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Are scenarios of energy demand in the building stock in line with Paris targets?

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Abstract COP21 led to an agreed target of keeping the increase in global average temperature well below 2 °C compared to pre-industrial levels. Due to its high potential for decarbonisation, the building stock will have to contribute a reduction of at least 85–95% in greenhouse gas (GHG) emissions until 2050. Policy-driven scenario analysis is, therefore, important for assisting policy makers who are called upon to develop a corresponding framework to achieve those targets. The research questions of this paper are (1) Do long-term scenarios (in particular those labelled as ambitious) of energy demand in buildings reflect the COP21 target? (2) If not: What are reasons for the gap in terms of scenario assumptions, in particular, regarding the policy framework in the corresponding scenarios? The method builds on following steps: (1) analysis of GHG-emission reduction in scenarios from the policy-driven, bottom-up model Invert/EE-Lab; (2) compare scenarios among each other and analyse if they are in line with Paris targets; (3) discuss possible explanations for any gaps and the implications on future modelling work and policy making. Results show that scenarios labelled as being "ambitious" for several EU MSs achieve GHG-emission reductions of 56–96% until 2050. However, just 27% of these ambitious scenarios achieve reductions above 85%. The reason is that policies for most of the modelled scenarios were developed together with

policy makers and stakeholders, who—for different reasons—were not willing to go beyond a certain stringency in the modelled instruments. In particular, this was the case for regulatory instruments, which show to be essential for achieving ambitious climate targets.

Introduction

COP21 led to an internationally agreed target of "holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels" (UNFCCC 2015). The EU contribution to this target will require greenhouse gas (GHG) emission reductions of at least 85–95% from 1990-levels until 2050. Due to its high potential for decarbonisation, the building stock will have to cover at least the same reduction (see e.g. European Commission 2011). This is a challenge for numerous actors to raise awareness, increase innovation and put climate mitigation measures into practice. Moreover, policy makers face the challenge to develop a corresponding policy framework.

Policy-driven scenarios are therefore important for assisting decision makers in this context. There are numerous scientific reports and academic journals assessing long-term energy demand in the building sector using different scenario frameworks, including

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Springer

energy price development, climate change, policy measures and technological change (Olonscheck et al. 2011; Asimakopoulos et al. 2012; McKenna et al. 2013; Töglhofer et al. 2012; Ó Broin et al. 2013; Steinbach 2015). These papers show similar future trends, namely, a decrease in heating energy demand in winter and an increase in cooling energy demand in summer. Decreasing heating energy demand is affected by improved thermal performance resulting, in particular, from mandatory efficiency standards for new buildings and building renovation. An increase in cooling energy demand, on the other hand, is driven by a warmer climate and rising comfort standards.

While many of these studies show a decrease in the energy demand for space heating, several others show that, in a reference case, the CO_2 reduction targets for 2020 or 2030 (e.g. Commission européenne 2016 for the case of EU-28), final energy demand (e.g. Müller and Kranzl 2015 for the case of Austria) or specific energy need for space heating Steinbach 2015 for the case of Germany) are not met and further political intervention is required. McKenna et al. (2013) for example, modelled energy demand scenarios for the German building sector until 2050 find that the reference scenario only leads to 17% energy savings in space heating and hot water from 2010 to 2050 and conclude that the 2020 target will not be met. In order to achieve higher renovation rates and an increase in energy savings, stringent regulatory policy instruments may be necessary, according to previous studies. For example, Ó Broin et al. (2013) show the impact of energy efficiency increase by 2050 in EU-27 building stock and the clear link to required policy instruments. The authors of this paper also contributed to the literature of scenarios of energy demand and CO_2-emissions in several studies, e.g. Kranzl et al. (2014); Müller (2015); Kranzl and Müller (2015), showing the need for a mix of policy instruments, including stringent regulatory approaches.

However, despite the wide range of scenarios and modelling literature, the authors of this study are not aware of a rigorous investigation into what extent these scenarios are consistent with the Paris targets. Although a number of the scenarios identified above have been classified as "ambitious", "climate mitigation" or "high policy intensity" scenarios, it is often not clearly documented how far their "ambition level" goes. Given the high relevance of the Paris targets on the one hand, and the building sector's energy demand and its related CO_2-

emissions on the other, we believe that it is essential to test such scenarios for their consistency with strong, or indeed almost complete, decarbonisation targets until 2050.

Hence, the research questions of this paper are as follows:

1. Do long-term scenarios (and in particular those labelled as ambitious) of energy demand in buildings reflect the COP21 target?
2. If not: What are reasons for the gap in terms of policy assumptions and modelling approach in the corresponding scenarios?

The scope of this paper is long- (2050) and medium- (2030) term scenarios of the building stock's energy demand (in particular energy demand for space heating, hot water and cooling), the applied mix of technologies, the mix of energy carriers and the resulting CO_2-emissions. We focus on scenarios for different European countries, developed with the model Invert/EE-Lab (see section "Methodology" for more details).

In the following sections, we will describe in detail our methodology, i.e. which scenarios were selected, a description of the model Invert/EE-Lab, and which indicators were selected to test the consistency with Paris targets. Next, the results of the analysis are discussed, presenting the selected indicators for a wide range of scenarios in select countries. Finally, some conclusions are discussed, along with potential policy implications.

Methodology

The process of work was organised according to the following steps:

1. Analysis of GHG-emission reduction in scenarios from the policy-driven bottom-up model Invert/EE-Lab carried out recently for European countries in eight EU and national projects;
2. Compare scenarios among each other by various indicators and analyse whether the scenarios lead to an achievement of GHG-emission reductions in the range of 85–95% until 2050;
3. Identify and discuss reasons for possible gaps in GHG-emission reductions, e.g. insufficient stringency of building codes, deficient economic incentives; for this purpose, we examined the related

scenario assumptions in terms of policy settings and other framework conditions and compared it to those scenarios with higher GHG emissions reductions.

System boundaries, scope of the study and selected scenarios

The current study focuses on space heating, hot water and cooling energy demand in both the residential and non-residential building stock. Since the main focus is on the achieved level of GHG reductions, the applied mix of technologies and energy carriers as well as the resulting CO_2-emissions are also taken into account. The analysis is restricted to the building sector and does not explicitly include scenarios and modelling of the electricity or district heating generation mix. This leads to certain implications on the selected indicators and also some limitations, discussed further below. The scope of the paper is long- (2050) and medium- (2030) term scenarios for different European countries, developed with the model Invert/EE-Lab. The scenarios were from different countries within the EU28 from eight projects, which were to some extent labelled as "ambitious" efficiency, renewable and/or climate change scenarios.

The projects and scenarios which were selected are as follows:

- IEE-project ZEBRA 2020: "ambitious policy scenarios" for 15 selected countries[1] (Bointner et al. 2016). In the project ZEBRA 2020, a current policy and an ambitious scenario were developed. Compared to the current policy, the ambitious scenario is based on more intensive policies, which lead to higher renovation rates and depths, more efficient new building construction, a higher share of renewable energy and corresponding CO_2 and energy savings. The detailed policy settings have been discussed with national stakeholders and policy makers. In particular, building codes have been strengthened in 2017 for new buildings and building refurbishment. Public budgets for subsidies have been increased and obligations to install RES-H

systems have been implemented in a more stringent way in the ambitious scenario compared to the current policy scenario. However, the detailed settings are country specific, based on the stakeholder consultation. For more detailed documentation, see Bointner et al. (2016). For the analysis in this paper, we selected only the "ambitious policy" scenarios.

