Exploration of qualitative scenarios towards climate neutrality of the German building sector

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Abstract

Scenario modelling is widely applied to quantify the development of energy demand and GHG emissions in a given time horizon. Transformation scenarios, on the other hand, are primarily qualitative visions of the future that align with energy transition objectives. Including current policies, technological developments and societal trends in the scenarios allows considering a wide range of possible future developments. Combining descriptive scenarios with quantitative modelling results provides rich insights and contextual understanding that enhance the overall robustness of the analyses. This paper develops a methodological approach for combining qualitative scenarios and quantitative modelling to analyse the future of energy consumption in the German building stock, which aims to become climate neutral by 2045. It describes a participatory process that was followed to develop different transformation scenarios, taking into account technical, social, political and economic aspects. The process included defining the geographical, content-related specification and the timeline of the scenarios, identifying relevant scenario factors, trends and uncertainties that could affect the German building sector, and describing underlying factors and assumptions regarding their future development. The paper then briefly presents an agent-based framework for quantitatively modelling the qualitative scenarios. By modelling the representative buildings as agents, the model can capture the details of individual buildings at the micro level, such as the efficiency of building components and renovation decisions, heating systems and technologies and their replacement, and occupant behaviour. Through an iterative exchange between scenario description and modelling, the qualitative scenarios representing different narratives are then translated into the mechanisms and parameters in the model. The presented approach will be used to quantify the developed scenarios for the energy demand of the German building stock until 2045.

Introduction

In line with the Paris Agreement and aiming at keeping the global temperature increase well below 2 °C, the European Commission presented its long-term vision for climate-neutrality by 2050 (European Commission 2021). This was followed by the European Climate Law (European Union 2021), which requires EU Member States to incorporate the measures into their national long-term strategies to ensure the targets are met. Germany opted to become carbon-neutral by 2050 in its Climate Protection Act (Bundes-Klimaschutzgesetz 2019). However, with the introduction of the amendment to the Climate Change Act in 2021, the German government tightened the targets, aiming for climate-neutrality by 2045 and increasing the 2030 target by 10 % to a 65% reduction of total greenhouse gas (GHG) emissions compared to 1990 levels. It also introduced an Immediate Action Programme to accelerate the decarbonisation of various sectors, focusing mainly on measures with a short-term impact (Federal Climate Change Act 2021). To ensure that the country is on the right track towards decarbonisation, the German government regularly evaluates the achievability of sectoral climate targets with existing policy instruments. With over 40 % of total energy consumption and around 15 % of the GHG emissions (dena 2022), the building sector plays a major role in the achievement or failure of Germany's long-term climate goals and, as in previous years, is one of the sectors that has failed to meet its targets (to gradually reduce its emissions to 67 million tonnes of CO_2 equivalent by 2030). The latest Projection Report (UBA 2023) acknowledges that Germany will miss its 2030 and 2045 targets unless additional measures are included in German climate protection policy. To be effective, such measures should address technical as well as non-technical aspects, and current trends that can have a short and long-term impact on energy demand in the building sector.

Against this background, and as part of the project "Roadmap for a climate-neutral building stock 2050 (RokiG2050)" within the accompanying scientific research project "Energiewendebauen", this paper develops a methodological approach to depict the projected development of energy demand and GHG emissions in the German building sector in the coming decades. It takes into account the current technical, social, political and economic situation as well as the earlier results of the RokiG2050 project. The aim is to combine qualitative scenarios, describing current and possible future pathways, with quantitative energy modelling. The descriptive scenarios have been developed through a participatory process, taking into account the potential drivers of future energy demand in the building sector.

Scenario modelling

Scenarios, understood as qualitative descriptions of possible futures, are one of the widely used foresight methods (Schoemaker 1991). They do not aim to predict the future by extrapolating historical trends, but rather to explore potential future developments by considering how different paths could evolve in the future (Dean 2019). They can therefore be used as an effective tool to deal with the uncertainties of short-term events, such as energy crises, or to explore the possibilities of long-term developments, such as dealing with global warming (Cordova-Pozo et al. 2023). Different approaches and techniques can be used to develop scenarios in terms of their content (simple vs. complex), input data (quantitative vs. qualitative) and development process (analyst-led vs. participatory). Scenarios can also be either explorative or normative. Explorative scenarios start from the current situation and explore possible futures under certain conditions, taking into account influencing trends and factors. Normative scenarios, on the other hand, start from a desired future and investigate the conditions and changes needed to achieve that desired future (Dean 2019).

Scenarios, which describe the future in a qualitative way are increasingly used in combination with quantitative methods such as modelling and simulation. Quantitative forecasting methods are helpful in foresight to identify and explore issues in more detail (Cuhls 2003). They can be relatively accurate in the short term, but cannot adequately capture qualitative factors such as political, social, environmental and technological future developments. In addition, it is often difficult to take account of structural discontinuities, since mathematical-statistical models assume that patterns observed in the past will continue to be valid in the future (Helm et al. 1999). Until the 1980s and 1990s, qualitative approaches and quantitative simulations were often used independently of each other, as both have their advantages depending on the specific research question (Alcamo 2008; Lamnek et al. 1993). There was a growing distinction between the two research directions (even within the same institute), differing scientific communities (foresight versus forecasting) and controversial discussions about their respective performance and possible applications (Flick et al. 1995). However, it soon became clear that there are many overlaps and common concepts between the methodological approaches (Moschner et al. 2010; Stummer et al. 2021), especially when individual methods are combined in a larger process. Thus, the combination of both two approaches, with qualitative foresight as an open view into the future and quantitative data from the past and present simulated into the future by different models, has been increasingly discussed as reasonable.

