

<https://doi.org/10.1038/s44168-025-00229-2>

# Carbon neutrality in the residential sector: a general toolbox and the case of Germany



Anna Hornykewycz<sup>1,2</sup>, Jakob Kapeller<sup>1,3</sup> ✉, Jan David Weber<sup>3</sup>, Bernhard Schütz<sup>3,4</sup> & Lukas Cserjan<sup>1,2</sup>

This paper presents a general framework for estimating the renovation and investment requirements associated with a socio-ecological transformation of the residential sector that effectively reduces the net emissions of the residential sector (close) to zero. The framework takes ecological and distributional considerations into account and aims to provide concrete outcomes suitable to inform policy-making, while being as parsimonious as possible on the side of data requirements. All key steps associated with this framework are compiled in an openly accessible toolbox that can be adapted to different country-specific contexts. This paper takes the German case as an example to illustrate the main assumptions, data requirements, and outcomes that can be derived from this toolbox.

Attaining carbon neutrality in the residential building sector is essential for successfully transforming modern economies to operate within the limits of planetary boundaries. This overall requirement gives rise to the more specific task of devising programs that facilitate such a transformation on domestic levels. We present a general toolbox that considers several key dimensions of interest suitable to assess, evaluate, or design such domestic programs. These dimensions include (1) the technological requirements for achieving a successful transformation, (2) the scale of effort required for implementing these technologies, (3) the investment costs associated with such an effort, (4) the economic impact of these investments, and (5) the distribution of the investment costs between the private and the public sector as well as within the private sector.

The toolbox presented here explicitly incorporates the notion of a ‘just transition’, understood as a governance strategy aiming to bridge social and environmental concerns in transformational policies<sup>1</sup> by explicitly incorporating considerations on justice and fairness<sup>2,3</sup>. In this view, the “principle of equity should be explicitly expressed in relevant policies”<sup>1</sup>. For this reason, our toolbox allows for considering the impact of domestic action programs on distributional aspects.

The toolbox is available in [open-access form](#) and can be adapted to the situation in different countries. Due to its modular structure, different components of the toolbox can be applied in isolation. We keep the data requirements of our framework as parsimonious as possible to ensure broad applicability. The focus of the toolbox is on improving the efficiency and consistency of the residential sector, complementing studies that emphasize the potential of greater sufficiency in the residential sector<sup>4,5</sup>. In this paper, we apply our toolbox to the case of Germany to illustrate its core functionalities and analytical potential.

The German building sector has, on average, suboptimal isolation standards and still makes heavy use of fossil energy sources. Since Germany committed to achieving climate neutrality by the year 2050, it represents a challenging and important case of application. While there exists a multitude of studies dealing with the transformation of the Germany residential sector specifically<sup>6–12</sup> or as part of a larger transformation scenario<sup>7,13,14</sup>, to date no standardized procedure for calculating renovation requirements has been developed. One reason for this missing standardization is that past studies lack transparency and replicability with respect to how renovation requirements as well as the related costs are determined. In addition, a consistent blind spot of existing studies is that the socio-economic impact of the proposed policy measures is not analyzed. The associated uncertainty about the socio-economic impact of transforming the German residential sector mirror the challenges and controversies associated with Germany’s past efforts to transform the residential sector, such as the debate over the Buildings Energy Act (Gebäudeenergiegesetz, GEG, often dubbed ‘Heizungsgesetz’ or Heating Act in public debate). This uncertainty underscores the importance of designing just and transparent subsidy schemes to ensure public support and political feasibility<sup>15</sup>. Against this background, we also aim to provide more clarity on the socio-economic and distributional consequences associated with a transition of the residential sector towards carbon neutrality.

