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How do system-wide net-zero scenarios compare to sector model pathways for the EU? A novel approach based on benchmark indicators and index decomposition analyses

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A R T I C L E I N F O

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A B S T R A C T

The use of scenarios and quantitative modelling to identify pathways for energy system transformations in line with the Paris targets is well established in the field of energy and climate policy. The resulting decarbonization pathways depend on both assumptions and the type of model used (e.g., integrated assessment models, energy system, macro-econometric or bottom-up sector models). The objective of this article is to analyze how energy demand sectors in system-wide net-zero scenarios for the EU compare to the results of sector-specific models. To this end, a novel approach referred to as "sectoral benchmarking" is developed and applied, combining the application of standard indicators such as energy intensity, electrification rate or carbon intensity with an index decomposition analysis. The combined approach allows visualizing how system-wide decarbonization pathways differ from the sector models' pathways by bringing the model output in a harmonized format for an efficient comparison. The analysis compares pathways from four different modelling tools: two European system models, one of which is an energy system model (EU TIMES) and the other a macro-econometric model (NEMESIS); as well as two sector-specific models, for transport (ALADIN) and for the industry and building sectors (FORECAST). We evaluate the system model's net-zero scenarios by comparing them to a corridor given by the sector models' current policy and net-zero emission scenarios. This corridor represents what the sector models deem as plausible from their bottom-up perspective within the boundaries of current policies and ambitions to reach net-zero.

Our results show that the system model net-zero pathways differ substantially from the sectoral perspective in all sectors. In the industry and building sectors, both system models' decarbonization ambitions are within the sector corridor, but the employed mitigation levers differ. In the industry sectors, the sectoral model achieves substantial CO_2 emission reductions with electrification, while the system models use more bioenergy (EU TIMES) or more energy efficiency (NEMESIS). In the building sector, both system models rely mostly on electrification, while the sector models relies on biomass and some district heat and electrification. In the transport sector, both system models' decarbonization ambition is substantially lower than the sector model's.

The observed differences are caused by a variety of factors, which we evaluate in this article. One reason is the system models' lower ambition to decarbonize the end-use sectors due to their ability to compensate with negative emission technologies across sectors. In addition, employed mitigation levers differ due to the models' differing capabilities to consider technologies as well as differences in the allocation of bioenergy to sectors.

Our findings can be used to determine how the different types of models can inform each other and to make the diverging decarbonization pathways more transparent to policy-makers and other relevant stakeholders.

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List of abbreviations

BECCS	Bioenergy with carbon capture and storage
CCS	Carbon capture and storage
GHG	Greenhouse gas
IDA	Index decomposition analysis
IAM	Integrated assessment models
LMDI	Logarithmic mean divisia index
NZE	Net Zero Emissions
WWH	Where we are headed

1. Introduction

The Paris Agreement has successfully established ambitious but commonly accepted international targets for climate mitigation and adaptation. In particular, it includes the goal of achieving a global balance of greenhouse gas (GHG) emissions and sinks during the second half of the 21st century [1]. This target has been adopted on the national and regional level by national authorities around the globe, mostly with an even higher ambition of reaching net-zero emissions by 2050 or earlier, in particular by the European Union (EU) in its Climate Law [2]. To achieve this target, the full decarbonization of the energy system plays a major role, given that the vast majority of GHG emissions results from the combustion of fossil fuels [3].

The use of scenarios and quantitative modelling to project the future evolution of anthropogenic GHG emissions [4] and to identify pathways for energy system transformations in line with the Paris targets is well established in the field of energy and climate policy [5]. It is well known that such scenarios do not only depend on the assumed socio-economic framework conditions and technology costs but also on the type of model applied [6,7]. For instance, it has been shown that the intertemporal cost optimization of integrated assessment models (IAMs) projects a higher contribution by negative emission technologies such as carbon capture and storage (CCS) in comparison to other types of models (e.g. Refs. [8,9]). Modelling tools able to highlight how we can achieve deep decarbonization at global, regional and/or sector level should ideally cover interactions between land use, agriculture, energy and economics [10,11] and advanced technological mitigation options [8,12] and consider social and societal responses [13–15]. No model, however, can really deal with all these aspects in a comprehensive way. That is why the scientific community uses a large spectrum of modelling tools [16].

On the one hand, large-scale global models such as IAMs and also other types of system-wide models (energy system or macroeconomic models) are useful to deliver long-term global climate mitigation strategies. However, their level of aggregation hides some region-specific conditions and constraints and limits an in-depth specific sector analysis. This can lead to potentially unrealistic outcomes according to expert assessments [17,18], e.g., pathways that rely too much on some technological options [19] and underestimate demand-side mitigation options [20]. Indeed, IAMs often strongly rely on supply-side mitigation and carbon dioxide removal. This is also reflected in the often not completely decarbonized end-use sectors of IAMs and system-wide models [20]. On the other hand, region- and sector-specific models, better equipped for more tailored assessments, are usually not able to consider regional interactions, feedback loop as well as macroeconomic effects [21] and they do not deliver a globally consolidated picture. Furthermore, sector models are not able to cover sector interactions endogenously. Instead, the models are fed with a fixed carbon budget or target that is linked with a certain temperature rise [20], though possibly calibrated and/or iterated with other sectoral models. However, they usually include a more detailed modelling of the sectoral dynamics and of the available mitigation options. These include for example demand-side mitigation options (such as demand reduction through behavioral changes) [9].

These differences in model outcomes pose a critical uncertainty, when it comes to deriving conclusions on the design of suitable energy and climate policy [22,23]. Therefore, it is highly important to compare the results of different models [24] and invoke the findings both for improving the different models and scenarios and for interpreting the remaining uncertainties correctly [16]. Thus, the validation of models is critical (e.g. Refs. [25,26]) to assess for different models capabilities in order to draw credible deep decarbonization pathways.

Against this background, the general objective of this article is to determine how sectoral bottom-up models' decarbonization pathways differ from those of energy system models. Due to the many output variables from the models, it is often challenging to compare model pathway designs and to understand how differences in chosen mitigation options affect emission reduction in a sector [27]. Even a sensitivity analysis only allows studying the effect of changing *one* variable at a time. In light of this difficulty, we develop a novel approach we call *sectoral benchmarking* building on selected benchmark indicators and the widely established index decomposition analysis (IDA) (see Ang and Goh [27] for an overview). This is an important addition to the literature, as it may help to understand and visualize how sectoral decarbonization scenarios differ from system-wide scenarios, and to determine how the different types of models can inform each other. It also helps to make the diverging decarbonization pathways more transparent to policy-makers and other relevant stakeholders.

Given strong evidence that demand-side mitigation is underrepresented in system-wide models both globally and in the EU [9,28], this paper is focused on the energy demand sectors in the EU. More precisely, the aim of this article is to assess the plausibility of EU mitigation pathways derived from system-wide models from the perspective of bottom-up sector models. The focus will therefore be on comparing the results of two European system-wide models EU TIMES and NEMESIS (which model the whole energy system *and* individual sectors) with a sectoral model of each of the three end-use sectors industry (FORECAST), transport (ALADIN) and buildings (FORECAST). The models were selected from a set of seven models within the European Horizon 2020 project PARIS REINFORCE based on availability of data output required to perform our analysis. The sector models differ by their sector coverage and modelling approach, as do the two system-wide models: one is an energy-system model and the other is a macro-econometric model. While the comparison of system models is not the focus of this work, our method nonetheless provides some insights on how the decarbonization pathways differ between these two types of system models.

In the literature, related approaches have been used by Peters et al. [29] as well as Wachsmuth and Duscha [9]. Peters et al. [29] have come up with a set of key indicators for tracking progress concerning the Paris Agreement targets based on an IDA of decarbonization scenarios. They have placed a large emphasis on the supply side covering CCS, fossil fuel switching, and various renewable energy sources. On the demand side, the only indicator they investigated was the overall energy intensity per GDP. In turn, Wachsmuth and Duscha [9] have used an IDA of decarbonization scenarios to argue that it is equally important to monitor the demand-side mitigation in a more disaggregated way. Accordingly, Duscha et al. [20] have used the results from bottom-up demand-side models to show that negative emissions in IAM results could be replaced by more ambitious demand-side mitigation. Still, there remains a gap with regard to an integrated approach to benchmark the results of system-wide models with the results of sectoral bottom-up models, which is addressed by this paper.

The paper is structured as follows: in section 2, the approach to sectoral benchmarking as a combination of benchmark indicators and an IDA is explained; in section 3, the findings from the application of sectoral benchmarking to the system-wide scenarios are presented; in section 4 the findings are critically discussed; the paper ends with a summary of the main findings and an outlook on future research directions in section 5.

2. Materials and methods

2.1. General approach

This article develops a novel analysis approach referred to as *sectoral benchmarking*, a combination of benchmark indicators and an IDA. We combine both methods, because they come with different benefits that help understand the differences between models. Their combination allows creating a transparent evaluation of decarbonization pathways. The indicators provide an overview over some key aspects relevant for climate policy measures that can be easily observed, e.g., electrification rate in transport. However, the indicators do not reveal the full picture of the emission reduction levers employed. E.g., if a model sees a lower electrification rate, what other measures are used to reach sufficient emissions reduction. In turn, the IDA allows comparing all emission reduction levers used and how they differ in their magnitude between models and scenarios over a fixed period of time. We have therefore combined the two methods in the following way: We use the benchmark indicators as the basis for our analysis, to which the IDA provides additional insights to better understand the indicator results. The resulting findings can provide a guideline which model outputs to check in detail and in particular which assumptions and mitigation levers to harmonize between system-wide and sectoral pathways. Furthermore, it can inform which kind of additional scenario runs can be particularly meaningful. In particular, the IDA allows for a better understanding of the absolute levers of decarbonization, in contrast to the benchmark indicators that show the relative aspects.

This work has mobilized four different modelling tools. Following the typology from Nikas et al. [30], these are two European models, of which one energy system model (EU TIMES) and one macro-econometric model (NEMESIS), and two sector-specific models, ALADIN for transport and FORECAST for the industry and the buildings sectors. The models, along with their classification, coverage and description are presented in Nikas et al. [31] and the detailed documentation of the four models can be found in the annex (section A.1). The models were harmonized for their assumptions on the main socio-economic criteria (population, fossil fuel prices, evolution of GDP) as far as model structures allowed and further cross-model consistency checks [7,32]. However, as documented in Nikas et al. [31], the models still differ in substitutability between technologies, technology availability and sectoral granularity. Further harmonization could be targeted but keeping the model characteristics different also allows for studying the broad range of possible future outcomes [24]. It is, however, crucial to understand how the different model characteristics affect the decarbonization pathways.

In the assessment, we use two set of scenarios produced by the models' armory of the PARIS REINFORCE research project. The first set of scenarios, the "Where we are headed" (WWH) scenarios, considers the potential evolution of GHG emissions based on already established policies and used the scenario protocol developed by Sognnaes et al. [33]. In this scenario set, current EU climate policies, as in legal text in October 2021, are implemented in the models up to 2030. Then, the system-wide models calculate the carbon price that allows reaching the same level of emissions in 2030 than with the EU climate policies and, after 2030, extrapolate this carbon prices growing as the GDP per capita in order to proxy a constant emissions mitigation effort up to 2050 (see Nikas et al. [31] for more details on the implementation of the WWH scenario). The sector models use a mix of the relevant sectoral policies and extrapolate their current ambition level, e.g. in FORECAST buildings, the current national policies for 2025–2030 are used and continued by extrapolation until 2050. This includes, for example, the application of non-ETS CO_2 price only by the EU Member States that currently apply it or have scheduled to start applying it by 2025 at the price development that the state has declared. For the transport WWH scenario in ALADIN, policies and mitigation targets established before the EU Fit-for-55 package were implemented (e.g. national subsidies and monetary incentives for electric vehicles). The second set of scenarios, the Net-Zero Emissions (NZE) scenarios, assess how an energy system transformation to net-zero GHG emissions can be reached in the EU by 2050, passing by the EU's updated target of −55% (w.r.t 1990) in 2030. For the system-wide models, this applies only across sectors, allowing for a compensation of remaining emissions in the demand sectors by negative emissions in the supply sector, while the sector models realize a nearly complete phase out of fossil fuels within the sector.

The *sectoral benchmarking* analysis is meant to reveal how the decarbonization pathways employed by the system-wide models are different from the sector models that cover techno-economic diffusion of innovative technologies from a bottom-up perspective. The method applied here is not used to validate the models but for an assessment of scenarios. Lots of the differences in decarbonization pathways are not related to the models themselves, but to the way general assumptions are translated to the models. An example is the implementation of current policies in the WWH scenarios, which depends on the parameters and variables available in the models. Here, a sectoral model can usually take into account more sectoral details. When this leads to a sectoral dynamic in the WWH scenario that is even faster than in the system-wide NZE scenario, the reasons should be evaluated closely.

The WWH and NZE scenarios from the sectoral models ALADIN and FORECAST are thus used as a benchmark to assess several indicator results of the system-wide NZE scenarios over time. Depending on where the system-wide NZE scenarios are located in the corridor created by the sector models' scenarios (more details in section 2.2), the degree of agreement between system-wide NZE scenarios and sector models' results can be assessed for the various sectoral levers. In particular, no deviations from the corridor indicate a certain agreement between the models, while larger deviations may point to important uncertainties in the indicator evolutions between the scenarios that should be checked in more detail. In this regard, the results of the IDA are used to foster the understanding of the differences by showing how the realized emission reductions are distributed across the sectoral mitigation levers. In the next sections, we explain the benchmark indicators and the IDA in more detail. More information on our approach and the PARIS REINFORCE framework can be found on the I^{2}AM PARIS website[1] and in the corresponding project report on the project's website.[2]

The analysis thereby adds to the findings of the recently published study on the stakeholder-driven model inter-comparison by Nikas et al. [31]. While this reference shows the differences in the WWH scenarios for CO_2-emission levels, primary and final energy, as well as for the role of key technologies such as CCS, hydrogen and electrification, it does not reveal the interplay of the different decarbonization levers. Our paper adds this interplay for both the WWH and the more ambitious NZE scenarios. Moreover, the sectoral benchmarking approach establishes a link between decarbonization levers and indicators, which enables us to understand which levers drive the differences between the indicators for the various models.

2.2. Benchmark indicators

It is widely established to compare energy system and sector scenarios based on key input and output data, in particular overall and sectoral activities, energy intensities, CO_2 intensities and the share of certain energy types. For the benchmark indicators, we have selected three to four such output variables per sector in an iterative procedure with the IDA, starting with activities and CO_2 intensities and adding

[1] See: www.i2am-paris.eu.