Qualitative and quantitative approaches are today combined in two directions: either narratives containing qualitative statements are first created with the involvement of experts and then transformed into quantitative parameters, model variables or input values for simulation models (see e.g. Mostafa Shaaban et al. 2023 and Voglhuber-Slavinsky et al. 2022), or quantitative modelling results are put into context by developing narratives to explain the modelling results (Rogge et al. 2020). Following the first combination approach, scenario modelling has been widely applied in the literature to address different topics (for example Hosseinali et al. 2013; Xu et al. 2018; Gómez et al. 2011). With the vivid discussion on climate change and global warming, scenario modelling has often been used as a method to quantify the future development of energy consumption and GHG emissions. Examples of this approach can be found in the work of Ozawa et al. (2022) who model different pathways towards carbon-neutrality in Japan, or Vögele et al. (2017) and Zhou et al. (2008) who use scenario modelling to calculate the energy consumption of the residential sector in Germany and the tertiary sector in China. Governments are also following this approach to evaluate different transition pathways and, where necessary, improve their policies to achieve climate goals. Examples include the evaluation of different scenarios by the German government (UBA 2023) and the European Commission (2021). Scenario modelling is also used in this paper to explore different future pathways for the German building sector in its transition to decarbonisation (Figure 1). The development process and the resulting qualitative scenarios are described in the next section, followed by the introduction of an agent-based building stock model that uses the scenario assumptions as model parameters and calculates the energy demand and GHG emissions of residential and non-residential buildings in Germany.

Participatory scenario development

METHODOLOGICAL BACKGROUND

As described in the previous section, in a changing environment characterised by increasing uncertainty, the ability to anticipate future developments at an early stage is becoming ever more important. The use of foresight methods such as scenarios and horizon scanning is therefore becoming increasingly interesting for industry and the public sector. In order to prepare for decisions and upcoming actions, it is necessary to

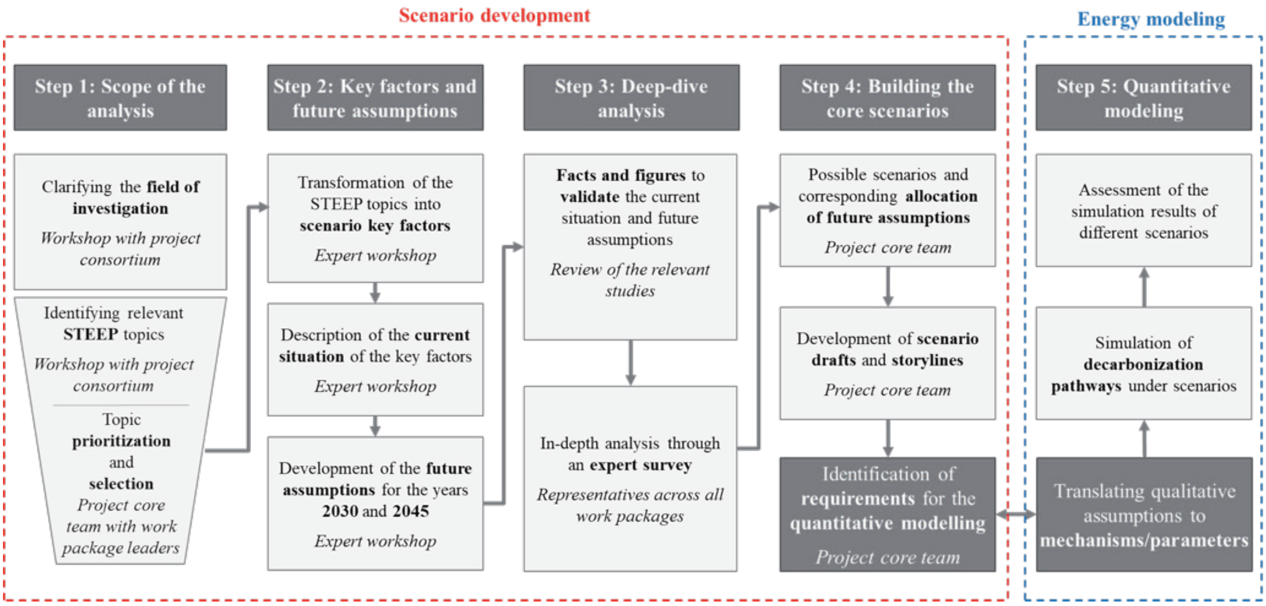

Figure 1. Scheme of the scenario modelling approach in the paper.

consider future developments. The greater the uncertainty, the greater the variety of future developments, the greater the scale of change and the greater the number of resources involved, the more important this consideration becomes. When dealing with the future, it is necessary to be aware of several important conditions related to its specific nature (Dönitz 2009):

- The future cannot be planned with complete accuracy and is always uncertain. It is therefore necessary to learn how to deal with uncertainty.
- It is important to consider the future of the field of investigation, and the immediate and wider environment.
- There is a connection between past, present and future. Recognising and defining this is an important task and at the same time a challenge for planning.