## Results

To reach the goal of climate neutrality by the year 2050, Germany set emission targets for all relevant sectors, including the residential sector (Section 4 of the Federal Climate Change Act (Klimaschutzgesetz, KSG)). Emissions are classified as direct and indirect emissions. Direct emissions entail all emissions that are directly *produced* within the residential sector

<sup>1</sup>Institute for Comprehensive Analysis of the Economy (ICAE), Johannes Kepler University Linz, Linz, Austria. <sup>2</sup>Socio-Ecological Transformation Lab (SET Lab), Johannes Kepler University Linz, Linz, Austria. <sup>3</sup>Institute for Socio-Economics, University Duisburg-Essen, Duisburg, Germany. <sup>4</sup>The Vienna Institute for International Economic Studies, Vienna, Austria. ✉e-mail: [jakob.kapeller@uni-due.de](mailto:jakob.kapeller@uni-due.de)

(e.g. through gas-based heating systems). Indirect emissions include all emissions that are *consumed* in the residential sector (e.g. electricity-based heating systems). The direct carbon dioxide (CO<sub>2</sub>)-equivalents attributed to the German residential sector are estimated to account for 14% of overall emissions in Germany. This share increases to at least 25% when also considering indirect emissions<sup>6</sup>.

The German residential sector consists of 19,4 million buildings. The majority of these are single or two-family houses (83%), while the remaining buildings are apartment buildings containing an average of seven flats<sup>16</sup>. Information on the quality of insulation and the type of heating system is collected in energy certificates (Sections 79–88 of the Buildings Energy Act (Gebäudeenergiegesetz, GEG)) that contain information on the year of construction, the last renovation, the heating system, and energy requirements. These data indicate that German heating systems are still mostly based on fossil energy sources as nearly 70% of all heating energy is provided by decentralized oil and gas heaters. In contrast, only 17% of all energy devoted to heating draws on renewable energy sources<sup>16</sup>. Against this backdrop, we first elaborate on the technical requirements before moving on to economic requirements and the consequences of the socio-ecological transition.

### Technical Requirements: Reduction and Decarbonization of Energy Use

Existing studies on the transformation of the German residential sector show a strong consensus on suitable technical strategies to achieve the climate goals: Reducing carbon emissions can be achieved by a combination of renovations dedicated to improve energy efficiency and the replacement of fossil-based decentralized heating systems. The latter typically relies on heating pumps, that use emission-free ambient heat, as well as the expansion of district heating. At the moment district heating in Germany still relies heavily on fossil fuels as only 12% are provided through renewable sources such as biomass, organic waste, geo- and solar thermal energy and waste incineration<sup>17</sup>. We take into account that replacing fossil fuels in the residential sector reduces *direct* emissions, but may increase *indirect* emissions as heating pumps require electricity to operate. To capture this potential outsourcing of heating-related emissions from the residential sector to the energy sector, we focus on the *emissions intensity* of the German residential sector. This more inclusive measure also captures indirect emissions induced by heating and thereby allows for a holistic assessment of how changes in the residential sector impact net emissions created.

**Renovation Rate.** Two different concepts have been dubbed ‘renovation rate’: First, the share of buildings that are subjected to some form of renovation and, second, the share of square meters that are subjected to a ‘full renovation’ (where partial renovations are aggregated into full renovations). As these concepts differ substantially, we try to achieve clarity in our analysis by defining the *renovation rate* as the share of buildings that undergo some form of energy-efficient renovation, whereas we will call the share of fully renovated living area the *full renovation equivalent*. For better clarity and comparability, our toolbox allows for calculating renovation rates according to both definitions.

Currently, the full renovation equivalent in Germany is approximately 1.15%<sup>13</sup>. Past studies typically recommend increasing the full renovation equivalent to 1.5–2%<sup>7,10,11,13,14</sup>. We show that this will not be sufficient to reach the climate goals. Based on our assumptions, it is necessary to increase the full renovation equivalent to 2.5% till 2045, which corresponds to a renovation rate of 3% per year. In contrast to past studies, which estimate or assume lower required renovation rates, our estimate relies on a transparent and replicable approach. This setup allows to explore sensitivity to specific assumptions, which is not doable for existing studies. A similar reasoning applies to economic approaches employed to calculate effective costs, which typically rely on net present value methods that underestimate the merits of systemic energy savings and do not adequately represent the decision criteria for private households.

In other words, the analysis facilitated by our toolbox suggests that prior studies have underestimated the necessary renovation rate. To complement and contextualize this main result, we additionally show that an increased renovation rate must be combined with a decarbonization strategy for external energy sources and a prioritization strategy that puts the renovation of badly insulated buildings first. These results are summarized in Fig. 1, Panels (A) and (B), which show how different assumptions impact the speed and intensity of emission reductions and plot these reductions relative to the official climate goals.