- IEE-project ENTRANZE: "ambitious scenario, high energy prices", for 8 countries[2] (Kranzl et al. 2014). Although there are country-specific deviations and exemptions, the general logic for the scenarios derived in ENTRANZE is as follows: scenario 1 refers to a moderate ambitious scenario according to current national and EU legislation; scenarios 2 and 3 are more ambitious, innovative and stringent policy packages. The decisions on policy packages to be modelled were made in policy group meetings, which resulted in country-specific deviations. The timeframe of the policy scenarios is from 2008 to 2030. More details are described in Kranzl et al. (2014) and in ENTRANZE - Data tool (n.d.). For the analysis in this paper, we selected the scenarios with the highest energy savings and highest share of RES-H in each analysed country.

- Mapping and analyses of the current and future (2020–2030) heating/cooling fuel deployment (fossil/renewables): unpublished sensitivities with higher support for RES-H/C, 28 European Countries[3]. In this project, the authors developed a current policy scenario, considering targets and measures concerning RES-H/C and energy efficiency, which were agreed upon or already implemented at the latest by the end of 2015. Within this scenario, all implemented instruments are assumed to be in place by 2030, including current financial support programs, without significant changes throughout the years. The timeframe of the scenarios is 2030.

- Energy scenarios for Austria 2015. Heating demand of small scale consumers. A project in the frame of the reporting obligations for the monitoring mechanism (Müller and Kranzl 2015). In this project, three scenarios were developed: The scenario "with existing measures" takes into account the currently implemented policy framework. The scenario "with

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[1] Belgium, Germany, Denmark, Spain, France, the UK, Italy, Lithuania, Luxembourg, Netherlands, Norway, Poland, Romania, Sweden, Slovakia

[2] Austria, Bulgaria, Czech Republic, Finland, France, Italy, Romania, Spain
[3] Austria, Belgium, Bulgaria, Switzerland, Cyprus, Czech Republic, Germany, Estonia, Spain, Finland, France, the UK, Greece, Croatia, Hungary, Ireland, Italy, Lithuania, Luxembourg, Latvia, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovenia, Slovakia,

additional measures" considers additionally measures which are under preparation and expected to be in place very soon. The scenario "with additional measures—plus" assumes a high policy intensity towards energy efficiency improvement and RES-H/C implementation. These policy measures were discussed and agreed upon with stakeholders and policy makers. The scenarios have been developed until 2050. For the analysis in this paper, we took into account the scenario "with additional measures—plus" and is labelled as "MonMech".

- Energy scenarios for Austria 2017. Heating demand of small scale consumers. A project in the frame of the energy scenarios 2050 and reporting obligations for the monitoring mechanism (Müller et al. 2017). Corresponding to the above-mentioned scenarios for Austria, two scenarios were developed: a "with existing measures" (WAM) and a "with additional measures—plus" (WAM-plus) scenario. However, in contrast to the scenarios from the year 2015, the overall objective of WAM-plus was to achieve consistency with Paris targets. In this paper, this scenario is labelled as "EnSzen".

- Long-term scenarios and strategies for the expansion of renewable energy in Germany considering sustainable development and regional aspects (Pfluger et al. 2017)

- This project provided two scenarios: A reference scenario, assuming that relevant measures of the "Energiewende" will no longer be in place; and, a basis-scenario, assuming further enhancement of Energiewende in all relevant sectors, including the building stock. We selected the latter, more ambitious "basis-scenario" for this paper.

- Scenario runs within the Briskee project[4] including all EU28 member states (see Fries et al. 2017). Only the residential sector was analysed. Within this project, a current policy run and a scenario with intensified policy measures for thermal efficiency and renewable heating systems were calculated. In an additional scenario, lower discount rates for low income households were introduced, which are estimated to lead to more investments in renewables and higher efficiency standards.

- H2020 project progrRESsHEAT: A current policy scenario and an integrated advanced policy scenario were developed for six target countries. The integrated advanced policy package includes a rising CO_2 price level, according to the EU reference scenario (EC 2016). Additionally, a strong political commitment to the increase in prices is given, which let investors consider the CO_2 price 10 years ahead for their investment and ensures secure conditions. Building codes in this scenario include raising obligatory shares of renewable supply for new buildings from 2020 on as well as for major renovations beginning in 2030. On the other hand, higher subsidies for building renovation and renewable heating and district heating are available, compared to the current policy.

A comparison to other scenarios from the literature would certainly be interesting and relevant. In particular, this is true for scenarios covering the German building sector, as in Repenning et al. (2015), Benndorf et al. (2013), Henning and Palzer (2012). However, at least for some studies (e.g. global scenarios of building-related energy demand in Ürge-Vorsatz et al. (2011), or the scenarios available at http://www.gbpn.org/), only part of the required information is available, e.g. energy demand development but no energy carrier mix. For this reason, the analysis is limited to scenarios derived with the model Invert/EE-Lab and we intend to extend this work in future studies to other literature. Furthermore, for the objectives of this paper, we need long-term scenarios; if possible, until 2050 or beyond. However, as explained above, some of the scenarios are available only until 2030. This will have certain implications on which indicators are to be selected (see below).

The model Invert/EE-Lab

The scenarios discussed in this paper were developed by the model Invert/EE-Lab. This model is a dynamic, bottom-up simulation tool that evaluates the effects of different policy packages (economic incentives, regulatory instruments, information and advice, research and technology development) on the total energy demand, energy carrier mix, CO_2 reductions and costs for space heating, cooling, hot water preparation and lighting in buildings. Furthermore, Invert/EE-Lab is designed to simulate different scenarios (energy prices, renovation packages, different consumer behaviours, etc.) and their respective impact on future trends of energy demand and mix of renewables as well as conventional energy sources on a national and regional level. More

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[4] http://www.briskee-cheetah.eu/briskee/

information is available in Müller (2012), Kranzl et al. (2013) or Kranzl et al. (2014) The model has been extended by an agent-specific decision approach, documented in Steinbach (2013a, b, 2015). The model Invert/EE-Lab has been applied in all countries of EU-28 (+ Serbia).

The core of the simulation model is a myopic[5] approach which optimises the objectives of agents under imperfect information conditions, and thereby represents the decisions concerning building-related investments. It applies a nested logit approach in order to calculate market shares of heating systems and energy efficiency measures depending on building and investor type. Hence, the key idea of the model is to describe the building stock, heating, cooling and hot water systems at a highly disaggregated level; calculate related energy needs and delivered energy; determine reinvestment cycles and new investment in building components and technologies; and, simulate the decisions of various agents (i.e. owner types) in cases where an investment decision is due for a specific building segment.