High levels of uncertainty do not automatically call planning into question, but do require greater flexibility. Various foresight methods can be used to identify uncertainties. One of the most important indicators of the quality of the scenarios, and thus of the quality of the assumptions, is the scope of the scenario factors analysed. However, the more variables are taken into account, the more difficult it is to manage them. An integral part of scenario analysis is horizon scanning, which refers to a systematic approach that aims to collect, analyse and interpret relevant information on future developments, trends and potential disruptions (Cuhls et al. 2015). The signals and trends identified through horizon scanning serve as the basis for scenario development by translating them into scenario factors. Our experience from diverse scenario projects shows that a participatory process is particularly suitable for the identification of scenario factors and the development of future assumptions (Dönitz et al. 2013). These experiences are also confirmed by other scenario users (Fink et al. 2002; Lipp et al. 2008; Ringland 2002). The relevant advantages are: the development of shared ideas about the future in a short time; the generation of more ideas through synergy effects (alternative concepts, different possibilities); the intensive discussion of possible developments; the promotion of the acceptance of the applied method and the results; and, in the case of successful workshops, positive side effects such as the broadening of one's own perception or building of networks. There are some special features depending on the type of scenario. For surrounding scenarios – referring to the external factors and conditions that impact an investigation field – participants with different backgrounds play a special role. The presence of representatives from other organizations operating in the same environment can help to avoid "group thinking" (Fink et al. 2002). The different, sometimes even conflicting, attitudes to the discussed topics support the creative exchange, especially when the collaborating or competing organization is involved in the process. The reason for this is that both benefit from the results.

LIMITATION OF THE METHOD

Participative scenario development is subject to several limitations, each of which contributes to questioning its effectiveness. Firstly, the need to prepare different solution approaches leads to a level of complexity that makes it difficult to rationalise the process. As the time reference moves further into the future, the degree of predictability decreases due to increasing uncertainties in the system under consideration. This highlights the difficulty of the method in providing sufficiently realistic scenarios over longer periods of time. In addition, it can be difficult to formulate qualitative statements precisely, which poses a challenge when communicating differentiated information. In particular, workshop-based scenario development, as an approach to participatory development, requires a relatively high level of development effort, which can be resource-intensive. The collection of relevant data for the scenarios requires considerable effort. The results achieved depend on the skill level of the scenario team and the intensity of the development, which emphasises the human factor in shaping the results. Criticism of workshop-based approaches focuses on following aspects (Schirrmeister et al. 2011):

- The area under investigation or its environment is too complex to be discussed in depth in all corresponding fields (many aspects are only discussed superficially).
- Involving all relevant actors leads to a large number of participants (less discussion time for each participant).
- The group dynamics may influence the results (over-estimation of some events or developments).
- A change in the framework conditions of a project is hard to be taken into account after a scenario workshop.

Besides the aspects named above which are related in particular to the assumption development, there are two main weaknesses of workshop-based approaches: Firstly, in addition to the different backgrounds of participants, the assembly representativeness requires a reflection what kind of variation is necessary to achieve the goal of the workshop. If the focus is on producing valid scenarios, professional and disciplinary backgrounds in all relevant fields would be most important. If it is on reflecting different views and desirability, different stakeholder views or social positions are important. This is not always possible to the full extent, e.g. due to lack of availability. Secondly, discussions are often influenced by short-term mood swings caused by the media.

WORKSHOP-BASED SCENARIO DEVELOPMENT

By integrating qualitative scenario development with quantitative modelling, we effectively address the limitations inherent in each individual approach. Qualitative scenario development provides a rich narrative context, offering insights into diverse factors that may influence outcomes. On the other hand, quantitative modelling brings precision and numerical data, allowing for a more concrete understanding of the potential scenarios.

A workshop-based approach was used to develop the German building stock scenarios, using horizon scanning to analyse the environment and a scenario method to explore possible futures. The scenario development process relied on the expertise of internal and external experts by conducting workshops at three levels with the project core team, the project consortium and external experts (see Figure 1). The consortium encompassed a spectrum of skills and knowledge relevant to the project objectives. The workshop with the external experts, who were representatives of projects funded by the German research initiative "Energiewendebauen", took place at one of the events of the accompanying research. A total of 11 participants, four from research and seven from practice covered a wide range of expertise, including social science, IT and data science, building materials and technology, and energy supply. The scenario process and its results – three scenarios for a climate-neutral building stock by 2045 – are presented below. These scenario stories represent qualitative descriptions of the future and will be used as the basis for modelling in the further course of the study. The development of the qualitative scenarios was conducted in four steps as presented in Figure 1.

