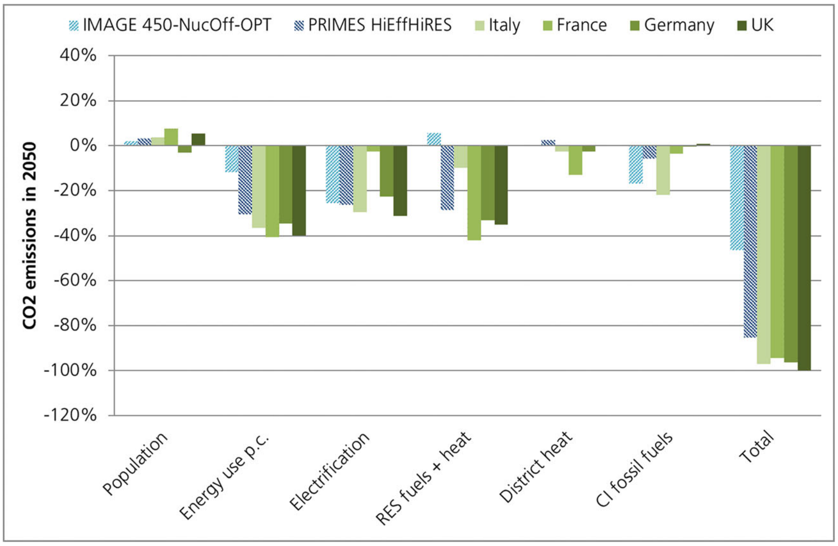

Fig. 3 Results of the index decomposition of changes in carbon emissions in the buildings sector from 2010 to 2050 (with time steps). *CI* CO_2 intensity, *p.c.* per capita, *RES* renewable energy source

the rate of renovation of non-commercial buildings increases to 2.5% until 2030 and then reduces to 0.8% between 2040 and 2050. Similarly, for appliances and lighting, most scenarios see it as optimal to replace each item in the stock only at the end of its lifetime as long as very ambitious minimum performance standards are in place.

Transport

For the transport sector, the reduction of carbon emissions in three of the national scenarios (91–100%) is much higher than in the other scenarios (70–74%). According to the index decomposition (see Fig. 4), the greater reduction in the French and the UK scenarios comes from a reduction of the transport activity compared to constant activity in the Italian scenario and more than 20% growth in all other scenarios. For both the French and the UK scenarios, this is based on empirical assumptions about how to reduce the transport of passengers and goods and make this more efficient. The German scenario has a much stronger contribution from electrification and the reduction of energy intensity. A closer look reveals that both of these are related to including the electrification of heavy-duty vehicles (HDVs) via trolley trucks—an option not yet covered in most other scenarios, although technologically well-established and already road-tested in the USA, Sweden, and Germany (Gnann et al. 2017). In addition, the respective contribution of energy efficiency, electrification, and bio−/synfuels is lower in the IMAGE scenario than in all the other scenarios due to the lower diffusion of electric vehicles and biofuels. The use of hydrogen, on the other hand, only features strongly in the IMAGE scenario, although it is considered in all the other scenarios. Changes in fossil carbon intensity are small.

The results for the transport sector are in line with Edelenbosch et al. (2017) and Yeh et al. (2017), who provide evidence of the minor contribution of limiting transport activity and energy efficiency in global IAMs, while Yeh et al. (2017) also find that energy efficiency and modal shifts are the main levers in bottom-up models. The IPCC's AR 5 also emphasizes that the increase in activity is a major challenge in the transport sector (Sims et al. 2014). To limit transport activity, the national scenarios envisage both a modal shift and the reduction of transport distances based on improved urban planning and the relocalization of industries. Ambitious fuel economy standards for all classes of vehicles are another crucial instrument driving the transformation of the transport sector in the scenarios. In the EU, standards for passenger cars and light-duty vehicles are currently not in line with those applied in decarbonization scenarios, and the standards currently being prepared for HDVs are likely to be not sufficiently stringent, either (see Wachsmuth et al. 2015). The even more ambitious electrification of HDVs includes the necessity to install overhead lines for a significant share of major transport routes. As a result, cross-border goods transport will require even stronger multi-lateral policy coordination.