The model allows for the definition of different owner types as instances of predefined investor classes; namely, owner occupier, private landlords, community of owners (joint-ownership), and housing association. Owner types are differentiated by their investment-decision behaviour and their perception of the environment. The former is captured by investor-specific weights of economic and non-economic attributes of alternatives. The perception-relevant variables, i.e. information awareness, energy price calculation, risk aversion, influence the attribute values. The modelling of agents is country specific, according to the characteristic situation, the relevance of various groups and data availability. More information on the specific selection and description of these groups is documented in Heiskanen and Matschoss (2012) and Heiskanen et al. (2013). For more details on the modelling of these aspects in Invert/EE-Lab, see Steinbach (2013a, b).

Invert/EE-Lab models the decision-making of investors concerning building renovation and heating, hot water and cooling systems. Policy instruments may affect these decisions (in reality and in Invert/EE-Lab) in the following ways:

- Economic incentives change the economic effectiveness of different options and thus lead to other investment decisions.
- Regulatory instruments (e.g. building codes or renewable heat obligations) restrict the technological options that decision makers have; limited compliance with these measures can be taken into account.
- Information, advice, etc.: Agents (mainly building owners) have different levels of information. Lack of information may lead to neglecting of innovative technologies in the decision-making process or to a lack of awareness regarding subsidies or other support policies. Information campaigns and advice can increase this level of information.
- R&D can push technological progress. The progress in terms of efficiency increase or cost reduction of technologies can be implemented in Invert/EE-Lab.

Input data regarding building stock data, economic and policy drivers, etc., are documented in the sources listed above for each of the scenario groups.

Indicators to assess whether a scenario is in line with the Paris COP21 agreement

As the objective of this paper is to assess the consistency of different scenarios with the Paris agreement, specific indicators need to be defined. Table 1 summarises the selected indicators and their definition.

The three indicators 3–5 described above are defined as change of the market share in the base year and the years 2030 and 2050, respectively. We are aware that these indicators could be avoided if a fully, sector-coupled modelling approach would be chosen. On the other hand, we believe that they also provide additional insights, which are often not available in cross-sectoral modelling in a transparent way.

Results

Figures 1 and 2 illustrate the range of direct and total GHG emissions in different scenarios and for various European countries, respectively. They indicate that the reduction of GHG emissions varies strongly across each scenario. Figure 3 presents an overview of the distribution of the main indicators, defined above. One of the most obvious results shows that none of the 2050 scenarios achieve sufficient CO_2-savings (i.e. >80%), if

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[5] The myopic approach implies that the model does not include a perfect foresight optimisation. We assume that investors optimise over the entire depreciation time considered. However, the investors are not (or only partly) aware that energy prices or investment costs might change over time.

Table 1 Selected indicators for scenario assessment

Indicator description	Indicator definition	Argument for including this indicator in the assessment
1. CO_2 emission reduction assuming constant emission factors for district heating and electricity; emission factors are country specific and refer to the base year (2012) of the scenarios.	$a_{1,t} = 1 - \dfrac{\sum_i \text{FED}_{t,i} \times \text{emi}_{t0,i}}{\sum_i \text{FED}_{t0,i} \times \text{emi}_{t0,i}}$	The first and most obvious indicator is the achieved reduction of GHG-emissions. However, there needs to be an approach to deal with GHG-emission factors for electricity and district heating. For this analysis, we have decided to strongly focus on the building stock as such. Thus, we decided not to distort results by assuming decreasing emission factors for these two sectors. This also would have to be distinguished between countries, making it difficult to identify key impact factors and drivers for decarbonisation.
2. CO_2 emission reduction excluding electricity and district heating.	$a_{2,t} = 1 - \dfrac{\sum\limits_i^I \text{FED}_{t,i} \times \text{emi}_{t0,i}}{\sum\limits_i^I \text{FED}_{t0,i} \times \text{emi}_{t0,i}}$ $I = \{i \in EC \mid i \notin \{\text{dh, ele}\}\}$	This second indicator focuses on direct emissions in the building stock, not considering the current structure and possible changes in the electricity and district heating generation mix.
3. Increase district heating from base year in percentage points (pp)	$a_{3,t} = \dfrac{\text{FED}_{t,dh}}{\sum_i \text{FED}_{t,i}} - \dfrac{\text{FED}_{t,dh}}{\sum_i \text{FED}_{t,i}}$	Indicator 2 may lead to distortion, in case that district heating and electricity would strongly increase, since the decarbonisation effort is just shifted to another sector. In order to take this into consideration, we also need to know about the increasing share of electricity and district heating to cover the building stock's energy demand. 1.
4. Increase electricity from base year (pp)	$a_{4,t} = \dfrac{\text{FED}_{t,ele}}{\sum_i \text{FED}_{t,i}} - \dfrac{\text{FED}_{t,ele}}{\sum_i \text{FED}_{t,i}}$	
5. Increase biomass from base year (pp)	$a_{5,t} = \dfrac{\text{FED}_{t,bio}}{\sum_i \text{FED}_{t,i}} - \dfrac{\text{FED}_{t,bio}}{\sum_i \text{FED}_{t,i}}$	The use of biomass as a decarbonisation option is of relevance, since biomass is expected to play an increasingly crucial role in sectors where carbon energy carriers are more difficult to substitute (e.g. aviation, industry). See e.g. the analyses in Forsell et al. (2016); Pfluger et al. (2017); Schipfer et al. (2017) or Kalt et al. (2016).
6. Energy savings compared to the base year (%)	$a_{6,t} = 1 - \dfrac{\sum_i \text{FED}_{t,i}}{\sum_i \text{FED}_{t0,i}}$	This indicator accounts for the share of final energy demand reduced from the base year until 2030 and/or 2050. It should be emphasised that this is not delivered energy, but rather final energy demand[a] in the sense of the renewable energy directive, i.e. including solar thermal and ambient heat.[b]
7. Installation of fossil-based heating systems	$a_{7,t} = \dfrac{P_{t,gas} + P_{t,oil} + P_{t,coal}}{\sum_i P_{t,i}}$	Due to the long lifetime of heating systems, a high share of the heating systems installed, e.g. in 2030, will still be in place in 2050. Additionally, markets typically do not change very quickly. For example, if the share of fossil heating systems in the installation of all new heating systems in the year 2030 is still extremely high, it would need strong regulatory policy instruments, as well as a complete change of the manufacturer structure to reduce this market share quickly. Moreover, stranded investments could occur in case that heating system replacement would be required before the lifetime has ended.

Table 1 (continued)

Indicator description	Indicator definition	Argument for including this indicator in the assessment
		Some scenarios are not available until 2050. So, in order represent the future decarbonisation perspective, we selected this indicator. Thus, this indicator allows an assessment also for those scenarios which have been modelled only until 2030.

Abbreviations and formula symbols: a_j, indicator j; $FED_{t,i}$, final energy demand in year t (2030 or 2050) and for energy carrier i (MWh); $emi_{t,i}$, specific CO_2-emissions in year t (2030 or 2050) and for energy carrier i (t/MWh); $P_{t,i}$, installed power of heating systems based on energy carrier i in year t (2030 or 2050) (GW); EC, considered energy carriers; t,. year; $t0$, base year (2012); i energy carrier i; dh, district heating; ele, electricity; bio, biomass; gas, natural gas; oil, oil; $coal$, coal

[a] We decided not to take into account primary energy demand due to the required assumptions of primary energy factors, which, indirectly, are partly reflected in the other applied indicators.