Step 1: Definition of the scope of the analysis: The focus here was on clarifying the field of investigation and identifying relevant factors. The STEEP approach was used for this purpose. It involves identifying and analysing existing or potential changes in factors grouped and arranged in the following order: **s**ocial, **t**echnological, **e**conomic and **p**olitical (Kozłowska 2020).

Step 2: Identification of the key factors and development of future assumptions: STEEP aspects were translated into key factors for scenario development in an expert workshop. The current status of the factors was described and assumptions about the future development of each key factor were made.

Step 3: Deep-dive-analysis of future assumptions: The factors and future assumptions were defined and described through literature research and a survey within the project. In addition, data and facts on current and future developments were collected in order to deepen the assumptions about the future.

Step 4: Analysis of the compatibility of future assumptions in relation to each other and building the core scenarios: Workshops were used to describe the future assumptions for different time frames. The assumptions were bundled into three scenarios.

Step 1: Definition of the scope of the analysis and identification of the key factors

The scope of the investigation was defined during an internal project workshop, with an emphasis on content, spatial, and temporal delimitation. The scenario development process began with defining the problem and specifying the thematic, spatial and temporal boundaries of the analysis. It was crucial to precisely formulate the questions relevant to the subsequent analysis. The scope of the study should not be too broad to avoid a large number of influencing factors, unmanageable assumptions about the future, and confusion about interdependencies. The discussion resulted in a description of the current situation in the area under study – the state of the art in the building efficiency – and a characterization of the main issues and challenges. This resulted in the following scope:

- in terms of content, related to building types: residential buildings and non-residential buildings
- spatially, related to the geographical area: Germany-wide with specifications for the individual federal states,
- timeframe, until the year 2045, with year 2030 as an interim target.

Once the research topic was defined and delimited, the environment of the field of investigation had to be defined. This included identifying and structuring all developments and aspects that influenced the field of investigation from both the present point of view and but also from the future perspective. For this purpose, the STEEP approach was used to identify the areas of influence on the climate-neutral building stock (societal, technological, ecological, economic and political). This identification was organised around the following leading questions: Which factors should be considered? What would be an added value in the context of the project? Are there important factors that do not fit into the STEEP categories? The exemplary results of this step are presented in Table 1. Note that factors may belong to several categories, as the STEEP method is about a structured approach to identifying the factors and not about an exact categorisation.

Step 2: Identification of the key factors and development of future assumptions

The selected STEEP aspects were converted into so-called scenario key factors during an expert workshop. For example, the STEEP factor "Global supply chains/disruptions" in

Table 1. Results of the STEEP analysis.

STEEP category	Relevant aspects (selected, but not including the complete list)
Society	Quality of life/comfort of building users Lifestyle/household structure and size/housing concepts Environmental education Bottleneck in craft businesses/craft capacities Demographic change
Technology	Building management systems Renovation/refurbishment solutions Solutions for new buildings Grid efficiency/demand side management Optimal vs. Non-optimal building operation Complexity of new energy-efficient solutions/consultancy expertise
Ecology	Extreme weather conditions Availability of resources Green gas/fuels/biomass and their availability in the building sector
Economy	Price of technological solutions Ownership structure Budget available in households Funding/investments Global supply chains/disruptions Private households as players in the flexibility market/new business models/opening of the electricity market
Policy and Regulation	Promotion of innovation/framework conditions for innovation Subsidies for plant and construction technology Legal requirements, e.g. “mandatory refurbishment” Global power shift/political development

the “Economy” category was transformed to the scenario key factor “Development of supply chains: Value creation process, order – production –delivery; resource availability” – belonging to the thematic group “society and economy” (see category 5 below). In some cases, the new factor became more tangible and easier to understand, while in other cases, it became a more comprehensive term. The transformation and definition of the key factors during the expert workshop aimed to achieve both outcomes depending on the specific STEEP aspect.

Not every aspect needs to be reformulated as a scenario factor. However, multiple scenario factors could be derived from one aspect. They represent essential aspects relevant to the topic of “building stock” today and in the future. The original STEEP categories were dissolved, and the 16 scenario key factors were grouped into five thematic categories, also reflecting the work already done in the previous stages of the project. The scenario factors are presented below. Note that even if they are grouped into different categories for clarity, these categories are not mutually exclusive, and the factors may be interlinked. Interlinkages are explored in a later step.

Category 1: Energy-efficient building refurbishment as a core component of the energy transition

- Serial refurbishment: the influence of serial refurbishment on increasing the refurbishment rate – where are the limits?
- Lower flow and district heating temperature: the influence of lower district heating temperature – where do problems arise in existing buildings?
- Refurbishment roadmaps: in particular, the influence of refurbishment roadmaps and their follow-up by the authorities
- Selection of the optimal energy system: in existing buildings, including electrification in the building sector: influence of energy prices, etc.