[2] See: The report (in press) will be published here: https://paris-reinforce.eu/publications/deliverables.

additional ones that appear particularly relevant in the IDA. The resulting indicators for each sector and the corresponding sector model are shown in Table 1. Further details on the selection and availability of variables are given in the annex (section A.2).

For each of the benchmark indicators, we consider the corridor spanned by the sectoral scenarios WWH and NZE. This corridor illustrates what the sector models deem as plausible from their bottom-up perspective within the boundaries of current policies and ambitions to reach net-zero for the following reasons: The **current policy scenario (WWH)** is used as the lower benchmark for the indicator outcomes of system-wide mitigation scenarios. It is possible that the system models' net-zero scenarios may show lower demand-sector ambition as they can compensate emissions between sectors. However, a lower ambition than the WWH sectoral benchmark is likely to suggest too limited use of the mitigation options at hand in the energy demand sectors. This may result from the fact that IAMs and energy system models usually have limited capabilities to represent sector policies beyond sectoral targets and carbon pricing [23]. Other policies are at best represented by a proxy indicator [34], e.g., energy efficiency policies as gains in energy intensity. Moreover, there are non-financial barriers to policy measures, which are covered more comprehensively by sectoral models. E.g., sectoral models capture the relevant technology stock and its transformation in more detail. The switch between technologies of an end-use application may have specific enablers or barriers related to the nature of the application or technology, which can be modelled at length in a sectoral model. In turn, some of the policy impacts in sectoral models cannot be translated to marginal abatement costs, which makes it difficult to implement the policies in cost optimizing system models [34]. A typical example are the barriers to thermal insulation of buildings such as high upfront investments with complex regulatory and/or technical requirements and the landlord-tenant dilemma, which are independent of the abatement costs [35].

The use of the sectoral **net-zero scenario (NZE)** as an upper benchmark is due to its more detailed coverage of sectoral dynamics that may limit the speed of decarbonization. If system-wide models show more optimistic developments than the sectoral net-zero scenarios for some of the benchmark indicators, this can result from a limited coverage of some sector-specific barriers. For example, IAMs are criticized for insufficient coverage of actor heterogeneity and diffusion of technological innovations [23]. For the NZE scenarios, it is expected that the system-wide models are usually no more ambitious in the demand sectors than the sectoral models, since the latter target net-zero emissions in the demand sectors, while the former often compensate for remaining emissions in the demand sectors by negative emissions in the supply sector.

Relative to the corridor spanned by the sectoral WWH and NZE scenario, we assess the sectoral indicators derived from the system-wide models' NZE scenarios. While a divergence from the corridor for certain indicators is of course possible, such a divergence highlights a development that requires further analysis. On the one hand, if a system model shows a stronger change in an indicator than in the sectoral NZE scenario, this could point to sector-specific limitations that are not considered, i.e., the system model's perspective is very progressive. On the other hand, if a system model shows a smaller change than in the sectoral WWH scenario, this constitutes a rather conservative development from the sectoral bottom-up perspective. While we argue that the sectoral corridors are useful to benchmark the system model NZE scenarios, we emphasize that sectoral models are not considered to deliver more plausible results in general. In fact, the corridor spanned by sector models functions as an orientation for comparisons in both ways: If the sectoral models indicators are substantially different from the system models, this could likewise reveal a lack of regard of system dynamics and cross-sector interaction (sector coupling) in the sector models.

Table 1
Sectoral benchmark indicators.

Sector	Indicator	Definition	Unit
Industry *Model used for benchmarking: FORECAST*	Change of energy intensity	Energy use per unit of GDP. Values for each year are calculated as the delta between that year and the start year 2020 for better comparison of the evolution of the indicator between models.	MJ/US $2010
	Electrification rate	Share of electricity in industry final energy demand	%
	Change of CO_2 intensity (net)	Total CO_2 emissions (excluding those permanently stored via CCS) per unit of industry final energy (only including direct emissions from the sector, not indirect emissions from electricity, district heat or hydrogen). Values for each year are calculated as the delta between that year and the start year 2020 for better comparison of the evolution of the indicator between models.	Mt CO_2/EJ
Buildings *Model used for benchmarking: FORECAST*	Change of energy consumption per capita	Buildings final energy use per person. Values for each year are calculated as the delta between that year and the start year 2020 for better comparison of the evolution of the indicator between models. A further disaggregation of the indicator into technology-related efficiency gains and reduction of building energy demand through (e.g., through changes in living area) would require energy service variables such as living area in m^2/person, which were not available for all models.	GJ/capita
	Electrification rate	Share of electricity in buildings final energy demand	%
	District heat rate	Share of district heat in buildings final energy demand	%
	Change of CO_2 intensity	Total CO_2 emissions per unit of buildings final energy (only including direct emissions from the sector, not indirect emissions from electricity, district heat or hydrogen). Values for each year are calculated as the delta between that year and the start year 2020 for better comparison of the evolution of the indicator between models.	Mt CO_2/EJ
Transport *Model used for benchmarking: ALADIN*	Change of energy consumption per capita	Transport final energy use per person. Values for each year are calculated as the delta between that year and the start year 2020 for better	GJ/capita

(continued on next page)

Table 1 (*continued*)

Sector	Indicator	Definition	Unit
		comparison of the evolution of the indicator between models. A further disaggregation of the indicator into technology-related efficiency gains and reduction of transport demand through (e.g., through changes in driving distance) would require energy service variables such as person-km, which were not available for all models.	
	Electrification rate	Share of electricity in transport final energy demand	%
	Biofuel admixture quota	Share of bioenergy in transport final energy demand	%
	Change of CO_2 intensity	Total CO_2 emissions per unit of transport final energy (only including direct emissions from the sector, not indirect emissions from electricity, district heat or hydrogen). Values for each year are calculated as the delta between that year and the start year 2020 for better comparison of the evolution of the indicator between models.	Mt CO_2/EJ

2.3. Index decomposition analysis (IDA)

In an IDA, changes in a variable over time are decomposed into the factors that contributed to this change [36]. The concept was developed originally to study the dependence between industrial activity and energy demand. Since then, the IDA approach has been applied in different frameworks and to different changing variables. Increasingly, CO_2 emissions changes have been analyzed using an IDA [37]. In this paper, we study the projected change of the variable CO_2 emissions between the years 2020–2050 for each energy demand sector. The variables influencing the CO_2 emissions changes are either driving forces such as population and economic activity or emission abatement levers such as energy efficiency or fuel switch. Hence, CO_2 emissions of a sector i (industry, buildings, or transport) are decomposed into contributing factors, corresponding to an adapted version of the Kaya identity. Here, CO_2 emissions encompass only direct emissions from the sector. Indirect emissions resulting from the production of electricity, district heat or hydrogen are not considered, meaning that higher shares of these energy types require stronger efforts in the supply sector. In a first step, captured and stored CO_2 emissions (CCS) are taken out of the Kaya identity, thereby moving from net to gross CO_2 emissions (see Ref. [9]).

The adapted Kaya identity is based on Ang [38]. It describes direct gross CO_2 emissions $C_{i,t}$ in year t as the product of its influencing activity variable $A_{i,t}$, the sectoral final energy demand $FED_{i,t}$ per activity, as well as the direct CO_2 emissions per unit of final energy use [38], as shown in equation (1):

$$C_{i,t} = A_{i,t} * \frac{FED_{i,t}}{A_{i,t}} * \frac{C_{i,t}}{FED_{i,t}} \tag{1}$$

The rationale on values used for CO_2 emissions is explained in the annex (section A.3.1). In line with Table 1, the factors are referred to as energy intensity $EI_{i,t}$ and carbon intensity $CI_{i,t}$, see equation (2):

$$C_{i,t} = A_{i,t} * EI_{i,t} * CI_{i,t} \tag{2}$$

The carbon intensity can be further broken down into the different shares of the fuel mix and thereby allow studying the impact of fuel switch changes [9]. The fuel mix consists of the fossil fuel share as well as the share of renewables (RES, including bioenergy and direct use of solar and geothermal energy) $s_{i,t}^{RES}$, hydrogen $s_{i,t}^{Hy}$, heat share $s_{i,t}^{HS}$, electricity share $s_{i,t}^{ES}$ (equation (3)). More details on the adapted Kaya identity can be found in the annex (section A3).

$$CI_{i,t} = CI_{i,t}^{fos} * \left(1 - s_{i,t}^{RES} - s_{i,t}^{Hy} - s_{i,t}^{HS} - s_{i,t}^{ES}\right) \tag{3}$$

With the adapted identity, the contribution of the individual non-fossil energy shares $s_{i,t}^{j}$ and the fossil CO_2 intensity $CI_{i,t}^{fos}$ of the remaining fossil fuels in the mix can be analyzed. The final identity is shown in equation (4).

$$C_{i,t} = A_{i,t} * EI_{i,t} * CI_{i,t}^{fos} * \left(1 - s_{i,t}^{RES} - s_{i,t}^{Hy} - s_{i,t}^{HS} - s_{i,t}^{ES}\right) \tag{4}$$

Depending on the sector, the shares of different energy sources vary. Annex section A.3.2 shows how the variables from the general decomposition identity are translated into sector-specific activities and levers for the three end-use sectors.

In the final step, the multiplicative elements of the Kaya identity are then transformed into additive elements to derive each variable's contribution to emissions reduction between 2020 and 2050 [27]. For this we use Logarithmic Mean Divisia Index I (LMDI I), which is the most recommended decomposition method for this according to Ang [36]. Detailed explanation on the LMDI method and why it is chosen here can be found in the annex (section A.3.3).

3. Results

3.1. Mitigation levels per sector

The CO_2 emissions changes between 2020 and 2050 for the EU28 in each model and both scenarios (WWH and NZE) are shown in Fig. 1 to provide a frame of reference for the sectoral benchmarking. The absolute emission levels in 2020 and 2050 can be found in the annex (section A.4). In 2050, the system-wide models create CO_2 sinks in the power sector for the other sectors with high net negative emissions using Bioenergy with Carbon Capture and Storage (BECCS). Therefore, the sectoral emission reductions in the system-wide NZE scenarios are substantially lower than in the sectoral NZE scenarios. It is noteworthy that in the transport sector the sectoral emission reductions in the system-wide net-zero scenarios are even lower than in the sectoral WWH scenario.

3.2. Industry

In Fig. 2, the benchmarking compares three indicators (energy intensity, electrification rate, net CO_2 intensity) for the sector model FORECAST (in green in Fig. 2) with the system-wide models NEMESIS and EU TIMES (light and dark blue) over time. The corridor of developments deemed most plausible from the perspective of FORECAST is highlighted (green shade). The indicators net CO_2 intensity and energy intensity have been calculated as the delta between each year and the start year 2020 to better compare the evolution of that indicator between the models. All data used in the figures can be found in the annex (A. 5).

In Fig. 3 the IDA results show the contribution of drivers and mitigation levers to emission changes between 2020 and 2050.

The indicator **net CO_2 intensity** measures total CO2 emissions (excluding those permanently stored via CCS) per unit of energy. By assumption, the FORECAST corridor for the indicator CO_2 intensity has a large bandwidth between WWH and NZE. EU TIMES NZE stays within the FORECAST corridor throughout the years indicating that its

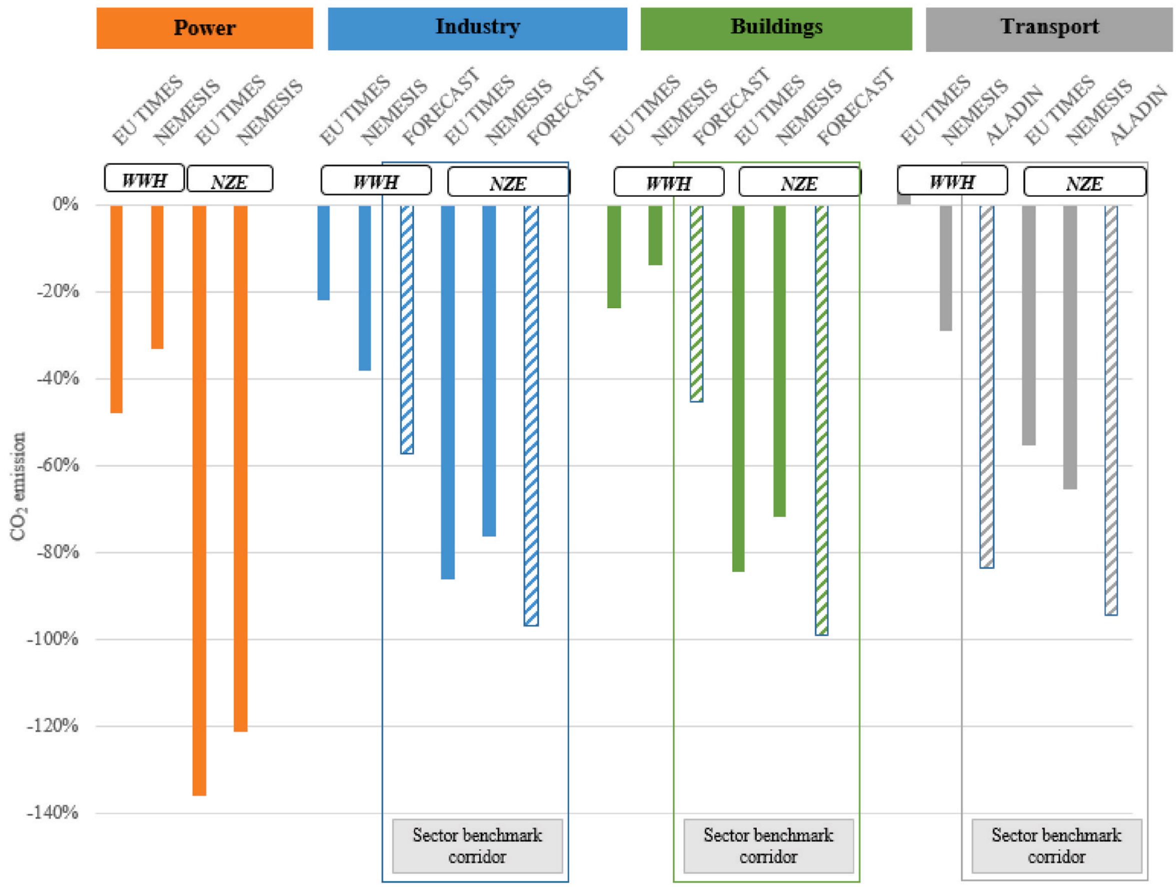

Fig. 1. Energy-related sectoral CO_2 emissions changes between 2020 and 2050 across models and scenarios. Data can be found in the annex Table A8.