[b] In the context of this indicator, lock-in effects need to be considered, i.e. to which extent are buildings renovated with insufficient depth, thus requiring an additional renovation measure before the end of the first measures' lifetime? Since the model Invert/EE-Lab foresees, to a limited extent, measures before the end of the lifetime, lock-in effects are indirectly reflected in the energy savings indicator. Thus, we decided to not add an indicator in particular for this aspect.
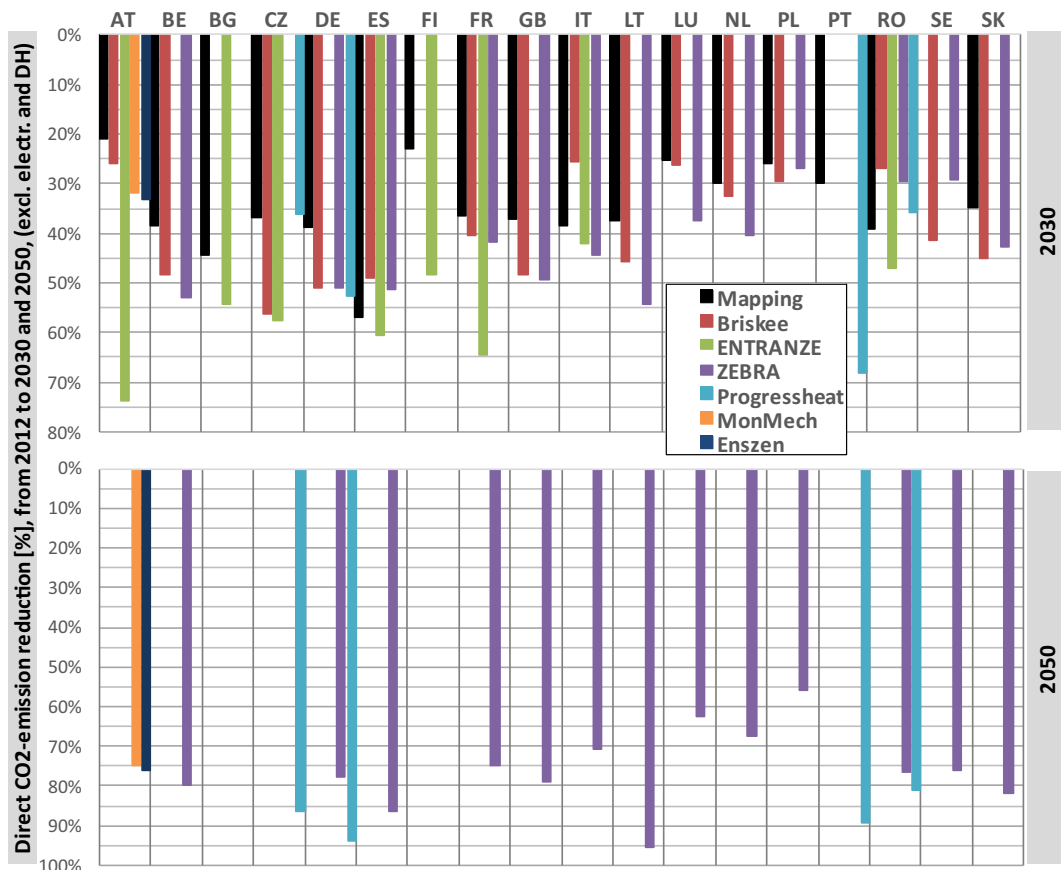

Fig. 1 Scenarios of direct greenhouse gas emissions for space heating and hot water (i.e. excluding electricity and district heating) in selected scenarios in select European countries
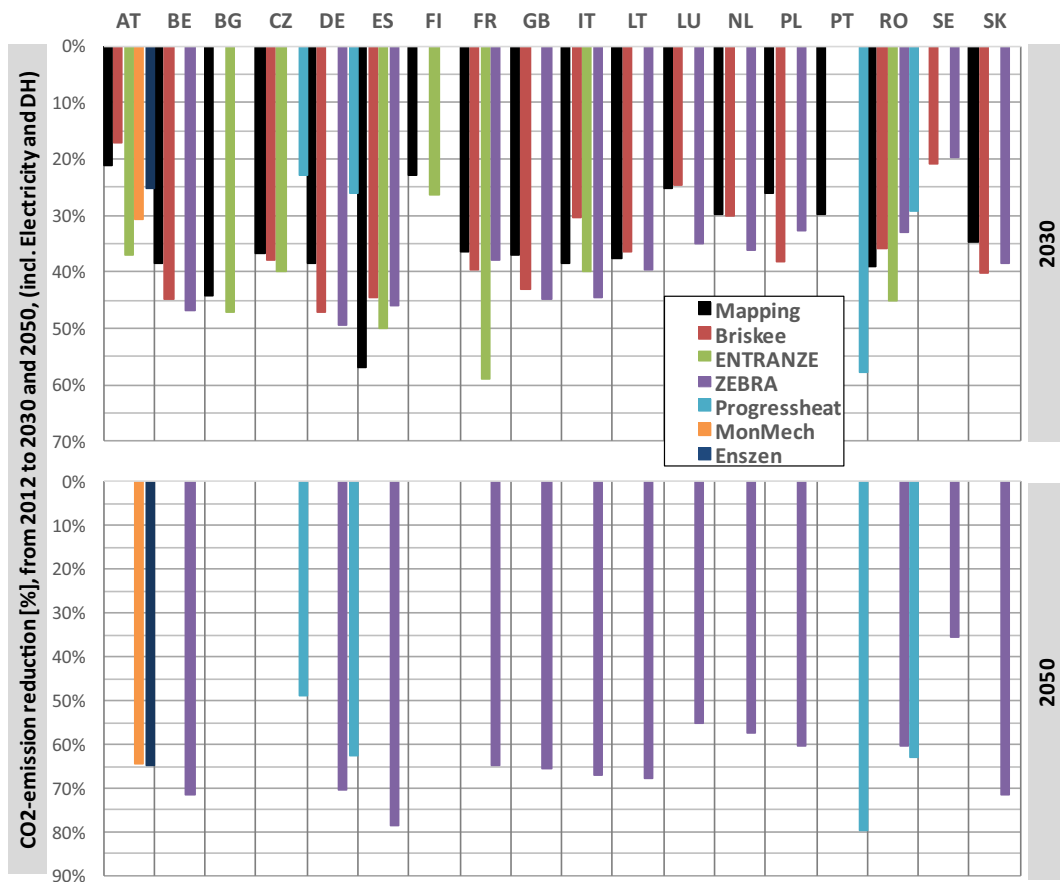
Fig. 2 Scenarios of greenhouse gas emissions for space heating and hot water (i.e. including electricity and district heating) in selected scenarios in select European countries

constant CO_2-emission factors for electricity and district heating are assumed. Assuming that decarbonisation efforts must also take place in these sectors, the indicator of the direct CO_2-emissions may be more relevant. However, also with respect to direct CO_2-emissions, only a few scenarios achieve levels of more than 85% CO_2-savings by 2050. This is a crucial finding because the intention of these scenarios is, in fact, to provide a significant increase in policy intensity. What is more, the discussion processes carried out within the project ZE-BRA2020 also showed that stakeholders and policy makers classified these measures as "highly ambitious"—in some cases even beyond what would be imaginable in the current political framework.