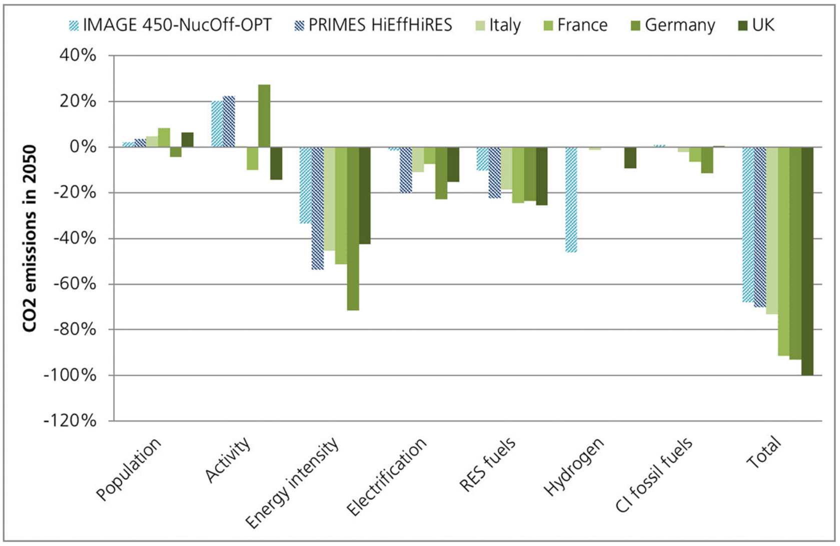

Fig. 4 Results of the index decomposition of changes in carbon emissions in the transport sector from 2010 to 2050 (with time steps). *CI* CO_2 intensity, *RES* renewable energy source

Industry

For the industry sector, again, three of the national scenarios feature a much more ambitious reduction of carbon emissions (93–103%) than the IMAGE scenario (61%) or the PRIMES scenario (74%). The index decomposition shows that the main reasons for the higher reductions in the national scenarios are the larger contribution of energy use per capita in some scenarios (up to 35% compared to only 8% in the PRIMES scenario) and the much higher shares of RES (see Fig. 5). For the UK, the contribution of electrification (43%) is also substantially higher than in the other scenarios (< 20%). The use of CCS, on the contrary, is only relevant for the IMAGE, the PRIMES, and the German scenarios. Expanding CHP use and reducing fossil fuel intensity via a shift to natural gas play an important role only in the European scenario (> 20%). For the national scenarios, those levers are less important because CHP and gas are already widely used in large parts of industries in the corresponding countries. As data on industrial activity is not available in several scenarios, this can only be approximated by the population, which shows only little impacts. However, the lower energy use per capita is partly based on the reduced production of energy-intensive products like clinker and steel. This is