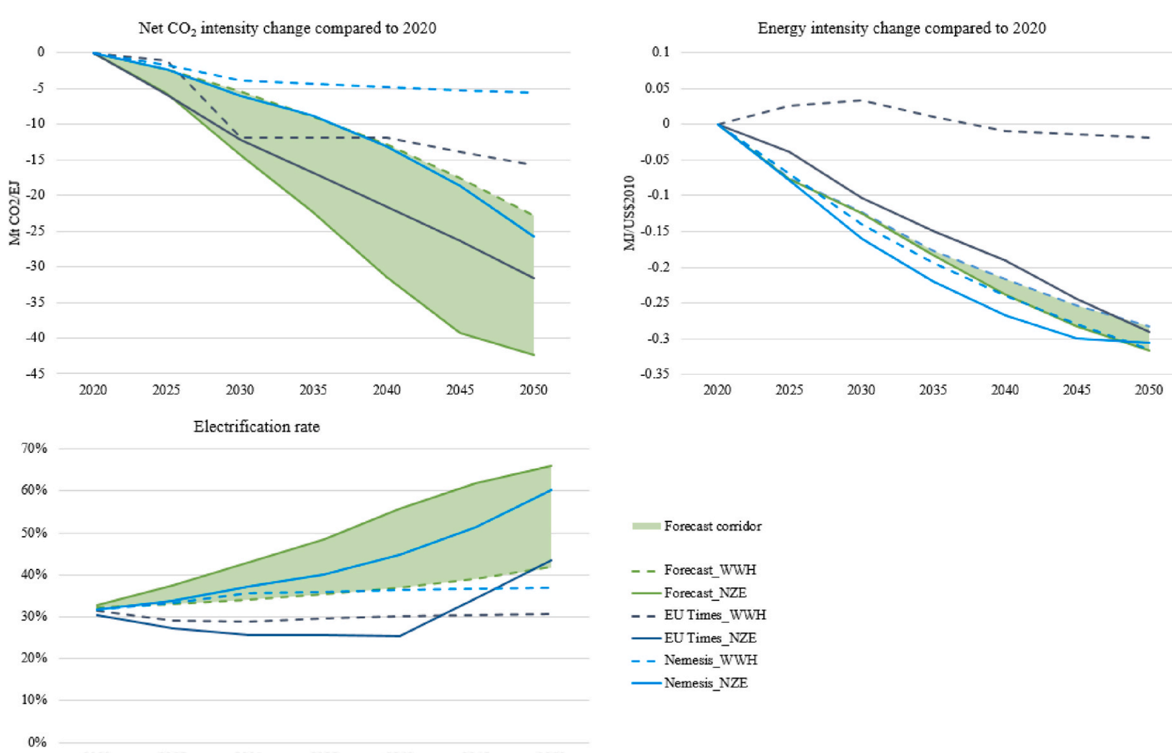

Fig. 2. Industry benchmark indicators (net CO_2 intensity and energy intensity compared to 2020, electrification rate). Data can be found in the annex Table A9.

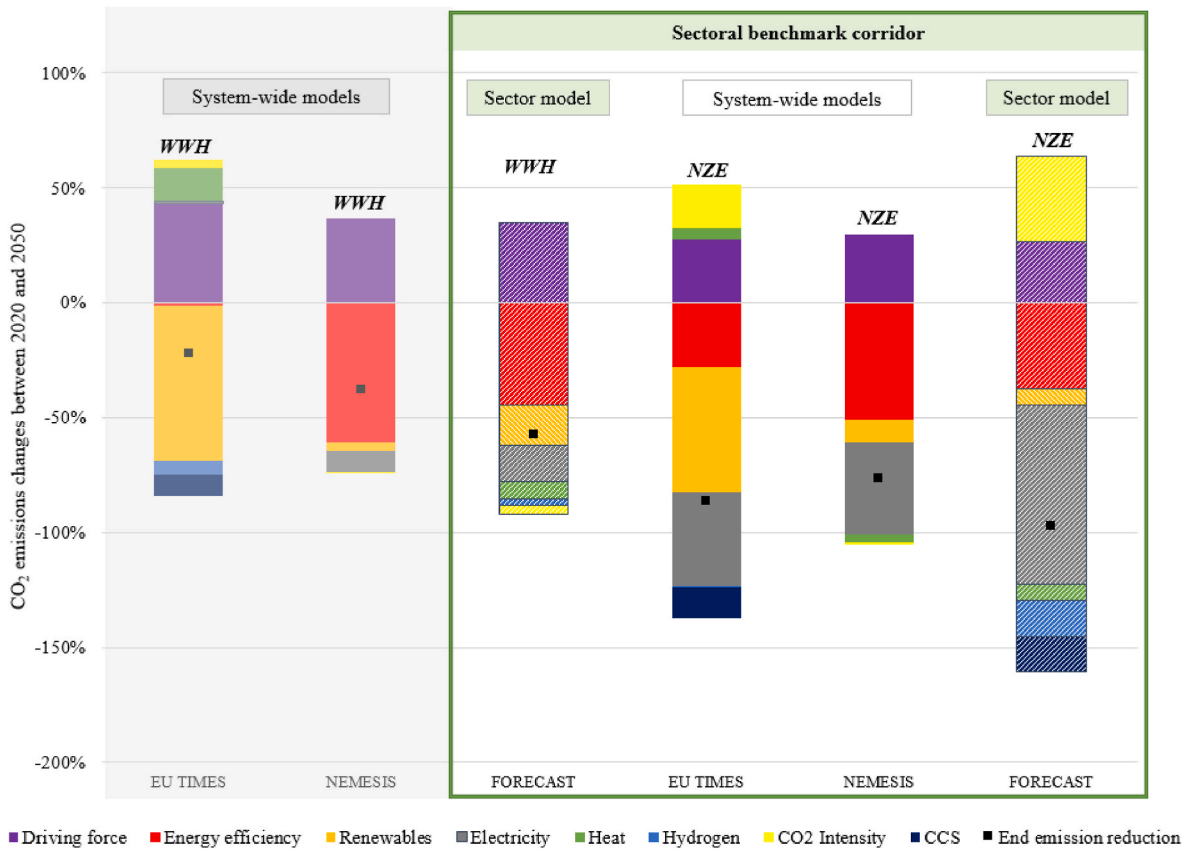

Fig. 3. Industry sector decomposition 2020 to 2050 (relative values). Data can be found in the annex Table A10.

reduction ambition is deemed plausible from the sector model perspective. The IDA however shows that the overall emission reduction between 2020 and 2050 is comparable between both models, indicating that EU TIMES starts from a much lower emission intensity than FORECAST. This is to be critically investigated in further model inspections. NEMESIS NZE emission reduction is more comparable to FORECAST WWH than NZE. Looking at the IDA results, we observe that there are two central decarbonization levers not used in NEMESIS: CCS and hydrogen. This is caused by the model not having the same technological detailed as the sector model FORECAST or the energy system model EU TIMES. In the two other models, CCS has a similar role in decarbonization. In FORECAST NZE, CCS is employed only in the cement sector (to both energy- and process-related emissions) due to the unavoidable process-related emissions by assumption. Hydrogen becomes much more important for decarbonization in NZE for FORECAST (-16%), while it plays a negligible role in EU TIMES. The role of hydrogen in industry is therefore potentially underrepresented as a decarbonization lever in the system models. In EU TIMES, decarbonization is mostly achieved through bioenergy use (-54%), which will be further addressed in the discussion section.

For **energy intensity** (energy use per unit of GDP), it can be observed that the corridor created by FORECAST is very narrow, as the WWH scenario already includes ambitious energy efficiency progress and a continuation of current trends in recycling and the material efficiency along the value chain. This is driven by a combination of policy (the Energy Efficiency Directive and the Renewable Energy Directive) and cost-competiveness (based on carbon price). In addition, the model includes a database on all EU production sites, considering new investor or manufacturer capacity announcements. Hence, for NZE, only some additional effective implementation in circular-economy-related measures remain as additional levers to reduce energy intensity. Overall, the trends of the three models' NZE scenarios are relatively similar. Looking at the IDA results, energy efficiency contributes - 38% to decarbonization in FORECAST NZE. The NEMESIS energy intensity indicators lie slightly below the FORECAST corridor, which suggests optimistic assumptions. This is mirrored in the high contribution of energy and material efficiency as well as circularity to decarbonization in the IDA for NEMESIS (-51%). Although the effect is small, this observation could be critically investigated with regard to the higher technology detail in FORECAST compared to NEMESIS, where end-use sector technologies are not explicitly modelled. The overall industry energy demand in EU TIMES without feedstocks (11.7 EJ in 2050) is higher than in NEMESIS and FORECAST (7.9–9 EJ in 2050). EU TIMES' total energy use only reduces slightly towards the years leading up to 2050 in NZE, while it reduces to a higher degree for NEMESIS and FORECAST. EU TIMES endogenously chooses the most efficient technologies available to satisfy demand, but the model assumes that industry energy demand grows with gross value added projections. Although overall energy demand is higher in EU TIMES, its energy intensity reduction pathway suggests consistency with sector model pathways.

The FORECAST corridor is very wide for the indicator **electrification rate** (electricity share in total energy use). In FORECAST WWH, at the assumed carbon price levels, biomass becomes a key decarbonization lever, as it is a more cost-effective solution than hydrogen and (to a lesser extent) direct electrification. This effect is also caused by the model not considering domestic and international limitations on sustainable biomass supply and competition with other demand sectors (i.e., household and power generation) in the WWH scenario. In the NZE scenario, the biomass sustainability is closely related to regional availability and land use, therefore the biomass potential is assumed to be limited to today's levels and its usage is to be more targeted [39]. Furthermore, the NZE scenario assumes additional policy support for the expansion of electrical and hydrogen applications. The electrification rate in NEMESIS NZE in 2050 is within the sector model corridor, while

EU TIMES NZE has a rate that is significantly below the corridor until after 2045. EU TIMES NZE pushes most of the decarbonization action via electrification into the last years, reaching the corridor in 2050. The lower initial electrification rate is explained by the model's reliance on bioenergy for decarbonization. The industry sector changes its decarbonization strategy towards electrification after 2040 when the use of bioenergy moves from the industry sector to the power generation, with the use of BECCS. The switch is driven by the limited availability of bioenergy resources in the EU and the necessity to employ BECCS technology to achieve the stringent emission target expected in ETS sectors in 2050. When looking at the IDA results, we see that the contribution of biomass ("renewables") is very high (-54%), but also electrification contributes significantly in EU TIMES in NZE (-41%), despite the late increase in electrification rate. This highlights that the high increase of electrification in the last ten years before 2050 is responsible for a large share of the overall decarbonization between 2020 and 2050, placing a large fraction of the effort on a comparably small period. In contrast, in the WWH scenario, more biomass remains available for industry after 2040 and electrification contributes less. NEMESIS NZE electrification rate is within the sector corridor and the IDA shows that the contribution of electrification to decarbonization is comparable to EU TIMES (-40%), but more evenly distributed over the years. Energy efficiency is however the main decarbonization lever in this model. Indeed, in macroeconomic models, as NEMESIS, sector production is defined with production functions that fix the level of production inputs in a total production function and the relative prices of the inputs. Thus, inter-fuels substitutions exist, marked with the electrification and substitution of non-energy inputs with energy, reducing the total energy consumption.

From the sectoral perspective, the potential of electrification to decarbonize industry could be further explored in the system models, in particular in EU TIMES, to relieve the dependence on scarce biomass and to distribute the mitigation ambition more evenly over the years.

3.3. Transport

Figs. 4 and 5 show the benchmark indicators and the IDA for the transport sector, respectively.

The changes in **CO_2 intensity** show the substantial differences in decarbonization between the sector model ALADIN and the other models. Even the more ambitious NZE results from the system models only reach the ALADIN WWH energy decarbonization level. This trend is explained by the system models' ability to share the burden of emissions reduction between the transport and the energy supply sector.

The sector model corridor of **energy use per capita** is substantially lower than the results for the other models from 2030 onwards. ALADIN already uses most energy efficiency measures in WWH, which is why the corridor for energy per capita is very narrow. The low energy consumption in ALADIN is largely driven by electrification of road transport and further efficiency increases of all transport modes by a mean of 30% between 2020 and 2050. Although the car fleet and therefore the total annual mileage decreases for passenger road transport, it increases for trucks and aviation (0.5%/a) and remains constant for shipping. In 2050, the energy use per capita even in the more ambitious NZE scenarios of the other models is not as low as in the WWH results for ALADIN. Accordingly, the IDA shows that energy efficiency has a negligible impact on decarbonization for EU TIMES. EU TIMES is the only model in which energy consumption per capita does not decrease steadily in the long term. EU TIMES NZE still uses 12 EJ of energy in the transport sector in 2050, while NEMESIS reduces it to 7.4 EJ and ALADIN to an even lower level of 4.4 EJ. ALADIN comprises of a high technology detail. It uses exogenous energy efficiency gains, driving profiles and willingness to pay for novel technologies to calculate energy demand. EU TIMES, in turn, calculates energy service demand changes in response to prices using own price elasticities. Our results show how this approach results in substantially higher energy demand for transport compared to ALADIN. The high difference in energy demand between the models should therefore be critically investigated from both the system and the sectoral perspectives.