The following table shows all indicators explained in the "Methodology" section for all analysed scenarios. The values refer to the definition of indicators as defined in Tables 1 and 2.

As can be seen in table 2, only a few scenarios show a reduction of direct CO_2-emissions of at least 85% until 2050. For instance: ZEBRA—"ambitious policy scenarios" in ES and LT; the "basis-scenario" for Germany from the project "long-term scenarios"; the progRESsHEAT scenarios for CZ and DE; and the EnSzen-scenario for AT. Each of these cases is discussed in more detail below. Additionally, the country results highlighted above do not reflect the fact that the necessity to reduce CO_2-emissions is not equally distributed across EU countries. Thus, Table 3 shows the total of CO_2-emission reductions (indicators 1 and 2) in the selected projects. Interestingly, from those projects covering more than one country, only the progRESsHEAT scenarios achieve CO_2-emission reductions beyond 85% (indicator 2, i.e. excluding district heating and electricity).
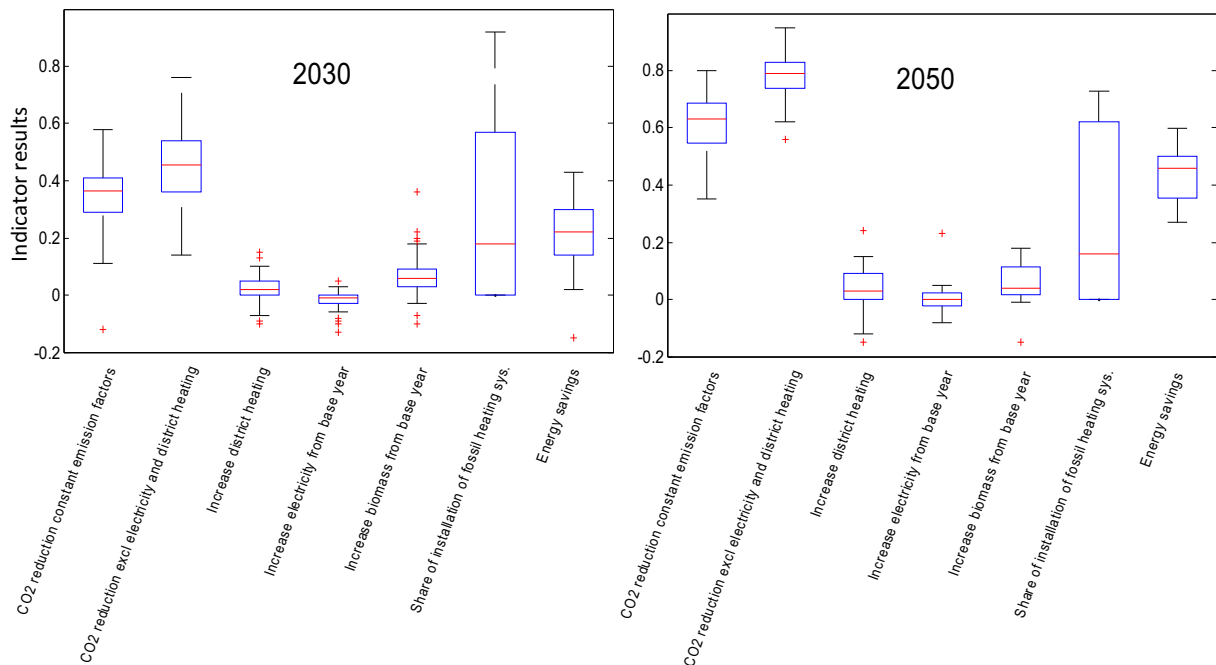
Fig. 3 Box plots of indicators to assess the Paris-consistency of selected scenarios. Boxes represent 50% of all data (1st to 3rd quantile); the red line represents the median and data points "+" represent outliers (not within Q1/Q3 ± 1.5× interquartile range (Q3–Q1))

Table 4 documents selected aspects of those scenarios which fulfil the consistency criteria, at least regarding indicator 2.

For the case of *Spain*, we see a mix of different drivers leading to this result. Firstly, there is a relatively high share of fuel oil in the current energy carrier mix. In all countries and scenarios, we see a strong shift from fuel oil to other energy carriers—both in the past and in our scenarios. Thus, there is a high potential for decarbonisation that is exploited in this scenario. Secondly, the share of solar thermal energy in the total final energy demand is much higher than in other countries and scenarios, reaching more than one third in 2050. Due to the fact that solar thermal collectors are still partly combined with fossil heating systems, the share of fossil-based installations in the heating system market of 2050 is still surprisingly high. However, due to building renovation and a high share of solar thermal energy, the resulting GHG emissions from these remaining fossil fuels are moderate.

In *Lithuania*, the largest part of the heating demand in the year 2012 is covered by district heating (43%) and biomass (37%). The scenarios lead to a strong increase in both of them (especially district heating) to an overall share of almost 90%. Despite the fact that solar thermal and ambient heat show only very moderate market growth in our scenario, the reduction of the remaining

direct GHG emissions is exceedingly high, mainly due to a considerable share of coal in the base year 2012 (7%). Moreover, a 55% reduction in final energy demand between 2012 and 2050 is among the highest of the considered scenarios.

What can be seen from the selected scenario for *Germany* is high energy savings of 56% until 2050. Remarkably, the share of biomass does not increase, which means that in, absolute terms, biomass use for heating in the building sector is reduced. However, the market share of district heating increases quite substantially by 11 percentage points. What is striking is the relatively high 34% share of fossil-based heating systems still in the boiler market in 2050. The reason this is in-line with a high reduction in direct CO_2-emissions is due to a substantial share of solar energy in the final energy carrier mix, i.e. many of the solar supported heating systems still use fossil-based energy carriers as a backup.

The progRESsHEAT-scenario for the *Czech Republic* reveals that, despite moderate energy savings, high CO_2-emission reductions are still possible. The main reasons for this result are: First, more than 21% of current energy demand is covered by district heating and around 16% by biomass. This means that with a corresponding increase in biomass, a quite significant share of overall heating demand can be covered. Second, direct electric heating

currently covers nearly 10% of the heating demand. By shifting a certain share of this electricity demand to heat pumps (not necessarily in the same buildings but across the whole building stock), it is possible to more than double the heat demand supplied with the same amount of electricity. And third, in the status quo, almost 10% of the heat demand is covered by very CO_2-intensive coal heating systems. Replacing them greatly contributes to a reduction of direct CO_2-emissions. Overall, it should to be noted that, due to the strong role of district heating and electricity, a significant part of the CO_2-emissions is accounted for in the energy conversion sector—which is why the CO_2-emissions assuming constant emission factors reduce only by less than 50%.