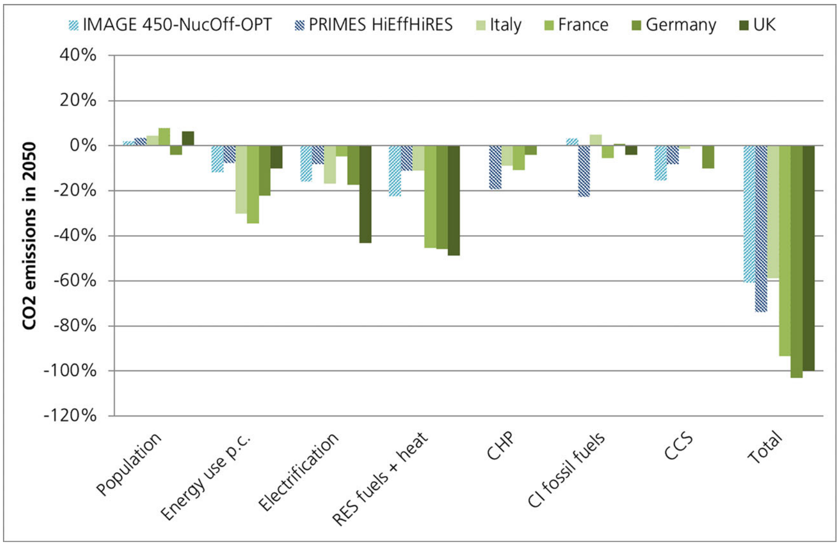

Fig. 5 Results of the index decomposition of changes in carbon emissions in the industry sector from 2010 to 2050 (with time steps). *CCS* carbon capture and sequestration, *CI* CO_2 intensity, *CHP* combined heat and power, *p.c.* per capita, *RES* renewable energy source

especially the case for the French scenario, but to a lower extent also for the German and Italian scenarios.

Kermeli et al. (2014) show that increased energy efficiency throughout all industrial subsectors can reduce the global industrial energy demand by 24% in 2050 compared to a business-as-usual scenario. Accordingly, substantial energy efficiency improvements, in particular of mature cross-cutting technologies like electric motors, are part of all the scenarios, mostly based on ambitious minimum performance standards. The IPCC's AR 5 emphasized that an absolute emission reduction in the industry sector requires a broad set of additional mitigation measures (Fischedick et al. 2014) including CCS, fuel and feedstock switches as well as recycling and more efficient use of materials. Having reviewed the modeling of industry in IAMs, Pauliuk et al. (2017) suggest the inclusion of important material cycles and their linkages to energy flows and capital stocks that are well known in industrial ecology but missing in IAMs. In the national scenarios, these aspects are partly included via assumptions on increasing material efficiency and recycling quotas, at least for the most energy-intensive products.

Moreover, Lechtenböhmer et al. (2016) point out that it is, in principle, possible to fully decarbonize the basic materials sector in the EU via electrification and synthetic fuels based on renewable electricity. However, this results in an electricity demand of the basic materials sector that is 13 times higher than today's demand mainly due to high conversion losses in the production of synthetic renewable fuels. In the evaluated national scenarios, additional emission reductions are achieved by high shares of RES fuels, dominantly biomass/biogas, as well as changes in the production structure, e.g., the substitution of cement clinker by cleaner alternatives and recycling in the iron and steel and aluminum industries. Most of these options are available today, though some of them like low-carbon cement currently have only a medium technology-readiness level and will probably not reach maturity before 2030 (Napp et al. n.d.). It is important to note that the emission reductions also concern process emissions. In the UK scenario, for example, total carbon emissions from iron and steel production are reduced by 58% through reuse, recycling, electric arc furnaces, biomass, and biogas for heat and top gas recycling.

Discussion of methodological issues and the associated sensitivity of the results

As pointed out, the independence of carbon and energy intensity assumed in an IDA is an approximation that is valid only within a small range around the carbon and energy intensities at a given point in time, i.e., for small changes of the intensities. In mitigation scenarios, however, the changes in both carbon and energy intensities are substantial.

With regard to this issue, comparing the index composition for 2010 to 2050 with and without intermediate time steps reveals some interesting differences. As a particularly meaningful example, we focus on the transport sector (see Fig. 6), but similar effects can be observed in the other sectors. The results of the IDA of both approaches for all sectors are provided in the supplementary online material.