**Prioritization.** There is a significant difference between renovating buildings in a random order and prioritizing the renovation of the buildings with poor performance metrics. In the long run both renovation strategies lead to climate neutrality. However, to achieve conformity with the climate targets over time, a prioritization of the buildings with poor performance metrics is necessary (see Fig. 1, Panel C). As the notion of ‘poor performance’ can be operationalized in different ways, our toolbox is designed to flexibly accommodate different strategies for implementing such a prioritization – for instance, by referring simply to efficiency classes as an ordering criterion or by using more precise measures like energy use of individual residential units or per square meter. The ordering used in Fig. 1 is based on the entire energy use of residential units.

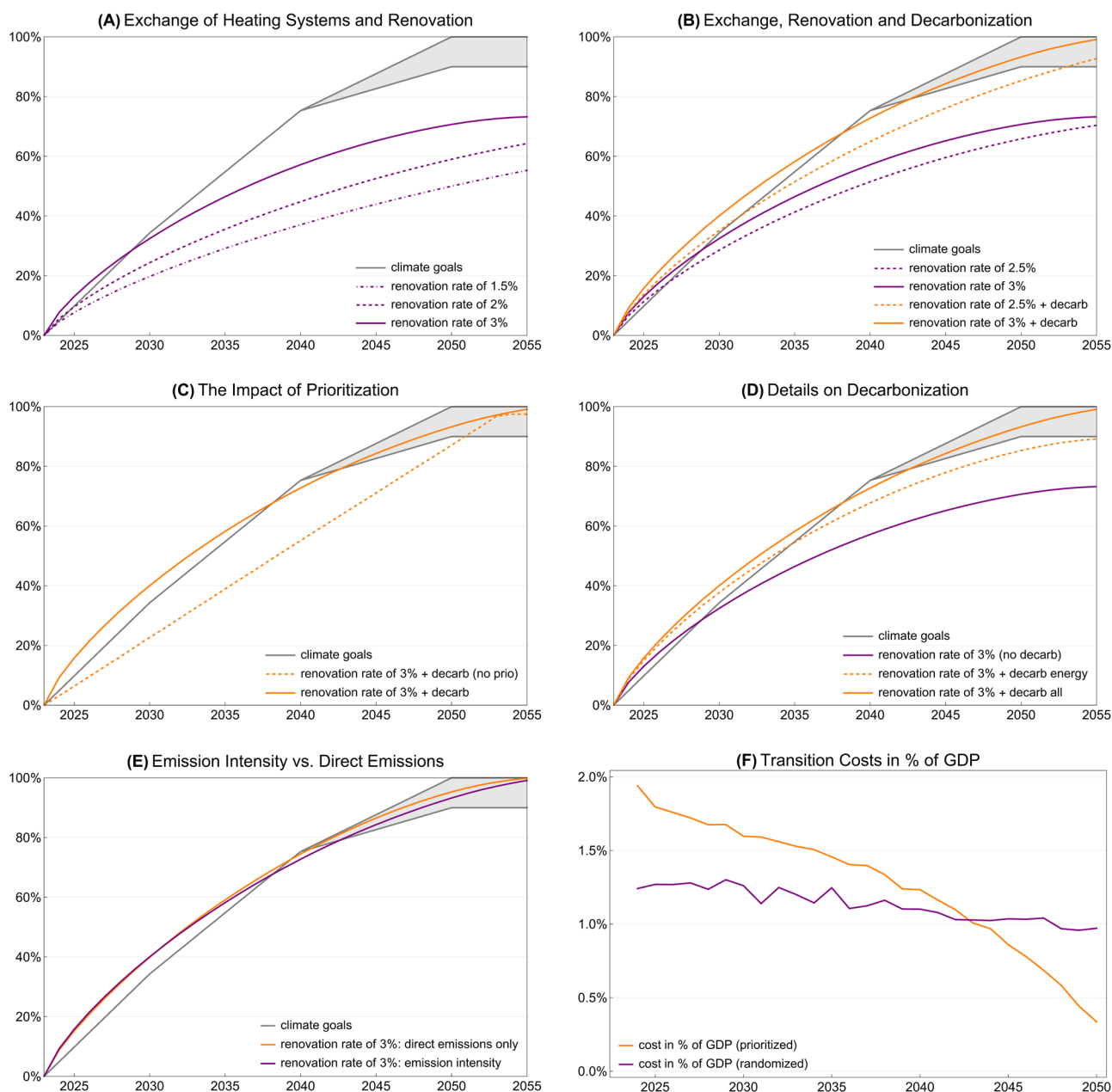
**Decarbonization.** The need to decarbonize external energy sources applies to the energy sector, which provides the main energy source for heating pumps, and the provision of district heating<sup>18</sup>. In this context, our toolbox allows for mapping the relative contribution achieved by decarbonizing these heterogeneous energy sources as illustrated in Fig. 1, Panel D. For doing so, we employ the notion of *emission intensity* in the residential sector as defined in the section on methods. This measure will be closely aligned with conventional estimates based on direct emissions if all external energy sources are truly decarbonized (see Fig. 1, Panel (E)), while differences will emerge as soon as outsourcing to other sectors occurs (as already observed in Fig. 1, Panels B and D).