Category 2: Integration of individual buildings into the overall system

- Flexibility requirements on the end consumer side (buildings)
- Digitization progress in the building sector: influence on demand-side management potential in particular

Category 3: New construction as a driver of innovation

- Increased efficiency through research and technological progress
- Mandatory climate-neutral (or even plus-energy) building operation for new buildings
- Mandatory use of photovoltaics (PV) in new buildings

Category 4: Regulatory framework conditions

- Subsidy programs: influence of changing subsidy programs, including “Efficient House 55/40” before and after 2022
- Regulatory restrictions for new constructions and conversions: including additional costs, possible savings
- Restrictions on renovations: including stricter minimum requirements for building refurbishment

Category 5: Society and economy

- Craftsman capacity and profitability of craft companies: shortage in craft businesses; lack of skilled labour during implementation; profitability of companies – prices and investments

- Development of supply chains: Value creation process, order – production – delivery; resource availability
- Income development: social inequality; ownership
- Household structure and size: lifestyles; living concepts; living space

The established scenario factors were described in two ways: First, the current status of the factors was described. Then, their possible future developments were formulated. For some scenario factors, only one possible future assumption was made, while for others different future assumptions were discussed.

Step 3: Deep-dive-analysis of the future assumptions

In order to address the criticism on the development of future assumptions in workshop-based approaches, these future assumptions were validated through a survey of involved experts within the project consortium. Following the initial generation of ideas on the future development of key factors (future assumptions) during the workshop outlined in step 2, the survey included the following points:

- Identification of relevant themes and specific factors:
  - The previous suggestion of key factors was listed and could be specified by participants.
  - Additional factors could be proposed or existing factors could be adjusted. However, this did not result in a change in the set of key factors.
- Description of the current situation in relation to each factor for 2022 (the year of the investigation).
- Description of future assumptions regarding the future development of the factors for 2030 and 2045, with the following questions:
  - Is there only one possible development state for a given point in time (future assumption A)?
  - Are there other possibilities due to uncertainties in this area? (future assumptions B, C or D)?

Furthermore, to enrich the assumptions about the future, the data and facts on current (Table 2) and future developments (Table 3) were collected from diverse literature sources. An example of this is shown in Table 2.

Step 4: Analysis of the compatibility of assumptions and building the core scenarios

A series of internal project workshops were used to finalise the descriptions of future assumptions for different time frames (2030 – as an intermediate step – and 2045). Three assumptions were identified for each key factor for the years 2030 and 2045 respectively. Table 3 presents an example of these assumptions. Assumption A always represents the most optimistic outcome, assumption C the most pessimistic one and assumption B a middle ground.

On this basis, the possible scenarios created by combining the assumptions of various factors were discussed. The future assumptions of each factor were then bundled into three plausible scenarios, with all assumptions A combined to form one scenario, all assumptions B for another one and all assumptions C for a third one. The three directions of the scenarios, positive, pessimistic and middle ground, were the results of the survey on future assumptions and internal workshops. The designed scenarios cover a wider range from optimistic to pessimistic future states in order to consider a broader range of developments. The scenarios based on assumptions A and C represent two rather extreme development options for the year 2030:

- "Sustainable transformation of the building sector" (Scenario A): This scenario outlines an optimistic vision for 2030, in which comprehensive measures have been taken to make the building stock more sustainable. The potential for increasing the efficiency of building has been fully exploited. This includes technological implementation, regulation and economic and social aspects such as trading capacity.
- "Skills shortage and uncertainties in the building stock development" (Scenario C): This scenario sheds light on the difficulties that could arise from a shortage of skilled workers, global supply chain disruptions, and a low investment readiness in the construction sector by 2030. The potential is largely untapped. The scenario describes a continuation of the status quo.

The "Challenges in transition and varied progress" scenario is based on assumptions B and represents a hybrid variant between the two extreme scenarios (A and C). It shows a differentiated development in 2030, characterised by partial challenges and limited progress. For the year 2045, all factors and assumptions (in all scenarios) show a development push in the direction of increasing building efficiency, so that the extreme negative variant in terms of efficiency (scenario C from 2030) is no longer justified. To provide an overview of the scenarios developed, the 2030 scenarios are described in the remainder of this section. These qualitatively described scenarios represent different frameworks for the subsequent modelling. The next step is to quantify the individual future assumptions and, if necessary, adjust them for integration into the model.

CLIMATE-NEUTRAL BUILDING STOCK SCENARIOS 2030

Scenario A: "Sustainable transformation in the building sector"

In 2030, the building stock has undergone a transformative development, characterised by positive assumptions and measures. The planned roll-out of smart meters, has been completed by 2030, despite pandemic disruptions, establishing the infrastructure for Demand Side Management (DSM). The minimum requirement of 80 % renewable energy in newly installed heating systems has exceeded the Coalition Agreement target of 65 %, and a ban on the use of fossil fuels in new installations has been introduced. The funding process has been simplified and digitized, rewarding resource efficiency, and there is increased support for climate-neutral construction and heat generators. Existing buildings benefit from federal funding for efficient heating networks, and the reinvestment of the CO_2 tax flows back into the existing stock. Energy efficiency standards such as KfW EH 100 are established for existing buildings, possibly with mandatory renovation plans to achieve the standards. Mandatory solar requirements for all new constructions are enforced,

Table 2. Facts and figures for current situation of key factor "income development: social inequality and property".