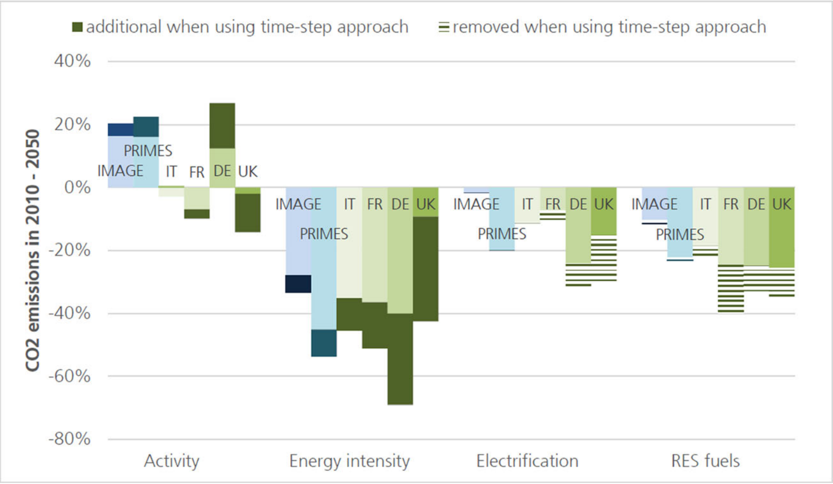

Fig. 6 Main differences of the results of the index decompositions of CO_2 mitigation in the transport sector from 2010 to 2050 with and without time steps. *DE* Germany, *FR* France, *IT* Italy, *RES* renewable energy source, *UK* United Kingdom

While the total reduction in the transport sector is not changed when including time steps by definition, there are significant changes in the impact of specific levers. In particular, the contribution of reducing energy intensities is rated higher for all evaluated scenarios if time steps are included. In contrast, the contributions of electrification and RES fuels are mostly rated lower. For the activity variable, the impacts are rated higher when using the time-step approach. These effects reflect that activity and intensity changes have a much higher impact when the CO_2 intensity is still high. All these effects are stronger for the more ambitious scenarios and the highest differences occur for energy intensity in the German scenario (29%) and in the UK scenario (33%). This shows that the lack of independence between energy intensities and the other levers becomes critical in the context of net-zero emissions. The changes for population, hydrogen, and fossil carbon intensity are comparably low (therefore not shown in Fig. 6).

Mathematically speaking, looking at net-zero CO_2 emissions means regarding a singular point in time, when CO_2 emissions fully decouple from their main drivers. The suggested separation of emission reductions via CCS in Eq. (1) at least avoids crossing this singular point and thus the inversion of the drivers' impacts. By adding intermediate time steps in Eq. (5), the order of changes during one time step is reduced and so the validity of the approximation is improved for each of the stepwise decompositions. The comparison of the results with and without time steps suggests that an IDA underrates the contribution of lowering energy intensities when the carbon intensity becomes marginal. Our approach does not remove this problem fully, but reduces it significantly, as it only occurs in the final time step. A more detailed analysis of the critical time step is a task for future research.

Finally, we note that the assumed independence of carbon and energy intensity may not be a reasonable approximation in mitigation scenarios even in the shorter term. This is the case for example with regard to electricity. Due to the priority dispatch for RES, a reduction in electricity demand will not reduce the amount of RES used at all. The opposite case, where the independence holds true, is the case of a RES quota, as currently applied in the EU's transport sector. A reduction of fuel use leaves the RES quota unchanged and thus, it reduces the total amount of biofuels used. In the longer run, when the RES shares increases, both the priority dispatch and RES quotas are likely not to persist. Nevertheless, those differences underline that short-term IDA should consider sectoral particularities of the dependence of energy and carbon intensities, too.

Conclusions and outlook

For the existing global mitigation scenarios that are consistent with the most ambitious Paris target of limiting global warming to 1.5 °C, it is deeply uncertain whether negative emissions can be provided to the extent required (Kartha and Dooley 2016). In this article, we have shown that national mitigation scenarios based on bottom-up modeling contain plausible reductions of carbon emissions in end-use sectors that are more ambitious than in the more aggregated scenarios.

This suggests that the high cumulative negative emissions in the global mitigation scenarios compatible with the 1.5 °C target can be significantly reduced by very ambitious demand-side mitigation strategies (sufficiency, energy efficiency, electrification, and fuel switching). We analyze the impacts of stronger demand-side mitigation on the EU's carbon budget in detail in a forthcoming companion paper (Duscha et al. 2018).