Three key policy implications emerge from these results. Firstly, a massive upscaling of renovation activities is necessary. Secondly, decarbonization of energy provision is essential to reduce the net emission impact of the residential sector and, finally, some regulatory strategy is necessary to ensure that units with inferior ecological performance are renovated with priority.

### Financial requirements, economic impact and distributional aspects

**Financial Requirements.** Currently, the annual sum of expenditures for energy-efficient renovations in Germany amounts to roughly 58 bn €. According to our calculations, implementing energy-efficient renovations as described above would induce additional costs of about 58 bn € per year. The total investment until 2050 sums up to 3.1 trillion € (in 2023 prices). Prioritizing the renovation of the buildings with poor performance metrics implies that an over-proportional share of total costs occurs in the early years. In the first year of the policy measure, additional costs of 81 bn € are anticipated, which amounts to about 1.9% of GDP, which over time decreases to 0.3% (Fig. 1, Panel F). In this context, we assume a real annual GDP growth rate of 1% and an inflation rate in the construction sector that corresponds to the overall inflation rate. As discussed below, we propose combining targeted public subsidies with regulatory means to meet these requirements. Regulatory means are thereby relevant for an effective prioritization of renovations, i.e. for renovating buildings with poor performance first, but also to ensure that owners, who do not qualify for a subsidy, cannot delay renovation measures.

**Economic Impact.** These additional investments in the residential sector have direct economic consequences, which are explored by making use of



**Fig. 1 | Emission reductions in the residential sector.** Panels A–E show expected emission reductions under different scenarios, while Panel F shows expected (additional) costs arising in a full-decarbonization scenario with a 3% renovation rate.

an input-output model. We find a—comparatively low—GDP multiplier of 1.16, which implies that every € invested in transformation measures will increase GDP by 1.16 €. This result is due to the low pre-production intensity of the affected sectors and the fact that many intermediate goods required for such an investment initiative need to be imported from abroad.

Our toolbox can be used to assess potential capacity constraints. We find that initiating the suggested transformation will increase employment in the construction sector by approximately 274,000 workers per year on average. In the early years, this demand reaches a maximum of 377,000 workers per year. Long-term estimates of labor market development in the German construction sector point to an endogenous decrease in labor demand in the construction industry<sup>19</sup>, which is why additional labor demand could be met partially through a decline in new construction projects<sup>20</sup> or strategic recruitment agreements to foster migration.

In principle, our proposed shift from constructing new residential units toward a strict focus on renovation-based policies has positive spill-over

effects on the emissions in the construction sector as renovations produce fewer emissions than construction<sup>21–23</sup>. As this associated reduction in emissions takes place in the industrial, not the residential sector (Attachment 1 to §5 Klimaschutzgesetz (Federal Climate Change Act, KSG)), it is not included in our toolbox. However, this change of emissions in the industrial sector could be added to the analysis to better incorporate this win-win situation.

The introduction of a retraining program for workers is advisable to compensate for potential bottlenecks by facilitating a shift of workers from similar industries<sup>24</sup> as well as to improve earnings gains for the respective workers<sup>25</sup>, which potentially originate from industries that suffer through a socio-ecological transformation of the German economy (e.g., coal mining, automobile industry). Hence, costs of such a job training program must also be weighed against the costs of unemployment.