ALADIN has a higher **electrification rate** in both scenarios compared to the system models, albeit EU TIMES being within the sector corridor towards 2050. In ALADIN, all transport modes are included except for international bunkers for shipping. Electrification is however only used in road transport and trains. Passenger cars are 100% and

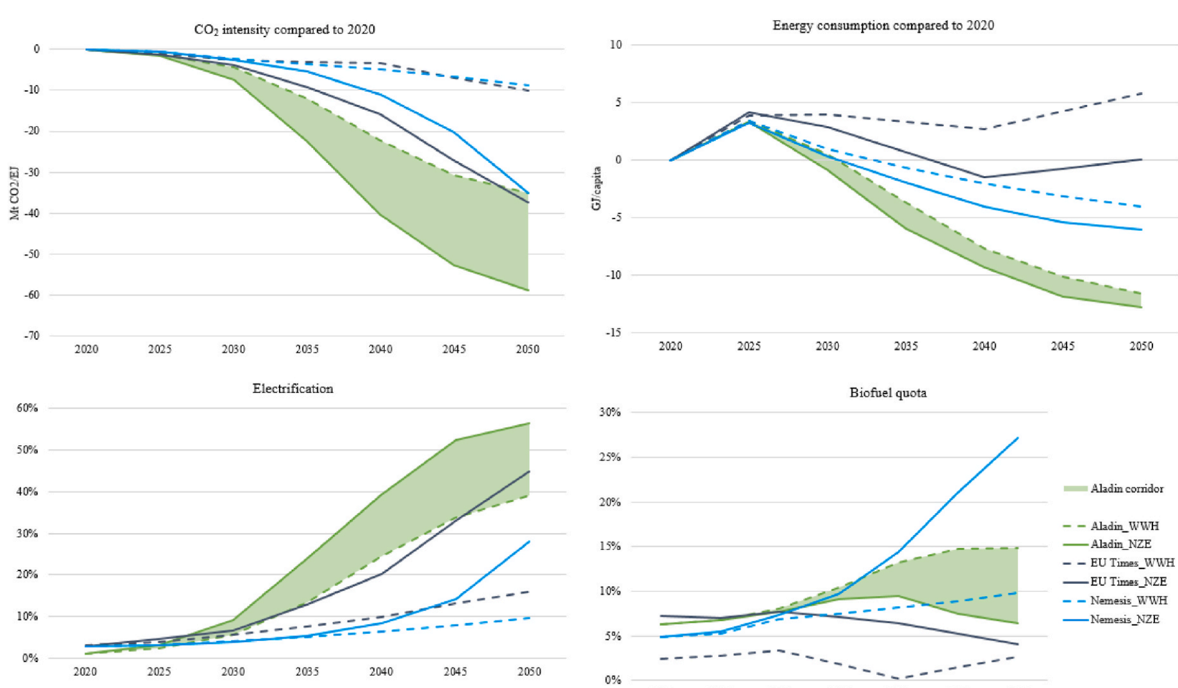

Fig. 4. Transport sectoral benchmark indicators (CO_2 intensity and energy consumption per capita compared to 2020, electrification rate and biofuel admixture quota). Data can be found in the annex Table A9.

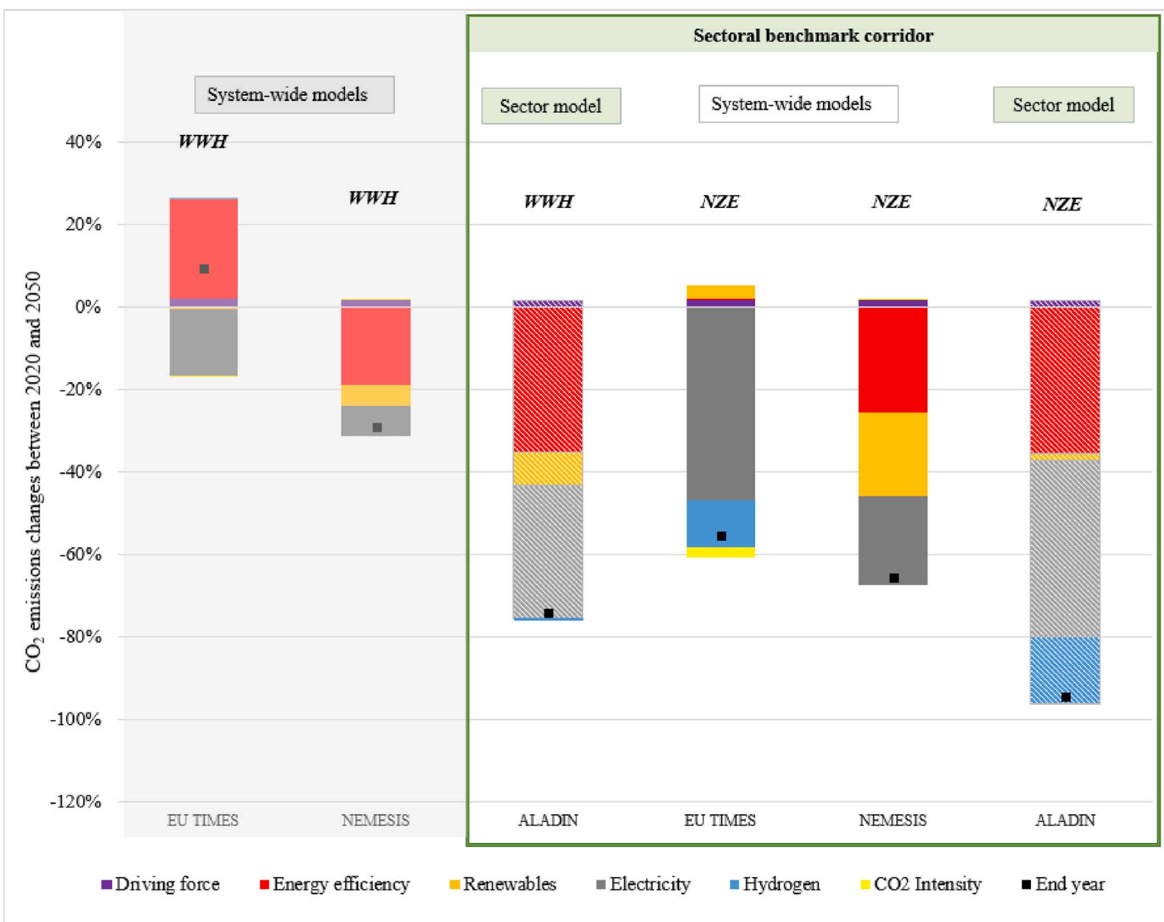

Fig. 5. Transport sector decomposition 2020 to 2050 (relative values). Data can be found in the annex Table A10.

trucks almost 100% electric by 2050, under the assumption that infrastructure includes fast chargers or overhead lines. This is a strong regional assumption, on which the system-wide model NEMESIS is comparably more conservative. NEMESIS electrification rate stays substantially lower than in NZE than in WWH, and which suggests that the model does not sufficiently reflect the decarbonization potential of decarbonization. This should be further investigated with regard to the lower technology detail in NEMESIS.

The available decarbonization levers depend on the transport mode (i.e. maritime, aviation, road or rail). EU TIMES covers the sectors road, rail, shipping and aviation, but exclude transport outside of the EU. For example, in EU TIMES, electrification is mostly applicable in road transport for passengers (cars, motorbikes and buses), while trucks employ electricity, hydrogen and natural gas to lower emissions. Road transport is not 100% electrified and decarbonized. In the IDA results, we see that the same levels of emission reduction are achieved through electrification (-43% for ALADIN and -47% for EU TIMES). Despite a similar contribution of electrification to decarbonization in ALADIN and EU TIMES, the high overall energy demand in EU TIMES leads to a significant amount of other energy carriers in the mix, and these are mostly of fossil origin. ALADIN has a low overall energy consumption, the non-electricity energy carriers are dominated by emission-free biofuels and hydrogen, with only a small share of fossil sources left.

The trends for **biofuel** use also differ between the models. ALADIN employs lower levels of biofuels in its more ambitious NZE scenario (0.3 EJ in 2050) than in WWH (1 EJ). In this model, biofuel and fossil fuel use is linked with each other, as fossil fuels are subject to a mandatory admixture quota. The reduction of fossil fuels therefore leads to a proportional reduction of biofuels even with more ambitious emission reduction. For NEMESIS, biofuels are a key decarbonization lever in NZE, and its quota lies substantially above the ALADIN corridor after 2038 (contribution of -20%). This is explained by the lack of alternative decarbonization options for some modes of transport in this model (no hydrogen or other electric fuels). The biofuel availability is considered highest in NEMESIS and lowest in EU TIMES, where biofuels do not contribute to decarbonization. Currently, NEMESIS does not have an upper limit on bioenergy availability, but the results are within the margin of EU potentials.

A key difference in sectoral and system pathways is the use of hydrogen, which is a decarbonization option in ALADIN and EU TIMES, but not in NEMESIS. Hydrogen is said to come into use with higher levels of decarbonization [31], which can be observed here by its higher contribution to decarbonization in ALADIN compared to EU TIMES. In ALADIN, aviation and navigation are decarbonized with admixture of mostly synthetic fuels (e-kerosene, e-diesel), as the sector uses the current admixture quantity of biofuels (0.72 EJ) as an orientation and aims not to exceed 1 EJ of bioenergy. With regard to aviation, only short term flights can be decarbonized by using alternative airplanes with direct hydrogen combustion starting in the 2040s. In EU TIMES, trucks use electricity, hydrogen and natural gas. Trains still use 15% of diesel, as an improvement of this transport mode is not assumed in the model. Intra-EU aviation achieves a 10% hydrogen penetration, while intra-EU navigation achieves 70% hydrogen and 30% natural gas (as a less emission-intensive fossil fuel compare to heavy fuel oil). In turn, NEMESIS shows that if hydrogen is not available and the potential of CCS in the power sector is more limited, the role of biofuels increases in transport. By comparing NEMESIS with ALADIN, it can also be inferred that hydrogen competes with biofuels within the sector and with BECCS cross-sectoral.

Transport is generally regarded as a hard-to-decarbonize sector, which is mirrored in the strategies of NEMESIS and EU TIMES which use burden-sharing with the power sector to achieve net zero emissions over all sectors. The sectoral perspective from ALADIN however shows that the transport sector can be decarbonized by itself but this is only achieved with a full electrification of the road sector in the next 30 years requiring strong infrastructure development for fast charging and

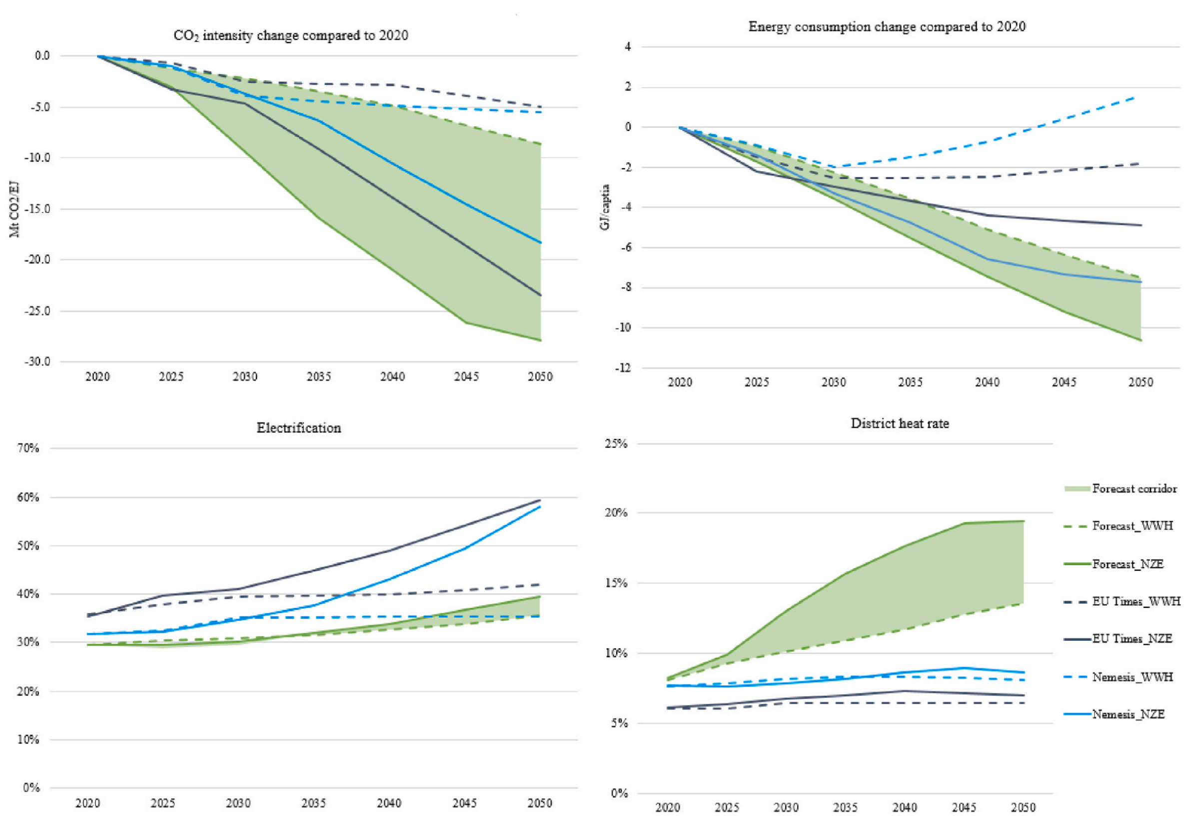

Fig. 6. Buildings sectoral benchmark indicators (CO_2 intensity and energy consumption per capita compared to 2020, electrification rate and district heat rate). Data can be found in the annex Table A9.