The case of *Austria* shows that the intentions of the scenario development and the ambition of assumed policy measures make a significant difference. Although the scenario MonMech from the year 2015 included measures far beyond the current state of policies, they were not targeted towards strong decarbonisation. However, the overall setting of the 2017 scenario work (EnSzen) was targeted towards the achievement of the Paris target. This was done by implementing a strong policy package consisting of an enhanced regulatory framework (i.e. strengthened building codes, renovation obligation, ban of oil heating systems, district heating priority areas), CO2-taxes up to 200€/tCO2 in 2050, increased role of subsidies, as well as more instruments for education, training and awareness raising.

On the contrary, the *lowest reductions in CO₂-emissions until 2050 take place in the ZEBRA scenarios for Poland (56%) and Luxembourg (62%).* For the case of Poland, the current political framework does not show any ambition to greatly reduce the high share of coal. This led to the fact that, even in the ambitious policy scenario, the stakeholders and policy makers involved in the ZEBRA discussion process did not consider it as realistic to implement strong RES-H policies. Even though the share of coal decreases, this is mainly in favour of natural gas. Moreover, the scenario continues the current trend regarding a decreasing role of district heating.

The results for the indicator "share of installations of fossil-based heating systems" reveal that the change in the boiler market will be a crucial challenge in the coming years. The scenarios in the project "Mapping" (Fleiter et al. 2016) highlight that, under current policy conditions, the share of fossil heating systems in the boiler market of 2030 is by far inconsistent with Paris targets. The share of fossil heating systems in new installations in most scenarios and countries is beyond 50%. However, in ENTRANZE scenarios, labelled again as "ambitious policy" scenarios, this share is significantly lower at least for some countries. The main reason is that, in particular for the cases of Austria and Finland, rigorous fossil phase-out policies were implemented in the policy scenarios.

Moreover, the share of fossil heating systems in these countries present in the base year is substantially lower than in other countries. Overall, it appears that only a few scenarios in selected countries achieve market shares of fossil heating systems below 50% in 2030. This shows that the model-based scenarios not only indicate a high inertia in the existing heating system stock, but also in the boiler market. It is evident that high shares of fossil heating systems in the newly installed stock contradict ambitious climate targets. However, surprisingly, there are also cases of scenarios achieving more than 85% of GHG-emission reductions with fossil heating system market shares of more than 30% even in 2050. This is only possible if high energy savings (at least 50% of final energy demand reduction) and high shares of solar energy limit the energy demand supplied by these fossil heating systems.

Discussion, conclusions and outlook

Overall, despite the fact that the analysed scenarios show significant progress in climate change mitigation, the speed of change (especially in the market of newly installed heating systems) is not fast enough. This is even the case in those scenarios labelled as "ambitious policy" in the different projects listed above. The literature beyond the studied scenarios includes some cases of (almost) complete decarbonisation, in particular for the case of Germany (Repenning et al. 2015, Benndorf et al. 2013 or Henning and Palzer 2012). However, in general, it can be stated that only recently and probably as one of the consequences of the Paris agreement, more activities have evolved with an ambition to model different pathways towards a complete decarbonisation (e.g. Crespo del Granado et al. 2018).

The description and analysis of the scenarios reaching more than 85% GHG-emission reduction reveals that two drivers matter: (1) current state of the building stock and related energy systems (e.g. relevant for the case of the scenarios for Lithuania, providing a good starting point for reduction of GHG-emissions)

Table 2 Comparative assessment of scenarios regarding CO_2-emission reduction (compared to the base year 2012), installation of fossil-based heating systems and increase of district heating, electricity and biomass. Bold values indicate more consistency with Paris targets. Italic values indicate lower consistency with Paris targets

Country	Project	$a_{1,i}$: CO$_2$ reduction assuming constant emission factors		$a_{2,i}$: CO$_2$ reduction excl. electricity and district heating		$a_{3,i}$: increase district heating from base year (pp)		$a_{4,i}$: increase electricity from base year (pp)		$a_{5,i}$: increase biomass from base year (pp)		$a_{6,i}$: share of installation of fossil-based heating systems		$a_{7,i}$: energy savings (reduction of final energy demand from base year)	
		2030 (%)	2050 (%)	2030 (%)	2050 (%)	2030 (%)	2050 (%)	2030 (%)	2050 (%)	2030 (%)	2050 (%)	2030 (%)	2050 (%)	2030 (%)	2050 (%)
FR	ENTRANZE	59		64		5		−4		7		39		32	
AT	ENTRANZE	37		74		13		−1		6		**10**		28	
BG	ENTRANZE	47		54		−1		−9		4		21		23	
CZ	ENTRANZE	40		57		1		1		9		25		28	
ES	ENTRANZE	50		60		2		−3		7		26		26	
FI	ENTRANZE	26		49		0		−3		1		**4**		13	
IT	ENTRANZE	40		42		1		1		5		66		29	
RO	ENTRANZE	45		47		−7		1		9		18		29	
FR	Mapping	36		37		2		−2		8		40		9	
AT	Mapping	21		57		13		−4		1		31		19	
BE	Mapping	39		42		5		−2		10		76		23	
BG	Mapping	44		51		−3		−6		12		21		10	
CH	Mapping	11		14		1		0		−10		70		2	
CY	Mapping	17		62		0		5		12		18		−15	
CZ	Mapping	37		52		2		−2		22		27		6	
DE	Mapping	39		38		1		−1		0		84		33	
EE	Mapping	54		57		−2		−6		13		6		22	
ES	Mapping	57		59		0		−5		36		15		4	
FI	Mapping	23		48		4		−9		5		7		2	
GB	Mapping	37		40		9		−2		3		75		30	
GR	Mapping	55		59		1		0		15		42		35	
HR	Mapping	39		63		10		−1		19		15		8	
HU	Mapping	39		47		4		−1		14		48		23	
IE	Mapping	29		27		0		−2		3%		92		19	
IT	Mapping	39		37		0		−1		9		57		23	
LT	Mapping	38		49		4		−1		−2		18		34	
LU	Mapping	25		27		4		−2		8		78		9	
LV	Mapping	28		18		1		−2		−7		51		29	

Table 2 (continued)