**Distributional aspects.** The distribution of residential property in most countries is highly uneven as large shares of residential property are held

by households at the upper end of the wealth distribution<sup>26</sup>. Hence, funding the transformation with a watering-can principle might be effective in technical terms, but it would redistribute taxpayer money from less wealthy individuals toward—already comparably wealthy—residential real estate owners. This would further speed up observed secular trends towards increasing inequality<sup>27</sup> and is also likely to reduce public support for such measures<sup>28</sup>.

According to HFCS data, the wealthiest 10% of the German population own 48% of residential wealth while the least wealthy 50% only own 3% of real estate property. These observations indicate that possible subsidies should ensure to not intensify wealth concentration as energy-efficient renovation measures on residential buildings lead to an increase in the value of the affected properties. If the properties were owned by private individuals, a subsidy would imply subsidizing private wealth. To avoid such a constellation, we assess the economic capacity of subsidized households based on private wealth and suggest to incorporate this into the subsidy decision. We argue that it is reasonable to link the extent of public subsidy to the (net) wealth position of subsidized households to (a) guarantee support to those who cannot afford the necessary renovation efforts, and (b) avoid using general tax revenues to subsidize the wealth of the richest households.

Specifically, we propose that a given segment of the least wealthy households receives funding for the full cost of the necessary renovations, whereas some upper segment of the wealthiest households has to bear the full cost of the renovations for households falling between these wealth extremes, the subsidy rate can be determined through linear interpolation. In our baseline application we employ threshold values of 65% (to demarcate the poorer segment that is fully subsidized) and 90% (to demarcate the richer households, which should receive no public funds), but these numbers could be adapted to local circumstances. According to our calculations, the German government would cover approximately 26% of the financing needs for buildings owned by private households (which corresponds to 21% of total costs when also taking institutional ownerships into account). This amounts to average public costs of around 24 bn € annually. In comparison, the German Climate Transformation Fund was set to allocate annual funds of over 200 bn €, of which 19 bn € were already set aside for building support<sup>29</sup>, which indicates that the overall scale of subsidies proposed is in a similar range as current policy proposals.

For institutional owners, we suggest considering discounted costs instead of full costs and restricting the use of subsidies to those renovation costs that cannot be amortized within thirty years. The main reason for this assumption is that institutional owners typically have a longer planning horizon and benefit directly from the impact of renovations on balance sheets, which often leads to an increase in equity that compensates a significant fraction of the investment costs even before cost-reductions are realized.

## Discussion

This paper is concerned with the question of how to conceptualize a trajectory towards climate neutrality in the residential sector. Using our toolbox, we find that this trajectory differs significantly from the estimates given in existing studies. The full renovation equivalent necessary to reach German climate goals is at least 2.5% till 2045—higher than previously expected. Additionally, we find that, to stay in line with the climate targets, buildings with poor performance metrics need to be renovated first. The required high renovation rate and prioritization imply a need for regulatory measures. Another major finding is related to sector linkages. Typically, the focus on a single sector takes direct emissions as a natural benchmark, which overlooks the potential outsourcing of direct to indirect emissions. By focusing on *emission intensity* as a key concept, we take implications for the energy provision into account to provide an integrated assessment demonstrating the need to decarbonize external energy sources.

Our estimates of the investment required to reach necessary renovation rates are also higher than in previous studies. This is partly due to the higher renovation rate and partly to the fact that existing studies usually employ a net present value method when calculating investment

costs. The net present value method discounts future cash flows and requires assumptions on the development of a variety of factors (e.g. future carbon and energy prices, interest rates, renovation costs) which may blur the picture of the necessary financial requirements. We argue that this approach is not suitable for private owners since, other than institutional owners, they are faced with a more short-term planning horizon. Moreover, due to different assumptions made the net present values method leads to a high variation in existing estimates of the required investment and has contributed to confusion on what costs to expect as well as on what economic impact the investment might have. According to our calculations based on full costs, an additional yearly investment of 58 bn €, which is about 1.3% of Germany's GDP, is needed. In a scenario based on our 'just transition' financing policy, 24 bn € of which would need to be carried publicly.