Due to the limited regional scope and time horizon, the national scenarios cannot replace the IAM-based design of pathways compatible with the Paris targets. On the other hand, it is difficult for global IAMs to address regional heterogeneity, in particular with respect to certain demand-side options (e.g., material cycles). Therefore, national bottom-up scenarios may help to judge and improve the plausibility of the global pathways. The sector results clearly identify several important differences between the national and the regionally more aggregated scenarios, among others, additional technology options and sufficiency-based demand reduction. However, the lack of sectoral activity variables for some of the scenarios prevented a complete separation of the contributions of energy efficiency and sufficiency, which both play an important role in keeping the 1.5 °C target achievable. We therefore recommend a higher disaggregation of scenarios, in particular, including additional sectoral activity variables in scenario databases, e.g., production values for energy-intensive goods.

Since the evaluated national scenarios are limited to emission reductions before 2050 and the extensive use of CCS is excluded for normative reasons in several scenarios, these scenarios have to push other mitigation options close to their technical limits in order to reach their targets. This may pose an obstacle to their realization. However, the scenarios only consider feasible mitigation options that are at least close to market maturity.

On the policy side, early action with regard to both energy efficiency and sufficiency is necessary in order to realize the ambitious reduction of carbon emissions found in the national scenarios thereby fostering a pathway compatible with the 1.5 °C target (cf. Wachsmuth et al. 2015):

- In the buildings sector, it is vital to reduce lock-ins of carbon emissions in the building stock to a minimum. Currently, the Energy Performance of Buildings Directive (EPBD) enforces "nearly zero" standards for new public buildings in the EU from 2018 on and for others after 2020. On the other hand, there are diverse renovation standards among member states, and the existing building stock in most EU countries is only affected to a minor extent (mainly by the energy performance certificates obligation of the EPBD). To achieve energy intensity reductions in line with the evaluated national scenarios, it is essential to ensure that building stock renovations meet the highest energy performance standards and that steps are taken to accelerate renovation rates substantially. Even more, policy instruments also have to address sufficiency to achieve higher thermal building comfort without additional energy use (cf. Wilhite and Norgard 2004).
- In the transport sector, ambitious fuel economy standards lay the foundations for significant emission reductions. In the EU, emission standards for road vehicles will be extended to include HDVs, but in general, these only decrease to the order of magnitude that is expected from market drivers anyway and need to be enhanced to be in line with the scenarios. In order to avoid carbon emissions from transport fully, passenger cars must be electrified and freight transport must switch to gaseous or liquid synthetic renewable fuels. The latter may be complimented by electrifying HDVs on the most frequented transport routes. Furthermore, the rising transport activity can be limited substantially by installing new kinds of mobility concepts (Creutzig 2016). All of these measures require early coordinated multi-lateral action to provide the necessary infrastructure.
- Ambitious decarbonization of the industry sector in line with the evaluated scenarios requires a broad set of mitigation measures in addition to cross-sectoral efficiency improvements. This includes fuel and feedstock switches, recycling, and more efficient use of materials, but also completely new production routes in particular for energy-intensive industries. Whether the main energy efficiency potentials will be realized currently depends mostly on the reforms of the European Emissions Trading System (ETS) for the upcoming phase IV (2021–2028) and on energy audits under Article 8 of the EU's Energy Efficiency Directive. Even in case of ambitious reforms, it is unlikely that there will be enough incentives to drive the radical process innovations required for a decarbonization of industry in line with the evaluated scenarios. Therefore, there is the need for special instruments addressing zero-carbon production routes like the EU-ETS innovation fund currently in preparation and multi-lateral efforts under Article 6 of the Paris agreement.

Peters et al. (2017) argue that the reductions of carbon intensities compared to historical trends are more substantial than the reductions of energy intensities in highly ambitious decarbonization scenarios. Our discussion of methodological aspects suggests that scenarios based on regionally aggregated models may at least partly underestimate the contributions of reducing energy use, in particular, if they apply a top-down approach to modeling energy demand. Moreover, standard index decomposition approaches may produce misleading results when applied to scenarios with emissions close to net zero or even below, because they do not reflect that emission intensities are likely to be much higher in the case of higher energy intensities. As discussed, using the highest available disaggregation of sectors and time steps limits this problem, but cannot fully remove it. We thus suggest interpreting the results from index decompositions of low-carbon scenarios with care and addressing the dependence of carbon and energy intensities as well as sectoral activities in future research.