<table>
<tr><th>Indicator</th><th>Facts and figures (examples)</th></tr>
<tr><td>Development of real and nominal earnings, consumer prices in the period 2008 to 2022</td><td>On account of the redesign of the earnings survey with data collection starting in January 2022, the indices of nominal and real earnings have now been rebased to 2022 and earlier results revised. The index of nominal earnings reflects the development of gross monthly earnings of employees including extra payments. Consumer prices rose by 6.9 % in 2022. The Federal Statistical Office (Destatis) reports that real earnings have thus decreased by an average 4.0 % compared with 2021, following their previous downward trend in the last two crisis years. In line with the development of nominal earnings, the decline was 0.9 percentage points higher than had been determined using the provisional calculation basis.

(Statistisches Bundesamt 2022)</td></tr>
<tr><td>Development of income inequality based on the Gini index in the period 2010 to 2022</td><td>In 2022, the Gini index* in Germany was 28.8 points, a decrease of 2.4 points. The average in the European Union (EU-27) was an estimated 29.6 points in 2022 (see also EU countries by income inequality in the Gini index). (Eurostat 2024).</td></tr>
</table>

** The Gini index or Gini coefficient is a statistical measure used to visualise unequal distributions. It can assume any value between 0 and 100 points (0 means absolute equality and 100 absolute inequality) and shows the deviation of the distribution of disposable income among individuals or households within a country from a completely equal distribution.*

Table 3. Example of a key factor with its current situation and future assumptions.

<table>
<tr><th colspan="3">Key factor "Development of supply chains" – Category 2 "Integration of the individual building into the overall system"</th></tr>
<tr><th>2022</th><th>2030</th><th>2045</th></tr>
<tr><td rowspan="3">Current Situation
The biggest challenges facing the construction industry are delays and problems in the supply chain as well as the availability of raw materials. There is an increasing shortage of materials in the construction industry. Furthermore, increasing globalisation and global consumer behaviour mean that supply chains can become long and complex. However, supply chain management is facing a fundamental paradigm shift. The supply chain is so closely interlinked with the production system of a company as well as the entire business model that it can no longer be viewed separately. It is increasingly becoming an extension of the own business. In general, the entire construction industry is complaining about a lack of materials. Most of the steel used in Germany comes from Russia or Ukraine, and these suppliers are now largely absent. However, there is also a shortage of asphalt, concrete and oil. There is a risk of a shortage of building materials wherever Russia, Ukraine and Belarus are involved in the process chain.</td><td>Assumption A (most optimistic)
Based on the lessons learnt from the pandemic caused by COVID-19, companies have managed supply risks much better, e.g. by holding more stock, developing alternative suppliers and supply routes, or also with more regional purchasing.</td><td>Assumption A (most optimistic)
Supply chains have become stable as the focus has shifted entirely to regional and national supply. The problems could be solved, not by abolishing just-in-time, but by selectively hedging against specifically recognised default risks.</td></tr>
<tr><td>Assumption B (middle ground)
Based on the lessons learnt from the pandemic caused by COVID-19, the companies have managed the delivery risks better – some regional or even local planning has begun.</td><td>Assumption B (middle ground)
Based on the lessons learnt from the pandemic caused by COVID-19, companies have managed supply risks much better and more closely, e.g. by holding more stock, developing alternative suppliers and supply routes, or also with more regional purchasing. The problems could be solved not by abolishing just-in-time, but by selectively hedging against specifically recognised default risks.</td></tr>
<tr><td>Assumption C (most pessimistic)
There are disruptions or impairments to global supply chains due to various risks. These include natural disasters that can bring production in the domestic economy to a considerable standstill or disasters in a third country that affect the international supply of operating resources. There are also deliberate interruptions, such as terrorist attacks, sabotage or actions by activists.</td><td>Assumption C (most pessimistic)
Based on the lessons learnt from the pandemic caused by COVID-19, the companies have managed the delivery risks better – some regional or local planning has begun.</td></tr>
</table>

and targeted funding programs and innovative business models lead to a renaissance of the craftsmanship industry with an improved reputation and sufficient capacity. Reducing inequalities through subsidies and financial support has led to an increase in renovation and modernization work. Companies have learned from the experience of the COVID-19 pandemic and have better safeguarded against supply risks. Advanced DSM business models allow automated control for large energy consumers, with users increasingly taking responsibility for their actions. Attractive electricity prices, buildings acting as prosumers, and automated determination of the best energy systems are a reality. Digitalisation extends to schedules throughout the entire building, and the carbon footprint is determined not only in terms of energy but also concerning materials. This comprehensive development reflects the successful integration of sustainable and efficient practices in the building stock, while cities and grid operators are well-prepared for increased demands. Technological advances and high transferability have led to increased efficiency in existing buildings. Climate-neutral operation is mandatory for new constructions and is gaining ground in some existing buildings. Community living for all ages is being promoted, and neighbourhood projects are gaining in importance. Serial renovations are widespread, while clear interpretation rules drive the adoption of energy-saving measures.