We further study the economic impact of this investment in an input-output framework. Due to a high dependency on imports (30% of initial investments), the multiplier of 1.16 is relatively low. While material bottlenecks are not expected, the investment strategy will generate an average of 274,000 new jobs in the construction sector. A drawback of the input-output method is that it cannot account for possible economies of scale effects arising from such prolonged investment, although scale effects would reduce overall cost, import-dependency and help to avoid labor shortages. The results of our analysis have two important policy implications. First, creating an innovation-friendly environment in Germany could help reduce import dependency and foster scale effects, thereby reducing costs and the required workforce. Second, measures to avoid short-term labor shortages could support the transformation.

Finally, we conceptualize a financing model that, in the spirit of a 'just transition' takes the highly unequal distribution of wealth into account. We propose that the state fully subsidizes renovation measures for the least wealthy households, while the wealthiest should carry the entire costs themselves. Households between these two groups could be subsidized according to a linear function. Providing subsidies conditional on household wealth, (a) can increase support for the necessary renovation efforts, and (b) avoids subsidizing the richest households' wealth. We develop a scenario for illustrative purposes in which the lowest 65% in the wealth distribution are fully subsidized whereas the highest 10% are not subsidized at all. In this scenario, the state would carry 26% of overall renovation costs. The relevant thresholds for this policy design choice can be adjusted manually in our toolbox.

A financing model fit for a socio-ecological transformation has to also take into account the situation of tenants. In Germany, the share of households who live in rental units is above the EU average. It is, therefore, important to constrain the extent to which renovation costs can be passed on by owners to tenants. The current legislation in Germany allows landlords to pass the costs of energy-efficient renovation onto the renters due to lower energy costs and higher living comfort. As evidenced by the debate surrounding the 'Heizungsgesetz', such cost-shifting measures have faced significant public backlash, emphasizing the need for balanced policies that fairly distribute the financial burdens between property owners and tenants. After all, the shift of the entire costs to the tenants is in tension with the increase in the economic value of the properties from which landlords benefit especially in the long run. This potential 'free lunch' in terms of long-term benefits for residential property owners requires additional regulatory measures to not undermine the basic tenets of a just transition approach to the socio-ecological transformation of the German residential sector.

## Methods

In this section, we present our toolbox that can be used to compute different transformation scenarios for any country of interest. Figure 2 summarizes the main steps of the underlying procedure to derive the necessary renovation rate (steps 1–4), associated costs (step 5), the overall economic impact (step 6), and related policy measures that are both considerate of distributional factors and fit to conduct the transformation (step 7). The toolbox makes use of a variety of macro-, meso-,