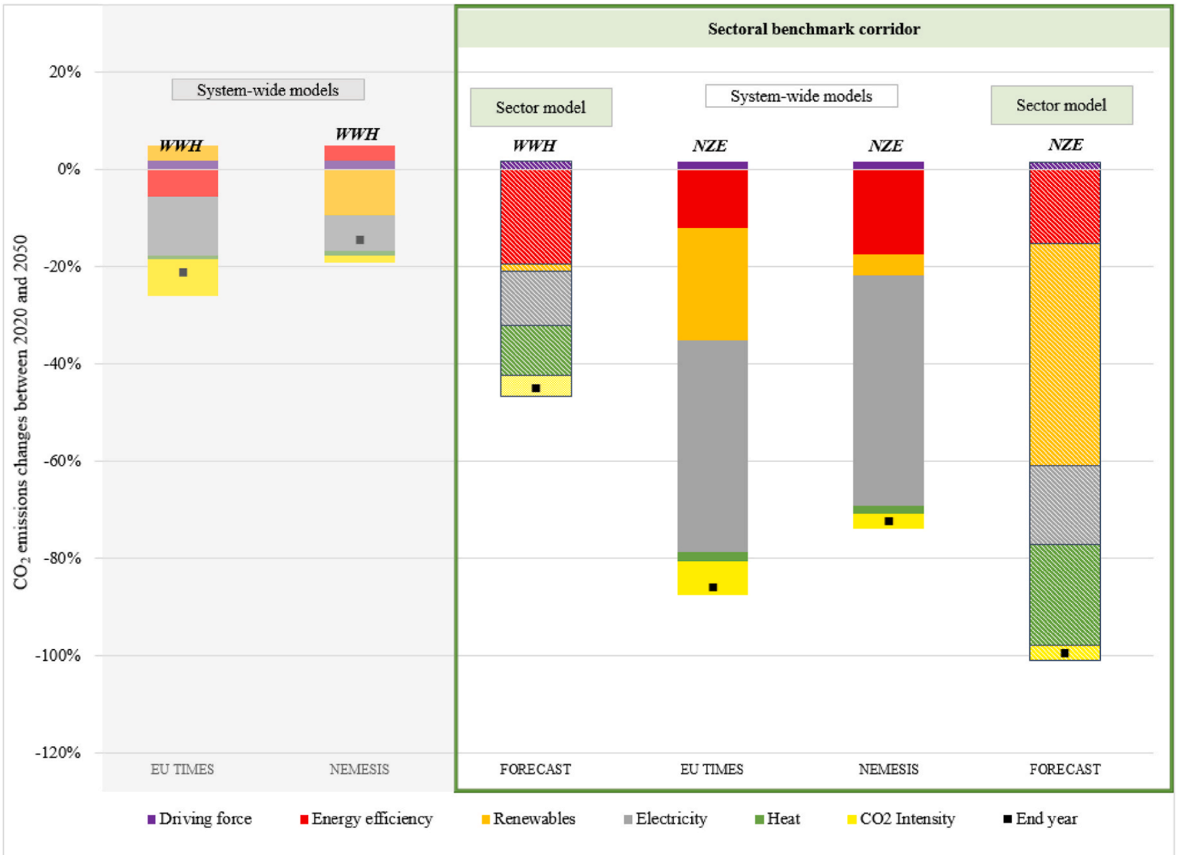

Fig. 7. Building sector decomposition 2020 to 2050 (relative values). Data can be found in the annex Table A10.

overhead lines. For EU TIMES, takeaways from the sectoral perspective mostly concern the use of energy efficiency as a decarbonization lever, as the model currently assumes no decrease in transport energy use. A third of transport fuels are fossil in 2050 in EU TIMES. The insights from the sectoral perspective for NEMESIS are different. The transport energy consumption in NEMESIS is considerably lower than EU TIMES, but compared to ALADIN, there is still potential for further energy efficiency measures. Second, to decarbonize the transport sector further, without relying on BECCS in the power sector, the infrastructure for electrification needs to be further developed. In addition, the use of hydrogen in transport would be needed. These measures reduce the dependence on the availability of sustainable biomass, but require substantial amounts of renewable electricity, which is available by assumption in ALADIN but its supply is not endogenously modelled as it is in the system models. The system models have to reflect the supply of several demand sectors requiring renewable electricity rather than looking at transport only.

3.4. Buildings

Figs. 6 and 7 show the benchmark indicators and the IDA for the building sector, respectively.

The corridor created by FORECAST for **CO_2 intensity** encompasses the other NZE scenarios, the system models are therefore not overly optimistic or conservative on the decarbonization of the energy mix in the building sector from a sectoral point of view.

For **energy consumption per capita**, the FORECAST corridor is relatively small, which is caused by the following effect: NZE includes more ambitious targets on the energy efficiency measures for appliances, lighting and heating, but the model outcome shows that the sector does not fully comply with the measures as determined by their costs (i. e., while there are higher efficiency classes for appliances available, the model does not necessarily choose them as they are not the most cost-effective option). In contrast, the efficiency classes in WWH are not as ambitious, but there is a higher compliance with them (i.e., the model choses the most efficient appliances available, as they are also the most cost-effective). This results in relatively similar energy per capita use in both FORECAST scenarios. EU TIMES is seemingly more conservative regarding energy efficiency compared to the sector perspective, while NEMESIS is within the sector corridor. The IDA shows that energy efficiency ranges from -12% in EU TIMES to -17% in NEMESIS. EU TIMES reduces energy intensity especially in the first few years, while it then stagnates more. NEMESIS starts from a higher energy consumption in 2020, but employs similar reduction patterns as the sector model. In 2050, the range of energy use lies between 12 and 14.6 EJ for all models, and thus does not differ much. It can be inferred that energy efficiency measures in the building sector do not increase substantially with higher climate change mitigation ambition for the sector model, and the system models can be considered to be still in the plausible range from this sector perspective.

The FORECAST corridor for **electrification rate** is also very small between WWH and NZE. The IDA results reveal that electrification is only the third largest decarbonization lever in FORECAST, and the model relies mostly on renewables (-46%, including mostly biomass and some solar thermal and ambient heat) and district heat (-21%) to decarbonize the building sector. Even in the more ambitious scenario, the electrification rate remains low because the model does not consider biomass scarcity that may result from its expanded use in other sectors; as well as the location of district heating networks that may reduce that lever's potential. Therefore, electrification is strongly competing with these two decarbonization levers. In addition, heat pumps as a key electrification measure only perform at high efficiency in new or well-insulated buildings. Due to the relatively low energy demand reduction, the model does not regard heat pumps as the most economic decarbonization option especially in non-refurbished buildings. FORECAST results do not show high renovation rates, which limits the number of buildings where electrification is the most cost-effective heating option. The other scenarios are above the FORECAST corridor, as they focus more on electrification and less on decentralized options. The IDA shows that renewables is not a substantial mitigation lever in NEMESIS (-4%). In this model, the use of renewables is lower in the more ambitious scenario than in the WWH, due to large energy saving and because bioenergy is used as BECCS in the power sector to reach net zero. EU TIMES also has a large contribution from renewables, but here, a large share of that (68% energy contribution to renewables in 2050) is ambient heat, geothermal and solar thermal heat. The IDA also shows that hydrogen is not used as a decarbonization lever in any of the scenarios: in NEMESIS and EU TIMES, it is not available, while it is not chosen by FORECAST.

The sectoral corridor for **district heat** lies significantly above the outcomes of the other models. The main difference comes from the steep increase of district heat in the NZE scenario. FORECAST has a more detailed representation of district heating compared to the system models, where heat is just considered an energy carrier like any other. Here, FORECAST can inform the system models to a certain degree. A caveat is that FORECAST's assumptions of district heating economics are based on densification of the existing grids via high connection rates. Grid expansion costs are neither included in the investment cost of the consumer's connection nor in the end-user price of district heat, as the model does not know the location of the district heating networks. This potentially underestimates the district heating cost and may thus overestimate its potential to decarbonize. FORECAST assumes that the heat grid is gradually decarbonized and the price projections for district heat reflect a switch to cleaner heat sources, but it does not consider any restrictions on the availability of clean district heat.

In turn, the system models' lower potential of district heat leads to a higher dependence on electrification. Technologies for electrification of building heat such as heat pumps exist today, but their wide-scale expansion across the building stock is hindered by the creation of electricity peaks in winter, efficiency-related cost concerns in older buildings, or heat source restrictions for heat pumps. Our results suggest that additional emissions reduction to decarbonize the building sector within its sector boundaries requires more renewables. In FORECAST, renewables are mostly solid biomass and some ambient heat, while the system models have to allocate scarce bioenergy across sectors. If net zero emissions can be achieved through burden sharing with other sectors, the building sector would rely more substantially on natural gas use, as can be observed in EU TIMES and NEMESIS compared to FORECAST. In general, the allocation of bioenergy use to sectors is very different between the models and influences the need for alternative decarbonization levers in the sector or across sectors.

4. Discussion

There are many reasons that can justify a deviation of the system-wide models' sectoral pathways from those modelled by the sector models, for instance comparing optimization with simulation models as well as different assumptions about biomass availability. A key observation is that high availability of negative emissions (mainly BECCS) in power generation allows for burden sharing of mitigation efforts between sectors in the system-wide models. BECCS is chosen by the cost-optimizing system models as the most effective system-wide lever for decarbonization. In the end-use sectors, this approach means that fewer of the remaining decarbonization options have to be exploited. Sectoral burden-sharing with BECCS is however also a strategy that relies heavily on bioenergy, which is an energy carrier that depending on the applied sustainability criteria, may only have a limited potential [40]. CCS as a technology has yet to reach large-scale market diffusion. Should the technology fail or not be available at a larger scale by the time it is needed, the decarbonization efforts could be at risk [19]. In many European countries, national restrictions on CCS are in place that prohibit both the storage of CO_2 as well as its export. The combination of bioenergy and CCS to decarbonize across sectors, therefore, brings large uncertainty and risks. In addition, our observations from the sectoral perspective show that system-wide cost optimal solutions may not adequately represent feasible transformation processes in the end-use sectors transport and buildings. Those sector-specific transformation processes may pose fewer risks as it means not relying on one technology (BECCS) too much. Due to the important role of BECCS in the power sector, it could be assumed that either biomass availability is higher in general in the system models, which cannot be assessed as the sector models do not account for the entire energy system, or that biomass is reallocated to the power sector from the demand sectors.

Looking at the end-use sectors, it can be inferred that none of the decarbonization pathways are alike, neither across models nor across sectors. The allocation of bioenergy to sectors is one key reason for those differences: In the industry sector, bioenergy use in FORECAST is comparable to the one in NEMESIS and significantly lower than in EU TIMES. In the transport sector, bioenergy use in ALADIN is substantially lower than in NEMESIS, but higher than in EU TIMES. In buildings, FORECAST projects a substantially higher bioenergy use than the system models. The change in bioenergy between the WWH and NZE models is also not consistent for all models: while the more stringent NZE targets lead to more bioenergy use in NZE than in WWH in some scenarios (e.g. NEMESIS industry and transport), others show the opposite (EU TIMES in all sectors). For the system models, it can be observed that decarbonization potential is mostly allocated to one end-use sector: for NEMESIS, it is transport, for EU TIMES, it is industry.

Another general observation is the difference in energy demand reductions across models, which is mirrored in the varying contribution of energy efficiency to the different sector's decarbonization pathways. These differences illustrate the varying mechanisms of the models to determine energy demand: EU TIMES, the energy system model that calculates energy service demand changes in response to prices, generally projects substantially higher energy demand than the sectoral models. The macroeconometric approach of NEMESIS, where the whole economic system is modelled and energy demand is a result of determined production functions, generally leads to lower energy demand than in EU TIMES, apart from the building sector, where they are similar. In fact, energy efficiency is a key lever for NEMESIS which also has not the technological details at hand that EU TIMES and the sector models have. Apart from industry, the sector models have a lower energy demand. This is most prominent in the transport sector, where the exogenous energy efficiency gains assumed in ALADIN lead to an energy demand that is a third of the demand in EU TIMES. Lastly, FORECAST determines energy consumption by diffusion through the technology stock and defining saving options for each process, reducing both its specific energy consumption and its process-related GHG emissions.

Despite these differences in energy demand, the high technological detail of EU TIMES allows this model to reach high decarbonization in industry and buildings, but not so in transport. Interestingly, the cost-optimal NZE scenario for EU TIMES is to allocate bioenergy to industry, and not fully decarbonize transport, while for NEMESIS, it is the other way around. In addition, our results also illustrate the impact of technological detail in the models on decarbonization pathways in the system models. While this informs policy makers on alternative decarbonization pathways if a technology fails (e.g., NEMESIS for scenarios without hydrogen or CCS in industry), it does impact the general comparability of pathways as they do not have the same solutions at hand. In any case, our findings about the high variation in the models' decarbonization pathways, across system models and between system and sector models, exemplify the necessity of comparing different types of models. This underlines where the usefulness of our approach lies: It does not identify a "correct" pathway to decarbonization but provides a rapid translation of model outputs into a harmonized format that can be easily understood and illustrates the differences in the models' pathways.

The input from sectoral benchmarking can be complemented with other ways of model and scenario validation. One such broader concept is the use of indicators for feasibility concerns by Brutschin et al. [41]. This judges the feasibility of pathways by applying absolute thresholds for selected indicators about various aspects including demand-side measures. Compared to the sectoral benchmarking, this has the disadvantage that it may neglect tipping points for these indicators in the dynamics of the system, but provides complementary information also with regard to other dimensions. Future research might consider combining this approach with a sectoral benchmarking.

A more direct approach than benchmarking is the linking of top-down and bottom-up models, which can lead to insights beyond those of the individual models, as has been pointed out by Krook-Riekkola et al. [42] in a national setting. However, achieving consistency requires multiple linking and linking of such models is highly non-trivial due to differences in model logics and comes with pitfalls [43]. A related approach is the coupling of various sectoral bottom-up models to a system-wide model. This is also highly complex due to the need for calibration of linkages between multiple models at the same time. It has been successfully applied on the national level (e.g. [44]) and is also explored for wider geographies, i.e. the EU and beyond [45].

Furthermore, the use of sectoral benchmarking does not – or only to a limited extent – deal with existing socio-economic barriers or environmental side-effects of the implementation of low-carbon economies. The social acceptance of global and local deployment of key decarbonization technology such as wind farms [46,47] or, as identified here, BECCS [48], requires knowledge sharing with and involvement of local citizens and stakeholders to favour their acceptance [49] whereas the mitigation of potential negative socio-economic impacts [50] and side-effects with regard to other environmental concerns [51,52] is essential (see Wachsmuth et al. [53] that dealt with such issues by translating the modelled pathways to socio-technical scenarios in co-creation workshops).

5. Conclusion and outlook

The objective of this article was to evaluate how energy demand sectors in system-model-based net-zero scenarios (with two different methods of techno-economic modelling) compare to the results of bottom-up sector models. By combining two methods, namely benchmark indicators and IDA, an in-depth analysis of differences and similarities between the sectoral pathways in the NZE scenarios from the system-wide models and the results of sector models is achieved. Our approach translates model output into a digestible and uniform format, from which model pathways can be critically investigated. The sectoral WWH scenario based on current policies was used as a lower benchmark and the sectoral NZE scenario approaching net-zero emissions within the sector was used as an upper benchmark to assess the system model scenarios.

The findings reveal that the system model net-zero pathways differ substantially from the sectoral perspective in all sectors. On the one hand, this is caused by the system models' lower ambition to decarbonize the end-use sectors due to their ability to compensate with BECCS across sectors. On the other hand, the employed mitigation levers differ compared to the sectoral perspective and also between the two system models.

In the **industry** sector, each of the models projects a different decarbonization strategy: the sector model relies mostly on electrification, EU TIMES on bioenergy and NEMESIS on energy efficiency. From a sectoral perspective, further exploration of the potentials to electrify industry heat and to use hydrogen can be considered for the system models in order to relieve the use of bioenergy. In addition, the lack of the industrial mitigation options CCS and hydrogen limits industry decarbonization in NEMESIS, and thereby increases the demand sectors' reliance on BECCS employed in the power sector, which should be critically examined.