Scenario B: "Challenges in transition and varied progress"

The usual vocational guidance tools have helped to address skills shortages in some regions, but capacity remains below target. Operational activities are often individual actions due to limited time and organizational resources, and long-term planning is lacking. Inequality has not been reduced and housing costs have increased as a proportion of disposable household income. Requirements for compliance with energy efficiency standards on change of ownership (e.g., KfW EH 75) remain. There are technology bans on the installation of new monovalent gas heating systems in new buildings and if reasonable, in renovations. The minimum requirement of 65 % renewable energy in new heating systems, as stipulated in the coalition agreement and set in the Building Energy Act, has been in force since 2024, but no further progress has been made. Climate-neutral operation is mandatory for new buildings, as are solar obligations for all new buildings (e.g., 60 % of suitable roof areas). Widespread application of these measures is still to come, but the path is clear. The digitization of the individual building renovation roadmaps focuses on specific components such as facades & basement ceilings and the heating system. In contrast to Scenario A, only part of the potential is exploited, especially in denser areas. The previously planned Smart Meter rollout can only be partially completed by 2030, particularly in areas with high electricity consumption in new constructions. There is no flexibility through buildings; instead, flexibility is achieved by integrating large centralised storage (electricity and heat). Although there is a commitment to ensure attractive electricity prices, this is not effectively managed. Cooling and electricity demand in buildings has increased compared to 2022, and modernization concepts only partially address this. Companies have better managed delivery risks due to lessons learned from the COVID-19 period, and some planning has started at the regional/local level. Efficiency improvements due to technological progress are moderate, as is transferability to and enforcement in existing buildings. Applying for financial support is complicated, and support is only available for very specific goals. Funding is available, but its distribution is not optimal – there is a clear eventisation of funding measures and a lack of long-term orientation.

Scenario C: "Skills shortage and uncertainties in the building stock development"

This scenario is a challenging development, characterised by a significant shortage of skilled workers, disruptions in global supply chains, and low investment readiness. The shortage of skilled workers has intensified due to the declining number of employed individuals and the working-age population, further exacerbating the pressure on the skilled workforce situation in the trades. Particularly, trades that serve commercial needs, the construction finishing sector, and parts of the main construction industry are facing additional challenges due to shifts in manufacturing professions and the trend towards academic qualifications. Investment readiness in the trades has decreased, and the order situation has worsened, with many companies operating at limited capacity. Global supply chains are exposed to various risks, including natural disasters that can significantly disrupt domestic economy production and intentional disruptions such as terrorist attacks or sabotage. Inequality has notably increased, and the proportion of housing costs to available household income has risen sharply. This has led to fewer renovation and modernization plans. The age structure has implications, as the number of older households has increased, while larger households are decreasing. The number of single-person households continues to rise, the share of partnerships with separate household management is growing, and an increasing number of people over 60 live alone, requiring larger living spaces. The solar obligation remains limited to individual states or cities. There has been no efficiency improvement through technological progress, and the transferability to and enforcement of existing buildings is low. Climate-neutral operation is not mandatory for new constructions but is limited to buildings with a pioneering role. Serial renovation is not cost-effective and does not lead to higher renovation rates. The challenges of the low-temperature system persist. There is no improvement in digitization, and flexibility is also lacking. The previously planned Smart Meter roll-out will probably not be achieved by 2030, neither in new nor existing buildings. There is also no tightening of current requirements, and fossil fuels remain attractive due to high electricity prices. There is limited financial support or obligation to change heating systems in existing buildings. The application process for financial support is complicated, and support is only available for specific goals. Funding is scarce, and the eventisation of funding measures and the lack of long-term orientation, is evident.

From qualitative scenarios to quantitative modelling

Following the qualitative scenario development, we simulate the decarbonisation pathways of the German building stock under different scenarios using the RENDER-Building model. RENDER-Building is an agent-based model for the building sector in Germany. The entire building stock is represented by a population of representative buildings (i.e., agents), each of which is assigned the following information:

1. sector, including residential and tertiary sectors (NACE classification);
2. building type, including residential buildings with different numbers of dwellings, and tertiary buildings, including office buildings, educational buildings, production buildings, etc.;
3. construction period, from "before 1990" to "after 2011";
4. location, including region (NUTS3 resolution) and seven levels of urbanization.

Based on this, further information is mapped to the representative building by combining different sources (e.g., IWU and DENA reports, Census data, Global Human Settlement Layer data), including building height, floor area, u-values of building components, orientation, number of units, unit users, heating systems and technologies, etc. Finally, the model is calibrated with final energy consumption data in a base year. The development of the building stock database is presented in Alibas et al. (2024). The agent-based framework allows the capture of heterogeneity in terms of building typology, efficiency, and technologies. Furthermore, the bounded rationality of building owners can be captured in the modelling of investment decisions, such as building renovation, heating system replacement. For each representative building, the details of the building and existing technologies could influence the feasibility and efficiency of the technologies under consideration. For example, if a building is old and has low efficiency, heat pumps may not be efficient or even feasible, then the agent can only choose gas or other types of boilers. The agent-based framework also supports modelling the interaction of agents, such as the constraints of scarce resources shared by all agents. All scenarios focus predominantly on the demand-side development and can later be used to interact with supply-side (e.g., district heating) modelling. In summary, to quantitatively model the decarbonisation pathways under different scenarios, the qualitative assumptions are translated into:

1. mechanisms that are applied to all the agents, e.g., the representative buildings are triggered to do mandatory renovations so that we can see the necessary renovation rate for reaching a specific decarbonisation target, as well as the demand for energy, craftsman, etc.;
2. technological or behavioural parameters, e.g., the availability of building components with certain efficiency levels (u-value) and heating technologies on the market, and the preference of agents for certain technologies.