Furthermore, Peters et al. (2017) have come up with a set of key indicators for tracking progress with regard to the Paris targets based on an index decomposition. They place large emphasis on the supply side covering CCS, fossil fuel switching, and various RES. On the demand side, in contrast, they only track the overall energy intensity per GDP. Having discussed both the additional mitigation options on the supply side and the dependence of carbon intensity reductions on energy intensity reductions, we suggest tracking the demand side in more detail as well:

- Firstly, given the different speeds of mitigation progress in the sectors, it is important to look at the energy intensities in each sector separately to monitor delays and lock-ins. The intensities should be complemented by the absolute energy uses, as it is important to avoid that the gains from lower energy intensities are compensated by higher activities.
- Secondly, sufficient electrification of the end-use sectors is a crucial prerequisite for their complete decarbonization. This implies that the sectoral levels of electrification are important indicators of whether the transformation of the end-use sectors is in line with the Paris targets, especially the 1.5 °C target.

Wilson et al. (2012) point out that the innovation efforts supporting demand-side-driven mitigation are substantially lower than those supporting supply-side-driven mitigation in spite of partially higher impacts. In summary, our analyses complement the findings of Wilson et al. (2012) by showing that the importance of demand-side mitigation options is underrated in long-term scenario analysis as well. To keep the demand for renewable energy within acceptable boundaries, reducing energy use will continue to be crucial even in the case of negative carbon intensities, which are required by all available mitigation pathways compatible with the 1.5 °C target.

Acknowledgements The results in this article originate from the project "1p5dEurope – What the 1.5 °C target means for the EU", which was funded by the German Ministry of Education and Research under grant number: 01LS1607A. The underlying research design and preliminary partial results were presented at the 15th IAEE European Conference "Heading Towards Sustainable Energy Systems: Evolution or Revolution?" in Vienna in September 2017 and published in the online proceedings in the form of an extended abstract. We thank Luise Wanner and Nadim Asra for their help with compiling the data and Gillian Bowman-Köhler for proofreading the manuscript. Furthermore, we are grateful to Alexandra Denishchenkova, Wolfgang Eichhammer, Felix Christian Matthes, and Joachim Schleich for fruitful discussions about the topic of this article. Finally, we thank four anonymous reviewers and the editors of this special issue for their comments, which helped to improve the manuscript substantially.

Annex

The structuration of the energy-related carbon emissions used for the index decompositions is visualized in Fig. 7.

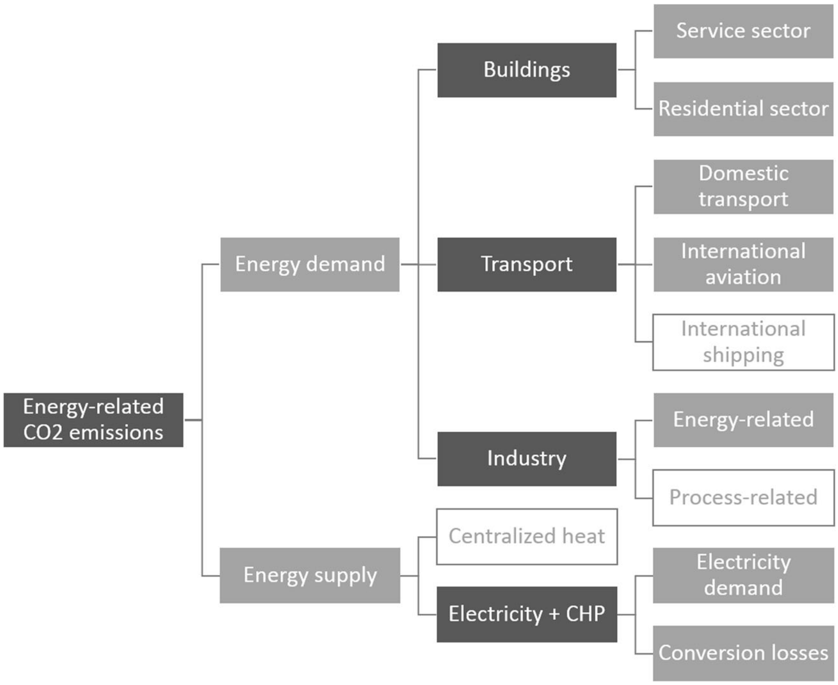

Fig. 7 The structure of the energy-related carbon emissions used for the index decompositions. Dark shading: decomposition analysis, light shading: included, white shading: excluded