For most indicators in the **transport** sector (energy use per capita, electrification and carbon intensity), the system-wide models appear not to reflect certain developments that the sector models already expect based on current policies. In the system-wide models, the transport sector exhibits a lower level of decarbonization compared to the other sectors and consequently benefits the most from the sector interconnections and the availability of carbon sinks in the power sector. The system-wide NZE scenarios do not show the same level of diffusion of novel technologies such as electrification of transport. However, the sector model achieves this strategy with a substantial reduction of overall transport energy demand, which is a strong prerequisite necessary to match the supply of renewable electricity needed for this decarbonization option. The sector model thereby shows the necessity of energy efficiency gains before making use of decarbonizing energy itself through the use of hydrogen and electricity.

The **building** sector shows that similar reductions in carbon intensity are achieved with different emission reduction levers: from a sector perspective, the system–model-based NZE scenarios appear optimistic about the diffusion of electrification in buildings, while they may be too conservative with regard to the impact of renewables (mostly biomass) and district heat. The system models have to allocate the available bioenergy over all sectors and both do not see it as the most viable option for the building sector. FORECAST, in turn, sees biomass as the main decarbonization lever. As the use of heat pumps is limited in non-refurbished buildings, the potential of electrification for decarbonization can be overestimated by the system-wide models, if the models include no vintage stock by buildings type. In turn, the diffusion of the district heat networks is highly region-specific and the estimation of its potential depends on the precision of the models to regard its outline. The sector model FORECAST, however, has also limited capabilities in the reflection of heat network extension cost and may be overestimating this potential. The learnings from the model perspectives go both ways: On the one hand, the more aggregated system models can evaluate if the potential of district heat has been sufficiently regarded and thereby potentially relieve the reliance on heat pumps depending on the building stock. The sector model, on the other hand, can be fed with potential heat supply restrictions.

In this paper, the sectoral benchmarking is focused on the energy demand sectors because there was evidence that demand-side mitigation is underrepresented in system-wide models. However, apart from certain supply constraints, for instance by absolute limits to biomass use or cost curves for hydrogen supply, demand-sector models usually take the avoidance of the indirect emissions as granted. This can lead to an over-exploitation of such levers. In turn, energy supply is usually covered in relatively high detail in system-wide models. Still, there are differences with regard to mitigation levers, in particular CCS [20]. Therefore, it can also be useful to apply a sectoral benchmarking with a bottom-up model that considers additional constraints such as the existing electricity grid [54] and to take into account life cycle emissions of the secondary energy carriers (hydrogen, electricity, bioenergy). Likewise, system-wide NZE scenarios with no or limited availability of biomass and/or CCS could provide interesting insights.

Credit author statement

Matia Riemer: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Validation; Visualization; Roles/Writing - original draft; Writing - review & editing.; Jakob Wachsmuth: Conceptualization; Funding acquisition; Methodology; Project administration; Supervision; Roles/Writing - original draft; Writing - review & editing.; Baptiste Boitier: Data curation; Resources; Software; Visualization; Roles/Writing - original draft, Writing - review & editing.; Alessia Elia: Data curation; Resources; Software; Roles/Writing - original draft, Writing - review & editing.; Khaled Al-Dabbas: Data curation; Resources; Software; Writing - review & editing.; Şirin Alibaş: Data curation; Resources; Software; Writing - review & editing.; Alessandro Chiodi: Data curation; Resources; Software; Writing - review & editing.; Felix Neuner: Data curation; Resources; Software; Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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A.1. Models

Table A1
Model overview based on I^{2}AM PARIS platform*, Nikas et al. [31] and further model-specific sources as indicated in the table. (*www.i2am-paris.eu)

Model (version)	EU TIMES	NEMESIS	ALADIN	FORECAST
Full name		New Econometric Model of Evaluation by Sectoral Interdependency and Supply	ALternative Automobiles Diffusion and INfrastructure	FORecasting Energy Consumption Analysis and Simulation Tool
Type	**System model:** Bottom-up energy system, technology-rich, linear optimization	**System model:** Macro-econometric	**Sector model:** Sectoral, agent-based simulation model to assess market diffusion of alternative drives	**Sector model:** Bottom-up sectoral simulation model
Short description and EU Disaggregation	EU TIMES is an enhanced version of the open source JRC-EU TIMES model [55], a European version of TIMES, designed for analyzing the role of energy technologies and innovation needs for meeting European energy and climate policy targets, representing EU Member States and neighboring countries, where each country is modelled as one region. It can consider policies affecting the entire energy system, sectors, group of or individual technologies/commodities [56,57].	The NEMESIS model [58,59]; is a sectoral, detailed macro-econometric system of models for every European country, for studying issues linking economic development, competitiveness, employment, and public accounts to economic and structural policies involving long-term effects [60]. It includes a detailed energy-climate module allowing to assess climate action in EU [31,32].	ALADIN [61] is an agent-based simulation model for assessing market diffusion of alternative drive (passenger and freight) vehicles in Europe until 2050, based on driving data of thousands of individual vehicles treated as agents, with changes in prices, user preferences, and model availability leading to alternative transport market diffusion [62].	FORECAST is a bottom-up simulation model for analyzing the long-term development of energy demand and emissions for the industry, residential and tertiary sectors at national level in the EU and neighboring countries, considering a broad range of mitigation options to reduce CO_2 emissions, combined with a high level of technological detail [63]. Technology diffusion and stock turnover are explicitly considered to allow insights into transition pathways and speed. The model further aims to integrate policies like for example carbon prices, energy taxes, subsidies (CAPEX and OPEX) or minimum standards.
Energy-related sectors modelled	Primary energy supply (including transformation); electricity generation; industry; buildings (residential and commercial); agriculture; and transport.	Primary energy supply (including transformation); electricity generation; industry; buildings (residential and commercial); agriculture; and transport.	Transport	Industry, buildings (residential and tertiary)
Inputs/drivers:				
- Economic inputs	GDP, price evolution and sector production growth,	GDP is endogenously determined even if calibrated on common assumptions for the WWH scenario. Other inputs: exchange rates, interest rates and GDP growth outside EU		GDP, gross value added, business cycle, industrial production for energy-intensive industry sectors
- Population inputs	Population, and number of households, household size, private consumption as a proxy for disposable income;	Population by age groups and educational attainment level	Driving data profiles of several thousand individual vehicles and other modes of transport (trips purpose, length of route, departure and arrival time), User acceptance (willingness to pay).	Population, number of employees in industry, number of households, development of housing and floor area per dwelling, employment
- Fossil fuel price inputs	Yes	Yes	Yes	Yes
- Targets inputs	CO_2 target (non-CO_2 exogenously determined), energy target, policy constraints and assumptions	CO_2 target (non-CO_2 exogenously determined)	CO_2 target	CO_2 target

(continued on next page)

Table A1 (*continued*)

Model (version)	EU TIMES	NEMESIS	ALADIN	FORECAST
- Energy inputs	Sources of primary energy supply and their potential, characteristics of energy technologies (efficiency, stock, availability, cost).	Power generation technology characteristics. End-use sector technologies are not explicitly modelled.	Cost of drive technologies per vehicles type, transport infrastructure (charging)	High technology detail: Nine sub-sectors (iron and steel, non-ferrous metals, paper and printing, non-metallic minerals, chemicals, food and drink and tobacco, engineering and other metal, other non-classified, and refineries). More than 80 process technologies and a variety of cross-cutting technologies. Five sub-modules cover: basic materials processes, space heating, electric motor systems, furnaces and steam systems. Heating degree days, monthly average temperature.
Harmonized inputs	• GDP, population, international fossil fuels prices, • Power generation technology costs • Demand drivers for transports, industry and buildings (cross-model consistency check)	• Endogenously determined GDP with cross-model consistency check • population, international fossil fuels prices • Power generation technology costs • Demand drivers for transports, industry and buildings (cross-model consistency check)	• International fossil fuels prices • Power generation technology costs • Demand drivers for transports (cross-model consistency check)	• Evolution of GDP as far as model structures allowed, population, international fossil fuels prices • Power generation technology costs • Demand drivers for industry and buildings (cross-model consistency check
Optimization/simulation	• Cost-efficient solution to decarbonize the energy systems • Partial equilibrium: drivers transformed into final energy demand, for which model produces energy supply • Energy service demand changes in response to prices depending on scenario design, using own price elasticities • Minimizes via linear programming the net present value of energy system cost, subject to constraints (energy, emissions)	• Economic instruments (e.g. carbon prices) are calculated by the model to reach pre-defined annual CO_2 emissions binding targets • Behavioral equations describe agents' optimal decisions with reduced functional forms. • Labor, investment, intermediate consumption: CES production functions are determined for each sector. • For each economic activity, energy demand is split in ten different energy sources through CES production functions • Logistic curves by technology are used in the power generation sector.	• Projection of stock, total energy consumption and CO_2 emissions. • Willingness to pay more assigned to each driving profile, subject to changes in the course of time because novel technologies become less attractive over time • Each agent optimizes its own functional form. • Market diffusion for alternative drives and fuels is determined by changes in prices, user preferences, and model availability, comparisons between electrification in road transport and the introduction of sustainable fuels in air and water transport	• Mitigation technologies are chosen based on discrete choice based on least total cost of ownership • Ambition level (qualitatively and quantitatively) is translated into model parameters such as carbon price, energy carrier prices, renovation rates, then explorative scenario run • For each process, saving options are defined, reducing the specific energy consumption and process-related GHG emissions by diffusing through the technology stock. • Diffusion based on boundaries and payback time (determined by end-consumer energy prices, European Union Allowance (EUA) prices and the saving potential) • Heat demand is calculated based on European building stock with age distribution, represented by market shares. • Technology-diffusion-based relative cost advantages of substitution alternatives. • Explorative scenario runs (simulation)
Which policies are modelled?	• Carbon emission constraint, carbon price, subsidies on technologies, feed-in-tariffs, renewable targets in gross final energy consumption,	• Carbon prices, sectoral and/or nationally differentiated carbon prices, Emissions caps in the EU-ETS sectors and others sectors and/or countries.	• Carbon prices • Subsidies, taxes (included in the total cost of ownership analysis) • EU emission targets (Fitfor55 package)	• Energy efficiency policies (modelled via investment decisions), energy taxes, carbon price • Subsidies, taxes, EU ETS, minimum energy performance, regulations on new installations of fossil fuel technologies
Outputs	• CO_2 emissions and energy demand • Annual stock and activity of energy supply and demand technologies.	• CO_2 emissions and energy demand • Economic variables (GDP and components, sector value-	• CO_2 emissions and energy demand	• CO_2 emissions and energy demand • Investment cost, energy spending, renovation rates,

(*continued on next page*)

Table A1 (*continued*)

Model (version)	EU TIMES	NEMESIS	ALADIN	FORECAST
	• Energy and material flows including emissions to air and fuel consumption, and associated costs	added, employment and production, etc.)		building efficiency, levelized cost of heat, technology mix.
Power (sub-sectors and technologies)	• Power: CCS, nuclear fission, hydro, biomass, geothermal, solar PV and CSP, wind • Heat: Geothermal, biomass	• Power: CCS, nuclear fission*, hydro*, biomass, geothermal*, solar PV and CSP, wind (* exogenously determined) • Heat:/	Not modelled	Not modelled
Industry (sub-sectors and technologies)				
- Process heat	Gas replacing oil/coal Biofuels Electricity Hydrogen	Gas replacing oil/coal Biofuels Electricity	Not modelled	Gas replacing oil/coal Biofuels Electricity Hydrogen
- Steam/Machine drives/CHP	Gas replacing oil/coal Electricity	Gas replacing oil/coal (No CHP) Electricity (NO CHP)		Gas replacing oil/coal Electricity
- Industry CCS included?	Yes	No		Yes
- Other	Behavior changes (lower material consumption)	Behavior changes (prices and incomes influencing demands).		Behavior changes (lower material consumption) .
Buildings (sub-sectors and technologies)				
- Heating:	Gas replacing oil/coal Biofuels Electricity Solar thermal Building shell efficiency Behavior change (less energy service demand, exogenously determined) Representation of energy efficiency in buildings with improvements	Gas replacing oil/coal Biofuels Electricity Solar thermal Industrial and urban wastes, Behavior change (less energy service demand)	Not modelled	Gas replacing oil/coal Biofuels Electricity Hydrogen Solar thermal Building shell efficiency Behavior change (less energy service demand), Four sub-groups (appliances and lighting, sanitary hot water, space heating, new and others), which are reflected by various end-uses. End-uses broken down into technologies, distinguished by efficiency classes. Stock of alternative appliances and the market share of different efficiency classes explicitly modelled, e.g. electric radiator, coal boiler, lignite boiler, natural gas boiler, oil boiler, solar thermal plus others, biomass boiler, district heating, heat pump, night storage heating
Transport (sub-sectors and technologies)				
- Road	Gas vehicles Hybrid and fully electric vehicles Hydrogen fuel cell vehicles Biofuels in fuel mix Efficiency	Gas vehicles Hybrid and fully electric vehicles Biofuels in fuel mix Efficiency	Gas vehicles Hybrid and fully electric vehicles Hydrogen fuel cell vehicles Biofuels in fuel mix Efficiency	Not modelled
- Rail	Electric Efficiency Hydrogen	Electric Efficiency	Electric, battery-electric trains Efficiency Hydrogen	
- Air	Biofuels in fuel mix Efficiency Hydrogen planes	Biofuels in fuel mix Efficiency	Biofuels in fuel mix Efficiency Hydrogen planes + eKerosine in mix	
- Marine	Biofuels Efficiency Hydrogen	Biofuels Efficiency	Biodiesel Efficiency Hydrogen, eDiesel	
- Other	Behavior changes (demand changes, such as travelling less)	Behavior changes (demand changes, such as travelling less). Efficiency gains are exogenously determined	Overhead catenary for heavy duty vehicles	
Use of biomass in the sectors in 2050 (EJ)	WWH: Total: 9.9 Industry: 6.4 Transport: 0 Buildings: 1.1 NZE: Total: 11.2 Industry: 2.6	WWH: Total: 6.7 Industry: 0.8 Transport: 0.8 Buildings: 2.9 NZE: Total: 13.4 Industry: 1.1	WWH: Transport: 1.0 NZE: Transport: 0.3	WWH: Industry: 1.2 Buildings: 1.2 NZE: Industry: 1.9 Buildings: 3.0

(*continued on next page*)

Table A1 (*continued*)

Model (version)	EU TIMES	NEMESIS	ALADIN	FORECAST
	Transport: 0.7 Buildings: 1.3	Transport: 2.0 Buildings: 1.8		
Additional references	[55,64]	[31,32,58–60].	[61,62,62]	[63]

A.2. Additional details on the benchmark indicators

The variables for the benchmark indicators were selected based on data availability. For the energy intensity variables, the following data was available.