In the example presented in Table 3, the material constraint may limit the renovation of buildings in each year. To quantify such an impact in the scenario simulation, we can introduce the available material for building renovation each year as an exogenous input. Such an input is developed based on empirical studies or expert estimates. Then, as shown in Figure 2, when the building agents are triggered to renovate the building in the model, their renovation plans (RPs) are inserted into a pipeline awaiting execution. By the end of each simulation year, all actions are proceeded one by one, until the available resources for that year are used up. The remaining actions will be executed in the next years when more material is available.

Discussion and conclusion

The German Climate Act requires the building sector in Germany to become climate-neutral by 2045, five years earlier than the target set in the European Commission's Climate Law. To ensure the achievement of short and long-term climate goals, the government regularly assesses the GHG emissions of different sectors in its biennial Projection Reports. The latest study proposes additional measures to avoid missing the targets in the building sector on the decarbonisation pathway. This paper presents the qualitative scenarios developed to describe the possible future pathways in the building sector, considering the influencing trends and factors. Through a scenario model-

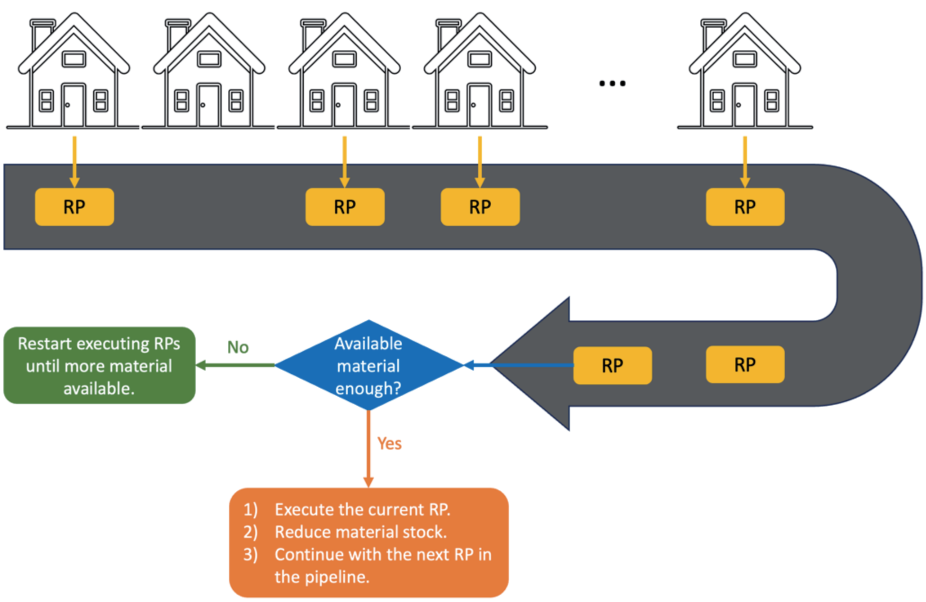

Figure 2. Execution pipeline of the renovation plans of buildings.

ling approach, it combines the benefits of qualitative foresight and quantitative simulation methods. As a first step and following a participatory process three explorative scenarios were developed, representing the negative, neutral and positive pathways. They describe a current picture of Germany's the political, social, economic and technical situation in 2022, and explore the different ways in which it could evolve under certain assumptions up to the years 2030 and 2045. The developed scenarios will then be translated into model parameters, in an agent-based building stock model to quantify the annual energy demand and GHG emissions in the building sector until 2045. They can therefore provide policy makers with good insights to design useful and efficient instruments to achieve climate targets. Scenario methods are now one of the most important methods for addressing future uncertainties and have been used to support strategic planning in German companies since the mid-1980s. By developing alternative scenarios, the spectrum of possible future developments is identified, and the handling of uncertainties is encouraged. However, there are some limitations to the use of scenario methods. The future will see more combinations of scenario stories or single assumptions about the future with quantitative models or backed up by surveys, because they have the advantage of linking subjective judgement and rational analysis, which is only meaningful to a certain extent. Mathematical models can help interpret qualitative statements and allow quantitative conclusions to be drawn about possible future social, ecological or political effects and conditions. In addition, the usually static representation at a selected point (in time) in the future gains analytical depth in dynamics through the combination with simulation models. Combining qualitative scenarios and quantitative modelling opens up many new possibilities and requires intensive collaboration between researchers. This combined approach enhances the robustness of our analyses and provides a more comprehensive perspective, leveraging the strengths of both qualitative and quantitative methods.

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