Country	Project	$a_{1,i}$: CO₂ reduction assuming constant emission factors		$a_{2,i}$: CO₂ reduction excl. electricity and district heating		$a_{3,i}$: increase district heating from base year (pp)		$a_{4,i}$: increase electricity from base year (pp)		$a_{5,i}$: increase biomass from base year (pp)		$a_{6,i}$: share of installation of fossil-based heating systems		$a_{7,i}$: energy savings (reduction of final energy demand from base year)	
		2030 (%)	2050 (%)	2030 (%)	2050 (%)	2030 (%)	2050 (%)	2030 (%)	2050 (%)	2030 (%)	2050 (%)	2030 (%)	2050 (%)	2030 (%)	2050 (%)
MT	Mapping	44		52		2		−13		17		18		24	
NL	Mapping	30		35		5		0		4		83		24	
NO	Mapping	32		41		0		0		−2		1		13	
PL	Mapping	26		18		−6		−1		3		73		11	
PT	Mapping	30		23		1		−5		1		67		14	
RO	Mapping	39		41		−9		1		16		7		12	
SI	Mapping	48		63		7		−4		18		6		14	
SK	Mapping	35		36		−1		−1		8		71		24	
DE	Long-term scenarios	40	71	45	**85**	6	11	−1	4	−1	0	58	34	29	56
FR	ZEBRA	38	65	42	75	5	10	−2	−1	2	−1	38	38	17	31
BE	ZEBRA	47	72	53	80	10	15	−1	−1	10	12	66	62	33	53
DE	ZEBRA	50	70	51	78	1	2	0	4	1	1	76	71	43	59
DK	ZEBRA	34	53	59	80	3	0	−2	−3	8	11	25	16	17	30
ES	ZEBRA	46	78	51	**86**	0	0	0	−2	3	4	25	38	28	43
GB	ZEBRA	45	65	49	79	9	24	−2	−2	4	6	68	66	34	46
IT	ZEBRA	45	67	44	71	0	1	−1	1	4	4	54	43	30	48
LT	ZEBRA	40	68	54	**95**	5	6	0	0	−3	4	7	3	36	55
LU	ZEBRA	35	55	38	62	3	9	−2	−2	11	15	75	73	19	34
NL	ZEBRA	36	57	41	67	5	14	0	2	5	7	79	62	30	48
NO	ZEBRA	32	67	41	74	1	−1	−3	−8	2	1	3	6	21	46
PL	ZEBRA	33	60	27	56	−6	−15	0	1	0	3	65	64	22	46
RO	ZEBRA	33	60	29	77	−7	−12	1	5	4	4	14	11	24	49
SE	ZEBRA	20	35	29	76	4	5	−5	−6	3	0	3	2	22	36
SK	ZEBRA	39	72	43	82	2	0	0	5	6	12	62	46	30	60
FR	Briskee	40		41		2		−3		9		39		13	
AT	Briskee	17		26		7		−3		0		32		20	
BE	Briskee	45		48		6		−1		8		73		33	
CZ	Briskee	38		56		2		−1		20		34		12	
DE	Briskee	47		51		5		−1		6		60		35	

Table 2 (continued)

Country	Project	$a_{1,i}$: CO$_2$ reduction assuming constant emission factors		$a_{2,i}$: CO$_2$ reduction excl. electricity and district heating		$a_{3,i}$: increase district heating from base year (pp)		$a_{4,i}$: increase electricity from base year (pp)		$a_{5,i}$: increase biomass from base year (pp)		$a_{6,i}$: share of installation of fossil-based heating systems		$a_{7,i}$: energy savings (reduction of final energy demand from base year)	
		2030 (%)	2050 (%)	2030 (%)	2050 (%)	2030 (%)	2050 (%)	2030 (%)	2050 (%)	2030 (%)	2050 (%)	2030 (%)	2050 (%)	2030 (%)	2050 (%)
DK	Briskee	33		54		6		−3		5		18		19	
ES	Briskee	45		49		0		−2		8		32		16	
GB	Briskee	43		48		10		−2		6		62		31	
IT	Briskee	30		25		0		−2		2		78		17	
LT	Briskee	36		46		−3		0		3		13		26	
LU	Briskee	25		26		4		−2		2		85		14	
NL	Briskee	30		32		4		−1		4		81		24	
PL	Briskee	38		30		−7		−1		4		59		23	
RO	Briskee	36		27		−10		0		12		12		14	
SE	Briskee	21		41		2		−8		8		6		16	
SK	Briskee	40		45		−1		0		6		70		32	
AT	MonMech	31	65	32	75	4	6	−4	−2	1	−4	34		19	52
AT	Enszen	38	70	48	96	6	6	−2	2	0	0	17	5	26	50
CZ	Progressh	26	49	53	86	4	3	1	3	14	18	28	14	6	27
DE	Progressh	48	62	59	94	5	5	3	23	6	3	38	18	36	56
DK	Progressh	33	52	54	82	5	6	−3	−5	6	10	15	19	19	32
RO	Progressh	29	63	36	81	−1	0	0	0	6	13	11	8	16	43

Table 3 Scenario results for the total of countries considered in the selected projects

	Share of EU-28 emissions of selected sector covered (In brackets: covered share excl. DH and electr.) (%)	Emission reduction compared to 2012 emissions			
		2030 (%) (In brackets: emission reduction of covered countries compared to mapping scenario)	2030 excl. DH and electr. (%)	2050 (%)	2050 excl. DH and electr. (%)
Mapping	97 (99)	36 (100)	38 (100)		
ZEBRA	90 (90)	42 (117)	46 (123)	65	75
ENTRANZE	35 (33)	47 (123)	55 (131)		
Progressheat	29 (29)	44 (124)	57 (148)	61	92
Briskee	90 (90)	40 (112)	42 (112)		
Long-term scenarios	22 (24)	40 (104)	45 (117)	71	85
MonMech	2 (2)	31 (146)	32 (56)	65	75
Enszen	2 (2)	38 (179)	48 (59)	70	96

and (2) strong focus on regulatory instruments in the modelling approach, backed economic support and awareness raising. The modelled instruments were strongly driven by the intention of motivated stakeholders and policy makers to gain new insights into a potential full decarbonisation pathway.

On the other hand, the analysis of non-compliant scenarios reveals four main reasons for gaps and key challenges: (1) too slow transition in the boiler market, (2) slow uptake of renovation activities, (3) lacking decarbonisation of electricity and district heating and (4) questions regarding the allocation of biomass resources. These challenges will be further discussed below (see also Pfluger et al. 2016).

Reasons for gaps of non-compliance scenarios and implications on modelling and policy making

Challenge 1: transition in the boiler market—how can a complete phasing out of fossil fuel heating systems be achieved by the year 2025–2030?

Due to the long lifetime of the heating systems, ambitious measures must be implemented at an early stage. A specific challenge would be switching from gas heating systems (which is "accepted" in an 80% reduction scenario) to central heating systems in combination with low carbon heat generation. Strict regulatory interventions can be a suitable measure to tackle this challenge but might also lead to problems of acceptance from building occupants. There is an increase in awareness and discussion on the question whether a certain share of current natural gas consumption may be covered by renewable gas, either biogas or solid biomass-based SNG or from power-to-gas plants. Although this question is not fully answered, it is clear that only a smaller share the current natural gas demand may be covered by renewable gas, in particular considering as well industrial gas demand and potentially increasing demand, e.g. in freight transport.