- For the industry sector, sector activity that affects energy use and hence CO_2 emissions is usually measured by e.g. "value added" or the GDP. Only GDP was available as a variable in all three models for the industry sector.
- In the transport sector, sectoral activity can be measured by e.g. transport activity (e.g. vehicle-km/year) or population. Only population was available as a variable and is harmonized across all three models for the transport sector. Therefore, we use population as the activity and "energy use per capita" as the energy intensity for this sector. This means that a change in driving distance per capita is included in the energy intensity so that it cannot be distinguished from energy efficiency gains.
- In the building sector, sectoral activity can be measured by e.g. floor space or population. Only population was available as a variable is harmonized across all three models for the transport sector. Therefore, we use population as the activity and "energy use per capita" as the energy intensity for this sector. This means that a change in living area per capita is included in the indicator so that it cannot be distinguished from energy efficiency gains.

A.3. Additional details on the IDA approach

A.3.1. Calculation of CO_2 emissions

CO_2 emissions are calculated manually for all fossil energy consumed using the same emission factors. Otherwise, differences in emission factors used in the models would create distortion effects in the IDA, which would be visible e.g.; in the fossil CO_2 intensity. The chosen emission factors are shown in Table A2 and are based on the sectoral EU mix[3] and IPCC emission factors.[4] The model's output is reported in the IPCC format, therefore, fossil fuels are aggregated as solid, liquid and gaseous fossil fuels. For example, hard coal and lignite are aggregated as "solid fossil fuels". In each sector, the emission factors vary slightly due to the respective sector-specific energy carrier mix.

Table A2
Emission factors for each type of fossil fuel and sector.

Mt CO_2/EJ	Industry	Buildings	Transport
Solids fossil fuels	100	95	n.a.
Liquids fossil fuels	75	74	74
Gaseous fossil fuels	56	55	55
Other fossil fuels	172[a]	n.a.	74

[a] Average value from a mixture of residual fossil fuels aggregated under "other energy carriers" in FORECAST (petroleum coke, derived gases, stack gas).

A.3.2. Variables from the adjusted Kaya identity in IDA

Tables A3-A5 summarize how the generalized variables from the adjusted Kaya identity (left column) are translated into the sector-specific IDA variables (right column), which are the variables shown and discussed in the results of the paper.

Table A3
Summary of variables in the industry sector.

Generalized variable names in Kaya identity	Description	*Sector-specific variable names used in IDA*
Sectoral activity $A_{i,t}$	Driving force of sector	*GDP*
Energy intensity effect $\frac{FED_{i,t}}{A_{i,t}}$	The energy use per unit of activity	*Energy efficiency (final energy use/GDP)*
Emission intensity of fossil fuel use $\frac{C_{i,t}}{FED_{i,t}}$	The carbon emissions per unit of fossil energy	*Fossil CO_2-intensity*
Share of energy source	Relative contribution of one energy source to the total energy supply mix	*Electrification, Renewables (bioenergy), Heat (district heat), Hydrogen*

[3] For further information, see: https://ec.europa.eu/eurostat/en/web/energy/data/energy-balances.https://ec.europa.eu/eurostat/en/web/energy/data/energy-balances.

[4] For further information, see: https://www.ipcc-nggip.iges.or.jp/EFDB/main.php.

Table A4
Summary of variables in the transport sector

Generalized variable names in Kaya identity	Description	*Sector-specific variable names used in IDA*
Sectoral activity	Driving force of sector	*Population*
Energy intensity effect	The energy use per unit of activity	*Energy efficiency*
Emission intensity of fossil fuel use	The carbon emissions per unit of fossil energy	*Fossil CO_2-intensity*
Share of energy source	Relative contribution of one energy source to the total energy supply mix	*Electrification, Renewables (biofuels), Hydrogen*

Table A5
Summary of variables in the buildings sector

Generalized variable names in Kaya identity	Description	*Sector-specific variable names used in IDA*
Sectoral activity	Driving force of sector	*Population*
Energy intensity effect	The energy use per unit of activity	*Energy efficiency*
Emission intensity of fossil fuel use	The carbon emissions per unit of fossil energy	*Fossil CO_2-intensity*
Share of energy source	Relative contribution of one energy source to the total energy supply mix	*Electrification, Renewables (bioenergy, solar and ambient heat), Heat (district heat), Hydrogen*

A.3.3. Logarithmic Mean Divisia Index I method

As described in section 2.3, the adapted Kaya identity consists of multiplicative elements. These are transformed into additive elements, expressing how the variable changes over time between 2020 and 2050 [27]. Such a transformation from multiplicative to additive elements can be done with different methods [36]: Two main categories exist: Laspeyres and Divisia methods. According to Ang [36] divisia methods based on weighted sum logarithmic change rates are a more scientific approach, in contrast to Laspeyres method based on percentage change rates. As it uses a logarithmic change rate, it yields a symmetric and additive indicator [65]. We use this method by employing a sub-category method called Logarithmic Mean Divisia Index I (LMDI I), found to be the most popular IDA method [38]. For the derivation of the formula based on the LMDI approach, we start from the variable of interest (CO_2 emissions) and its variation from a start year 0 (2020 in our case) to an end year T (2050 in our case) (equation (A1)):

$$\Delta C_{total} = C_T - C_0 = \sum_{i=1}^{n} \Delta C_i \tag{A1}$$

The variable ΔC_i describes the changes in CO_2 emissions caused by individual factors i. We then calculate the logarithmic mean of this change between two different points in time C_0 and C_t using equation (A2):

$$L(C_t, C_0) = \frac{(C_t - C_0)}{\ln(C_t) - \ln(C_0)} \tag{A2}$$

Each variable affecting CO_2 emissions either as an emission driver or as a mitigation lever changes between 2020 and 2050, and that change is calculated as a logarithmic change rate $\ln\left(\frac{X_t}{X_0}\right)$. Here, X stands for the drivers or mitigation levers. Each driver's or mitigation lever's contribution to the change in CO_2 emissions is calculated by combining the logarithmic mean with the logarithmic change rate (equation (A3)):

$$\Delta C_x = \frac{(C_t - C_0)}{\ln(C_t) - \ln(C_0)} * \ln\left(\frac{X_t}{X_0}\right) \tag{A3}$$

For the intensity variables, the individual formulas are shown in Table A6.

Table A6
LMDI I formulas for the intensity variables in the Kaya identity

Variable name	Variable symbol	LMDI formula
Driving force/activity	$A_{i,t}$	$\Delta C_A = \frac{(C_t - C_0)}{\ln(C_t) - \ln(C_0)} * \ln\left(\frac{A_{it}}{A_{i0}}\right)$
Energy intensity	$EI_{i,t}$	$\Delta C_{ep} = \frac{(C_t - C_0)}{\ln(C_t) - \ln(C_0)} * \ln\left(\frac{EI_t}{EI_0}\right)$
Fossil fuel intensity	$CI_{i,t}^{fos}$	$\Delta C_e = \frac{(C_t - C_0)}{\ln(C_t) - \ln(C_0)} * \ln\left(\frac{CI_t}{CI_0}\right)$

To study the effects of fuel mix switches on CO_2 emission changes, the formula is extended to encompass the change rate of the energy source (ES) j and the general development of the entire energy mix. The share of fossil fuels in the fuel mix is calculated by subtracting non-fossil sources from total final energy consumption in a sector (equation (A4)):

$$\ln\left(\frac{s_{fossil,T}}{s_{fossil,0}}\right) = \ln\left(\frac{\frac{ES_T^{Total} - \left(ES_T^{RES} + ES_T^{HS} + ES_T^{ES} + ES_T^{Hy}\right)}{ES_T^{Total}}}{\frac{ES_0^{Total} - \left(ES_T^{RES} + ES_T^{HS} + ES_T^{ES} + ES_T^{Hy}\right)}{ES_0^{Total}}}\right) \tag{A4}$$

$$\ln\left(\frac{s_{fossil,T}}{s_{fossil,0}}\right) = \ln\left(\frac{1 - s_{i,T}^{RES} - s_{i,T}^{Hy} - s_{i,T}^{HS} - s_{i,T}^{ES}}{1 - s_{i,0}^{RES} - s_{i,0}^{Hy} - s_{i,0}^{HS} - s_{i,0}^{ES}}\right)$$

The problem of having zero values in LMDI models is avoided by using a fossil fuel share factor which gives the proportion of fossil fuel in the total final energy mix [66]. In a final step, the contribution of each non-fossil energy source is calculated by multiplying equation A 4 with a weight factor ω_j. The weight factor expresses how one non-fossil energy source changes in relation to the change of all energy sources. It is calculated by dividing the contribution of energy source j to the total emission change ΔC_j by the summed up emission changes from all energy sources $\sum_j^n \Delta C_j$ (equation (A5)).

$$\omega_j = \frac{\Delta C_j}{\sum_j^n \Delta C_j} \tag{A5}$$

As explained in 2.3, in long-term scenarios, the use of carbon capture and storage (CCS) and bioenergy with carbon capture and storage (BECCS) increases significantly and with it the need to account for zero or negative emissions in IDA. These values cannot be solved by the LMDI method [67]. To address this problem, several solutions are discussed in literature [27]. One option is to take CCS out of the Kaya identity and subtract it from the total final emissions (e.g. [9]), which has been done in this analysis. Therefore, the decomposition is only done for the gross CO_2 emission before the removal and CCS is assessed separately (equation (A6)). All formulas for the different energy mix variables are summarized in Table A7.

$$C_{2,gross} = C_{2,net} + CCS \tag{A6}$$

We show the IDA results as relative CO_2 emission changes between the start year 2020 and the final year 2050. By setting the start-year CO_2 emissions to 100% the contributions of the driving forces and mitigation levers are calculated by dividing their contribution to absolute emission changes by the total start-year emissions.

Table A7
LMDI formulas for the energy mix variables

Variable names	Variable symbol	LMDI formula
Share of renewables in energy mix (mostly bioenergy)	$s_{i,t}^{RES}$	$\Delta C_{res} = \frac{(C_t - C_0)}{\ln(C_t) - \ln(C_0)} * \ln\left(\frac{s_{fossil,T}}{s_{fossil,0}}\right) * \omega_{RES}$
Share of heat in energy mix	$s_{i,t}^{HS}$	$\Delta C_{HI} = \frac{(C_t - C_0)}{\ln(C_t) - \ln(C_0)} * \ln\left(\frac{s_{fossil,T}}{s_{fossil,0}}\right) * \omega_{HS}$
Share of electricity in energy mix	$s_{i,t}^{ES}$	$\Delta C_{EI} = \frac{(C_t - C_0)}{\ln(C_t) - \ln(C_0)} * \ln\left(\frac{s_{fossil,T}}{s_{fossil,0}}\right) * \omega_{ES}$
Share of hydrogen in energy mix	$s_{i,t}^{Hy}$	$\Delta C_{PtX} = \frac{(C_t - C_0)}{\ln(C_t) - \ln(C_0)} * \ln\left(\frac{s_{fossil,T}}{s_{fossil,0}}\right) * \omega_{Hy}$
CCS (Captured emissions)	*CCS*	Taken out of the Kaya identity, therefore not the LMDI formula is used but the absolute change between the base year and current year

IDA results differ whether they are calculated directly between two time points (e.g.; 2020 and 2050), or whether they are calculated using several intermediate time steps (e.g., from 2020 to 2025) in between, as is explained in Wachsmuth and Duscha [9]. When intermediate time steps are included, the results reflect more accurately which variables contributed to the emissions changes, which is why we calculate the results with five-year time steps between 2020 and 2050 and then add the results to get the total change between 2020 and 2050.

A.4. 2020 and 2050 emission levels

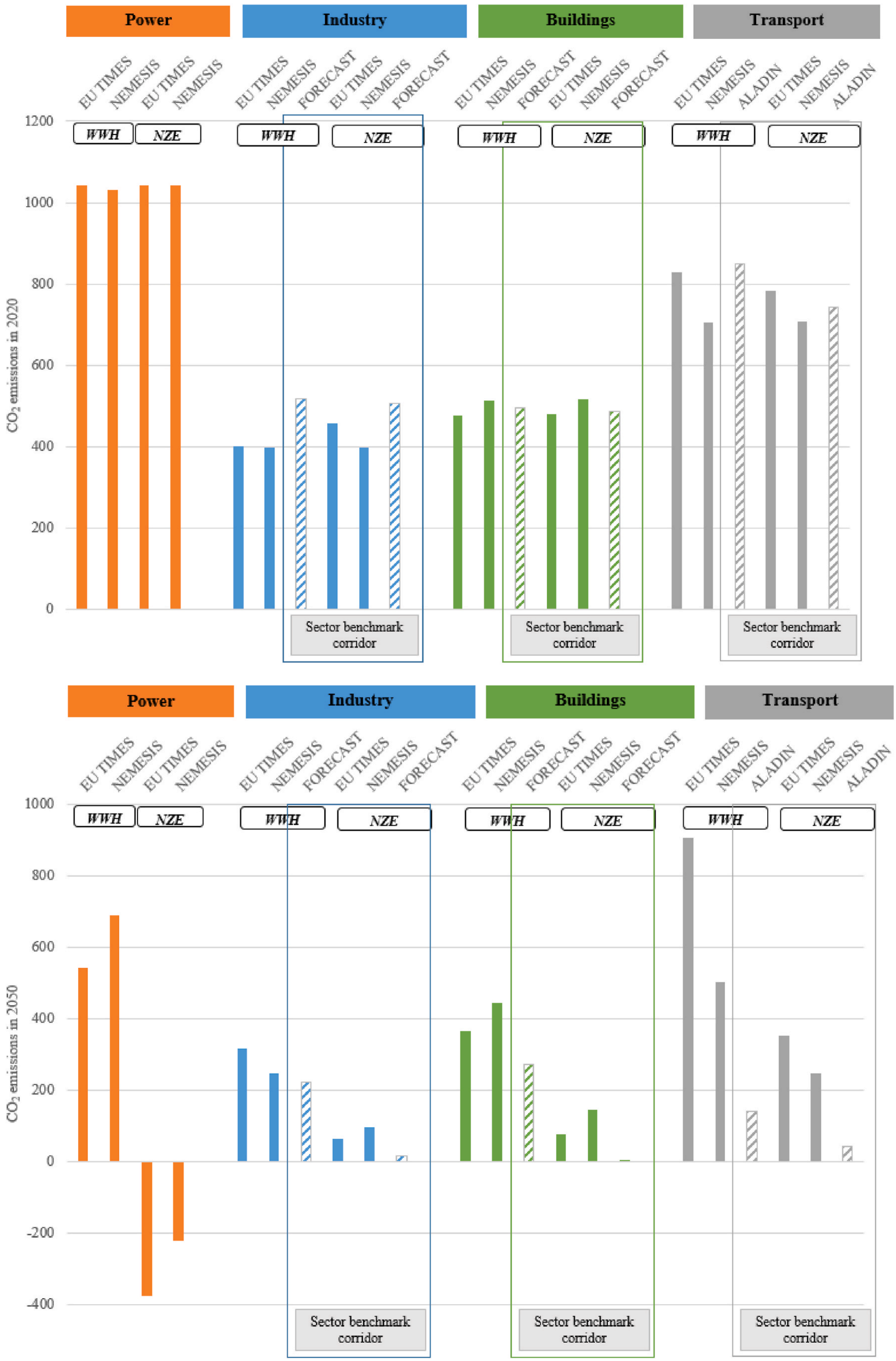

Fig. A1. Sectoral CO_2 emission levels in base year 2020 and target year 2050 across models and scenarios. Data can be found in Table A8. Slight deviations in start level emissions are caused by some model's decarbonization measures starting before 2020. The displayed emissions should only be made up by energy-related (combustion) emissions but for some processes in the industry sector, a differentiation into combustion or process emissions is not always feasible. These differences in the allocation of emissions to combustion or process emissions can explain some of the deviations in the industry sector.