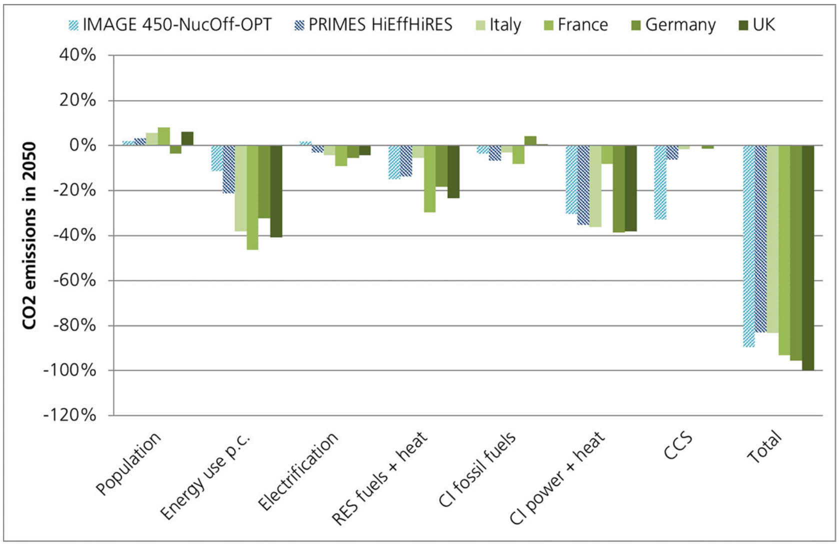

Fig. 8 Results of the index decomposition of the changes in energy-related carbon emissions from 2010 to 2050 (with time steps). *CCS* carbon capture and sequestration, *CI* CO_2 intensity, *p.c.* per capita, *RES* renewable energy source

Source: own representation

As an aggregation of the sector results, we provide here an analysis of the overall reduction of energy-related carbon emissions from 2010 to 2050. The overall level of ambition is similar for the EU PRIMES and the Italian scenario (83%), while the other three national scenarios are more ambitious by 10–16 percentage points. The EU's level of emission reduction in the global IMAGE scenario is in-between these two groups (see Fig. 8).

The index decomposition reveals that the main differences concern changes in the energy use per capita, the deployment of renewable fuels and heat and the use of CCS. The French scenario also shows a large difference in the contribution of reducing the carbon intensity of power generation. However, this only reflects that the carbon intensity of power generation in France is already very low today because of the high share of nuclear power.

The largest difference is for the use of CCS, which reduces the EU's carbon emissions by 33% in the IMAGE scenario, by 6% in the PRIMES scenario and by a marginal 0–2% in the national scenarios. Reducing the energy use per capita makes a much greater contribution to carbon reduction in the national scenarios than in the EU and global scenarios. It is three to four times higher than in the IMAGE scenario and double that in the PRIMES scenario. In contrast, the impacts of changes in population, in the share of electricity and heat as well as in the carbon intensity of fossil fuels all vary by approximately 10% only. It is striking, however, that the share of electricity and heat decreases in the IMAGE scenario.

The reasons for the varying contributions become much more apparent in the sector-level results. Nonetheless, the overall picture suggests that a more ambitious reduction of CO_2 emissions in the end-use sectors may significantly reduce the need for CCS. This finding is also supported by Solano Rodriguez et al. (2017), who point out that the important role played by bioenergy with CCS in the European scenario they evaluated is due to the lack of mitigation options in the buildings and transport sectors in the underlying model and that newly available options need to be included on a regular basis.

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