Challenge 2: both the renovation rates and renovation depths have to be further increased compared to an 80% reduction scenario

Renovation rates should be increased to 2.5% or even 3% earlier than in an 80% reduction scenario. Historical renovation rates in recent years are estimated to be below 0.1% and up to around 2% for a few countries in Europe, with most member states

Table 4 Policy mix in selected scenarios

Scenario	Specific design elements of the policy mix determining the level of ambition	Institutional settings leading to policy assumptions in the model	Year[a]
ES—ZEBRA	Renewable heat obligations: starting with moderate obligations only for new buildings, they are increasingly also applied in cases of major renovation and heating system replacement; mandatory efficiency improvement with strong compliance, achieved partly by proper advice and economic support.	Discussions in a small group of policy makers. Involved policy makers intended to illustrate potential impacts of ambitious policies in contrast to current policies. Focus of the project was on nZEB standards.	Late 2015–early 2016
LT—ZEBRA	Focus on economic support of building renovation and efficient new building construction.	Consultation of selected policy makers in bilateral meetings. Policy makers emphasised the economic rationality of building owners requiring economic support. Focus of the project was on nZEB standards.	Late 2015-early 2016
DE—long-term scenarios	Slightly increased stringency of building codes, stricter mandatory instruments for RES-H; from 2035 also including heating system replacement, continued and partly increased economic support (subsidies), backed by increased awareness raising campaigns;	Numerous meetings and feedback loops from stakeholders in the involved ministries and beyond. Intention of the scenario was the analysis of related "Energiewende" policies.	2015
CZ—progressh.	Intensified renewable heat obligation, from 2030 also for building renovation and heating system replacement; increased budgets for subsidies, in particular for RES-H; favourable financing conditions for DH; CO2-taxes(*), Awareness and information campaigns regarding the instruments mentioned above.	Discussions in a small group of policy makers. Involved policy makers intended to illustrate potential impacts of ambitious policies contrasted to the current scheme.	Mid 2016-mid 2017
DE—progressh.	Slightly increased stringency of building codes, stricter mandatory instruments for RES-H; from 2035 also including heating system replacement, continued and partly increased economic support (subsidies); CO2-taxes(*), favourable financing conditions for district heating, Awareness and information campaigns regarding the instruments mentioned above.	Discussions in a small group of policy makers. Involved policy makers intended to illustrate potential impacts of related "Energiewende" policies.	Mid 2016-mid 2017
AT—EnSzen	Mandatory renovation of inefficient buildings, not renovated within the last 30 years; mandatory replacement of coal and oil based heating technologies older than 27 years within 10 years after 2025. Ban of coal and oil in new buildings after 2022. CO2-taxes(**), slightly rising budgets for subsidies, awareness and information campaigns regarding the instruments mentioned above.	Numerous meetings and feedback loops from stakeholders in the involved ministries and beyond. Intention of the scenario was the development of a "Paris consistent" transition pathway of the energy system. However, stakeholders took into account limitations regarding the speed of policy implementation.	Mid 2016-mid 2017

[a] This column indicates the year where most of the modelling work and iterative discussions with policy makers were done, not the year of publication.

*CO_2-prices increase to about 31 €/tCO2 in 2030 and to almost 90€/tCO2 in 2050

**CO_2-prices increase to about 40 €/tCO2 in 2030 and to 200€/tCO2 in 2050

around 1–1.5% (see e.g. ZEBRA2020 or the European Building Stock Observatory). However, we want to emphasise that, despite the efforts in these projects to define harmonised approaches of an equivalent major renovation rate, the national statistical primary data is still too diverse and thus difficult to compare across countries. Nevertheless, public acceptance problems are expected in increasing renovation activities, especially in the case of financing and economic feasibility of renovation measures in buildings with low-income households in both rental dwellings and owner occupied single-family homes.

Challenge 3: decarbonisation of electricity and district heating generation required

The supply sectors (electricity, district heating) have to be completely decarbonized for a 95% reduction, such that the use of efficient district heat and heat pumps lead to reduced emissions in the full energy supply chain. Even the reduction of direct CO_2-emissions (i.e. excluding GHG emissions from electricity and district heating) to a level beyond 90% is challenging. If substantial emissions from district heating and electricity remain, decarbonisation is not possible.

In this context, it should be noted that the energy demand for heating often does not correlate with the availability of the renewable energy (solar, wind). The use of heat pumps can increase the peak load, which can lead to capacity bottlenecks in the power supply. The demand peaks caused by electrical heat pumps can be relevant for the design of distribution networks due to the relatively high simultaneousness. A certain controllability of the heat pumps is almost indispensable with such a high share and targeted emissions reductions. Note that this effect is less relevant in district heating networks with multiple supply options. Due to the potential flexibility in supply (combination of cogeneration, power-to-heat and peak-load boilers), heating networks could provide a balance between heat and electricity demand and supply peaks. Additionally, there is a need for a re-conceptualization of heating networks (i.e. temperature levels and integration of waste heat, solar heat and ambient heat). The optimal share of district heating in an almost carbon-free heat supply system is still an open issue and will need to be clarified in further research. All of these aspects can only be addressed in a

sector-coupled model, which is of high relevance, but out of scope of this paper.

Challenge 4: how much biomass is available for heating purposes and what is the electricity mix for the operation of heat pumps?

In nearly complete decarbonisation scenarios, the question of optimal biomass allocation becomes increasingly relevant since biomass would be demanded in the mobility, industry and the conversion sector. *Consequently, in the case of a complete decarbonisation of the building sector, there is rather less biomass available than in less ambitious scenario.* Thus, there is a need for a cross-sectoral analysis of the potential and efficient allocation of biomass. Since the presented scenarios do not include a holistic energy (and resource) system modelling but rather a detailed representation of the building stock, there is no clear answer possible. However, it is evident that an overly high share of biomass allocated to the low-temperature heating sector may contradict reaching climate targets in other sectors, in particular in industry or transport.

Outlook and general conclusions for modelling and scenario development

This paper should be considered a starting point for assessing how current scenarios, reflecting also expectations of policy makers and stakeholders, are in line with Paris targets. In addition to the work presented in this paper, a more comprehensive literature review would be interesting. Moreover, cross-sectoral effects in the electricity sector should be addressed. Nevertheless, we believe that this would not substantially alter the overall conclusions derived in this paper.

The question then arises as to what we, as modellers and the modelling community in general, should learn from these results. First, *modelling and scenario development is always embedded in a certain institutional setting*. Clients, stakeholders and policy makers typically are involved in an interactive discussion process, which is essential to increase the impact of scenarios on real life policy making. At the same time, we should be aware—and the results of this paper support this fact—that the involvement of these stakeholders can decrease the ambition level of scenarios, bringing them to a level that—for these specific stakeholders—is in their interest or which they think is compatible with

current policy decision-making processes. Thus, modellers are often faced with a tension of their own intrinsic motivation to illustrate possible pathways of (almost) complete decarbonisation and the interests of clients, stakeholders and policy makers. This also leads to the question of the responsibility of the modelling community to also actively drive the discussion process and not act only as "recipients of orders".

Second, methodological questions might occur. *To what extent are models able to deal with highly ambitious climate and policy targets?* In general, techno-economic bottom-up models such as Invert/EE-Lab are better suitable for modelling more extreme transition pathways. However, there are also components in the model which reflect the inertia of changes in the stock of heating systems and buildings. Although this inertia is in line with what empirically can be observed, it cannot be completely ruled out that—under a strong, joint societal effort towards decarbonisation—investment cycles and replacement rates of technologies could greatly change, even if this would be associated with higher private and societal costs.

Finally, this paper also leads to the question *to what extent do scenarios matter for the policy process?* Is it important that there are also Paris-consistent scenarios out there? We believe that scenarios at least should reflect the current reality of the discourse. If this is true, then the conclusions of this paper are alarming. Moreover, we think that one objective of scenarios is to show the range of possible futures. So, as long as energy demand scenarios do not at least include some examples of Paris consistent future pathways, the discourse does not even include this agreed and adopted target as a conceivable and possible future. Thus, the modelling community—including the authors—and future projects in this field face the challenge to change this situation.

Compliance with ethical standards

Conflict of interest   The authors declare that they have no conflict of interest.

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