A.5. Data used in figures

Table A8
Data CO_2 emission reduction, 2020 and 2050 levels for Fig. 1 and Fig. A1.

Sector	Power					
Scenario	WWH	WWH	NZE	NZE		
Model	EU TIMES	NEMESIS	EU TIMES	NEMESIS		
2020	1043	1033	1043	1041		
2050	543	690	−377	−223		
Emission reduction	−48%	−33%	−136%	−121%		
Sector	Industry					
Scenario	WWH	WWH	WWH	NZE	NZE	NZE
Model	EU TIMES	NEMESIS	FORECAST	EU TIMES	NEMESIS	FORECAST
2020	403	399	517	458	399	507
2050	315	247	221	62	94	15
Emission reduction	−22%	−38%	−57%	−86%	−76%	−97%
Sector	Buildings					
Scenario	WWH	WWH	WWH	NZE	NZE	NZE
Model	EU TIMES	NEMESIS	FORECAST	EU TIMES	NEMESIS	FORECAST
2020	478	515	496	480	516	489
2050	365	444	271	75	145	5
Emission reduction	−24%	−14%	−45%	−84%	−72%	−99%
Sector	Transport					
Scenario	WWH	WWH	WWH	NZE	NZE	NZE
Model	EU TIMES	NEMESIS	ALADIN	EU TIMES	NEMESIS	ALADIN
2020	828	706	849	783	707	743
2050	905	501	139	350	245	42
Emission reduction	9%	−29%	−84%	−55%	−65%	−94%

Table A9
Benchmarking indicator data for Figs. 2, 4 and 6.

Scenario	Sector	Indicator	Unit	2020	2025	2030	2035	2040	2045	2050
FORECAST_WWH	Industry	Energy intensity	MJ/US$2010/yr	0.64	0.56	0.51	0.46	0.42	0.38	0.35
FORECAST_WWH	Industry	Electrification rate	%	0.32	0.33	0.34	0.35	0.37	0.39	0.42
FORECAST_WWH	Industry	CO2 intensity (net)	Mt CO2/EJ/yr	44.5	42.2	39.1	35.6	31.8	26.9	21.6
FORECAST_WWH	Buildings	Energy/capita	GJ/capita	33.5	32.5	31.2	29.9	28.4	27.1	26.0
FORECAST_WWH	Buildings	Electrification rate	%	0.30	0.30	0.31	0.32	0.33	0.34	0.36
FORECAST_WWH	Buildings	District heat rate	%	0.08	0.09	0.10	0.11	0.12	0.13	0.14
FORECAST_WWH	Buildings	CO2 intensity	Mt CO2/EJ/yr	28.8	27.2	26.2	24.9	23.5	21.5	19.7
FORECAST_NZE	Industry	Energy intensity	MJ/US$2010/yr	0.63	0.55	0.51	0.45	0.39	0.35	0.31
FORECAST_NZE	Industry	Electrification rate	%	0.33	0.37	0.43	0.48	0.56	0.62	0.66
FORECAST_NZE	Industry	CO2 intensity (net)	Mt CO2/EJ/yr	44.0	38.3	29.6	21.6	12.5	4.7	1.6
FORECAST_NZE	Buildings	Energy/capita	GJ/capita	33.3	31.6	29.7	27.8	25.8	24.1	22.7
FORECAST_NZE	Buildings	Electrification rate	%	0.30	0.30	0.30	0.32	0.34	0.37	0.39
FORECAST_NZE	Buildings	District heat rate	%	0.08	0.10	0.13	0.16	0.18	0.19	0.19
FORECAST_NZE	Buildings	CO2 intensity	Mt CO2/EJ/yr	28.0	25.0	18.7	12.1	7.0	1.9	0.1
EU TIMES_WWH	Industry	Energy intensity	MJ/US$2010/yr	0.70	0.72	0.73	0.71	0.69	0.68	0.68
EU TIMES_WWH	Industry	Electrification rate	%	0.31	0.29	0.29	0.30	0.30	0.30	0.31
EU TIMES_WWH	Industry	CO2 intensity (net)	Mt CO2/EJ/yr	31.9	30.7	20.0	20.0	20.0	17.9	16.1
EU TIMES_WWH	Buildings	Energy/capita	GJ/capita	32.3	30.8	29.8	29.8	29.8	30.1	30.5
EU TIMES_WWH	Buildings	Electrification rate	%	0.36	0.38	0.40	0.40	0.40	0.41	0.42
EU TIMES_WWH	Buildings	District heat rate	%	0.06	0.06	0.06	0.06	0.06	0.06	0.06
EU TIMES_WWH	Buildings	CO2 intensity	Mt CO2/EJ/yr	27.6	27.0	25.1	25.0	24.8	23.7	22.6
EU TIMES_WWH	Transport	Energy/capita	GJ/capita	23.1	27.0	27.1	26.4	25.8	27.3	28.9
EU TIMES_WWH	Transport	Electrification rate	%	0.03	0.04	0.06	0.08	0.10	0.132	0.161
EU TIMES_WWH	Transport	Biofuel admixture quota	%	0.02	0.03	0.03	0.02	0.00	0.02	0.03
EU TIMES_WWH	Transport	CO2 intensity	Mt CO2/EJ/yr	69.9	68.8	67.3	66.8	66.4	63.0	59.9
EU TIMES_NZE	Industry	Energy intensity	MJ/US$2010/yr	0.70	0.66	0.59	0.55	0.50	0.45	0.41
EU TIMES_NZE	Industry	Electrification rate	%	0.30	0.27	0.26	0.26	0.26	0.34	0.44
EU TIMES_NZE	Industry	CO2 intensity (net)	Mt CO2/EJ/yr	31.0	25.1	18.8	14.1	9.4	4.60	−0.6
EU TIMES_NZE	Buildings	Energy/capita	GJ/capita	32.2	30.0	29.2	28.5	27.8	27.5	27.3
EU TIMES_NZE	Buildings	Electrification rate	%	0.35	0.40	0.41	0.45	0.49	0.54	0.59
EU TIMES_NZE	Buildings	District heat rate	%	0.06	0.06	0.07	0.07	0.07	0.07	0.07
EU TIMES_NZE	Buildings	CO2 intensity	Mt CO2/EJ/yr	28.0	24.7	23.4	18.9	14.2	9.4	4.5
EU TIMES_NZE	Transport	Energy/capita	GJ/capita	22.9	27.1	25.8	23.6	21.4	22.2	23.0

(continued on next page)

Table A9 (*continued*)

Scenario	Sector	Indicator	Unit	2020	2025	2030	2035	2040	2045	2050
EU TIMES_NZE	Transport	Electrification rate	%	0.03	0.05	0.07	0.13	0.20	0.33	0.45
EU TIMES_NZE	Transport	Biofuel admixture quota	%	0.07	0.07	0.08	0.07	0.06	0.05	0.04
EU TIMES_NZE	Transport	CO2 intensity	Mt CO2/EJ/yr	66.4	65.2	62.6	57	50.4	39.4	29.1
NEMESIS_WWH	Industry	Energy intensity	MJ/US$2010/yr	0.58	0.52	0.44	0.39	0.35	0.31	0.27
NEMESIS_WWH	Industry	Electrification rate	%	0.32	0.33	0.36	0.36	0.36	0.37	0.37
NEMESIS_WWH	Industry	CO2 intensity (net)	Mt CO2/EJ/yr	37.6	35.8	33.6	33.2	32.7	32.3	32.0
NEMESIS_WWH	Buildings	Energy/capita	GJ/capita	35.6	34.7	33.6	34.1	34.9	36.0	37.2
NEMESIS_WWH	Buildings	Electrification rate	%	0.32	0.33	0.35	0.35	0.35	0.35	0.35
NEMESIS_WWH	Buildings	District heat rate	%	0.08	0.08	0.08	0.08	0.08	0.08	0.08
NEMESIS_WWH	Buildings	CO2 intensity	Mt CO2/EJ/yr	27.9	26.8	24.1	23.6	23.1	22.7	22.4
NEMESIS_WWH	Transport	Energy/capita	GJ/capita	20.2	23.7	21.1	19.5	18.1	17.1	16.1
NEMESIS_WWH	Transport	Electrification rate	%	0.03	0.03	0.04	0.05	0.06	0.08	0.10
NEMESIS_WWH	Transport	Biofuel admixture quota	%	0.05	0.05	0.07	0.08	0.08	0.09	0.10
NEMESIS_WWH	Transport	CO2 intensity	Mt CO2/EJ/yr	68.0	67.5	65.6	64.5	63.1	61.4	59.4
NEMESIS_NZE	Industry	Energy intensity	MJ/US$2010/yr	0.58	0.51	0.42	0.37	0.32	0.28	0.28
NEMESIS_NZE	Industry	Electrification rate	%	0.32	0.34	0.37	0.40	0.45	0.51	0.60
NEMESIS_NZE	Industry	CO2 intensity (net)	Mt CO2/EJ/yr	37.6	35.2	31.6	28.7	24.4	18.8	11.9
NEMESIS_NZE	Buildings	Energy/capita	GJ/capita	35.6	34.3	32.3	30.8	29.1	28.3	27.9
NEMESIS_NZE	Buildings	Electrification rate	%	0.32	0.32	0.35	0.38	0.43	0.49	0.58
NEMESIS_NZE	Buildings	District heat rate	%	0.08	0.08	0.08	0.08	0.09	0.09	0.09
NEMESIS_NZE	Buildings	CO2 intensity	Mt CO2/EJ/yr	28.0	27.0	24.3	21.6	17.4	13.5	9.7
NEMESIS_NZE	Transport	Energy/capita	GJ/capita	20.2	23.4	20.6	18.3	16.2	14.8	14.2
NEMESIS_NZE	Transport	Electrification rate	%	0.03	0.03	0.04	0.05	0.08	0.14	0.28
NEMESIS_NZE	Transport	Biofuel admixture quota	%	0.05	0.05	0.07	0.10	0.14	0.21	0.27
NEMESIS_NZE	Transport	CO2 intensity	Mt CO2/EJ/yr	68.0	67.5	65.4	62.7	56.9	47.57	33.0
ALADIN_WWH	Transport	Energy/capita	GJ/capita	24.1	27.6	24.7	20.4	16.5	14.0	12.6
ALADIN_WWH	Transport	Electrification rate	%	0.01	0.02	0.06	0.14	0.24	0.34	0.39
ALADIN_WWH	Transport	Biofuel admixture quota	%	0.06	0.07	0.08	0.11	0.13	0.15	0.15
ALADIN_WWH	Transport	CO2 intensity	Mt CO2/EJ/yr	68.4	67.2	63.9	56.3	46.0	37.6	33.5
ALADIN_NZE	Transport	Energy/capita	GJ/capita	21.1	24.5	20.2	15.1	11.8	9.3	8.4
ALADIN_NZE	Transport	Electrification rate	%	0.01	0.03	0.09	0.24	0.39	0.52	0.56
ALADIN_NZE	Transport	Biofuel admixture quota	%	0.06	0.07	0.08	0.09	0.10	0.07	0.06
ALADIN_NZE	Transport	CO2 intensity	Mt CO2/EJ/yr	68.4	66.7	60.9	45.8	28.00	15.7	9.6

Table A10
IDA data for Figs. 3, 5 and 7.

WWH									
Sector	Industry	Building	Transport	Industry	Building	Transport	Industry	Building	Transport
Model	EU TIMES	EU TIMES	EU TIMES	NEMESIS	NEMESIS	NEMESIS	FORECAST	FORECAST	ALADIN
Driving force (GDP/population)	43%	2%	2%	37%	2%	2%	35%	2%	2%
Energy efficiency	−1%	−6%	24%	−61%	3%	−19%	−44%	−20%	−35%
Renewables	−67%	3%	0%	−4%	−9%	−5%	−17%	−1%	−8%
Electricity	1%	−12%	−16%	−9%	−7%	−7%	−16%	−11%	−32%
Heat	14%	−1%	0%	0%	−1%	0%	−8%	−10%	0%
Hydrogen	−6%	0%	0%	0%	0%	0%	−2%	0%	−1%
CO2 Intensity	4%	−8%	0%	−1%	−2%	0%	−4%	−4%	0%
CCS	−9%	0%	0%	0%	0%	0%	0%	0%	0%
End year	−22%	−21%	9%	−38%	−15%	−29%	−57%	−45%	−74%
NZE									
Driving force (GDP/population)	27%	1%	2%	29%	2%	2%	26%	1%	2%
Energy efficiency	−28%	−12%	0%	−51%	−17%	−25%	−38%	−15%	−35%
Renewables	−54%	−23%	3%	−10%	−4%	−20%	−7%	−46%	−2%
Electricity	−41%	−44%	−47%	−40%	−47%	−22%	−78%	−16%	−43%
Heat	5%	−2%	0%	−3%	−2%	0%	−7%	−21%	0%
Hydrogen	−1%	0%	−11%	0%	0%	0%	−16%	0%	−16%
CO2 Intensity	19%	−7%	−3%	−1%	−3%	0%	37%	−3%	0%
CCS	−14%	0%	0%	0%	0%	0%	−16%	0%	0%
End year reduction	−86%	−86%	−55%	−76%	−72%	−65%	−97%	−100%	−94%

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