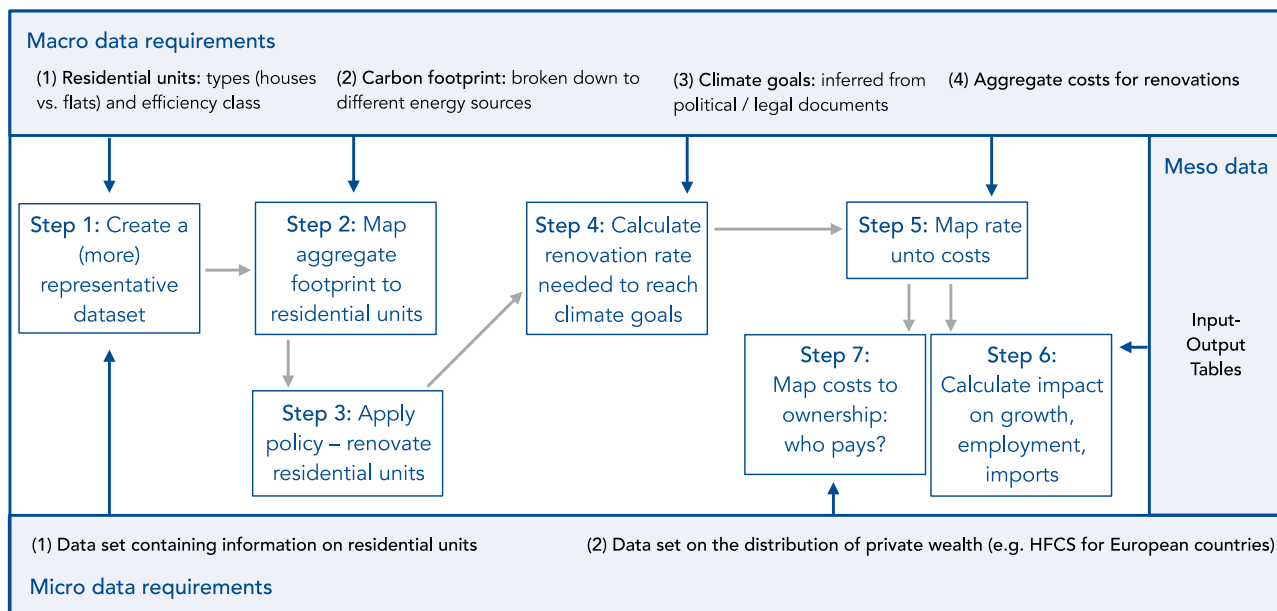


Fig. 2 | Summary of the steps incorporated in our toolbox to derive reliable results and viable policies for a transformation of the residential sector. All these steps can be also applied in isolation.

Table 1 | Data requirements of the toolbox for analyzing transformation requirements in the residential sector

Information	Source
<b>Aggregate Level</b>	
Distribution of energy efficiency classes across residential buildings (ideally including information about the distribution across both single- and two family buildings and apartment buildings)	30
Distribution of single- and two-family buildings and apartment buildings	16
Residential units per efficiency class	30
Distribution of heating sources	40
Aggregate efficiency per square meter per year	16
Emission factors for relevant energy sources	41-42
Total cost of energy-efficient renovations in 2014 (including exchange of heating systems)	43
Full renovation equivalent apartment buildings	13
Full renovation equivalents single and two-family buildings	13
Cost of heating pumps including installation	6
The relative surface area of windows, walls, basement ceilings, and roofs per building	36
Cost for material and installation of windows, walls, basement ceilings, and roofs per building	36,37
<b>Sector Level</b>	
Construction cost index	44
Input-Output Data	45
<b>Micro Level</b>	
Average size of both single- and two-family buildings and residential buildings	46-49
Type of heating (energy source) for each residential unit	48,49
Distribution of net wealth and residential wealth	Eurosystem Household Finance and Consumption Survey (HFCS)

and micro-data. An overview of the data necessary to replicate our study for other countries can be found in Table 1.

### Getting the Sample Right

In our toolbox, we assume the availability of microdata on the residential sector. As available data might not be representative of core dimensions of interest, we employ a two-dimensional stratification approach that replicates the known aggregate distribution of (1) housing types and (2) energy efficiency classes. By doing so, we provide a useful starting point to avoid biased results due to selection problems. In addition, the toolbox allows the extraction of aggregate properties from the stratified sample that can be compared with available macro-information, such as the average energy efficiency per square meter and year, to verify the validity of the stratified sample.

For the German case, we use the RWI-GEO-RED Real Estate Data, a dataset that provides information on the German real estate sector. It consists of raw data from the real estate platform *immoscout24.de* on which owners of residential properties provide excessive information to potential tenants and buyers, including data on heating facilities and energy requirements. The RWI dataset is, however, not representative of Germany as older single or two-family houses are less likely to be rented out or sold. Since these buildings tend to have a low energy efficiency class, this leads to an underrepresentation of low energy efficiency buildings in the RWI sample. We counter this shortcoming by applying *step 1* of our procedure as described above.

This method reproduces aggregate information on the distribution of efficiency classes quite accurately<sup>30</sup>. Plausibility checks support the thesis that our stratified data are representative of German residential buildings. In principle, this basic method can also be applied to sub-national units (regions, counties) as long as the respective data requirements, as summarized in Table 1, are met.

### The Aggregate Footprint

To be able to test different renovation strategies on our dataset, we first need to derive an accurate estimate of the aggregate emission footprint for our dataset. To do so, we combine information on heating systems and the insulation of buildings and link them to their corresponding emission factors to assess the aggregate emission footprint of our adjusted sample. This

allows us to calculate the emissions for each building in the sample before and after a renovation is undertaken. When doing so, we use the concept of *emission intensity* to capture the effect of different transformation paths on direct as well as indirect emissions.

The latter aspect is especially relevant as, to this day, electricity supply as well as the provision of district heating in many countries remains strongly dependent on the use of fossil fuels<sup>31</sup>, which reduces the positive effects achieved by switching from fossil-based heating to electricity-based or district heating. In this context, our toolbox captures both dimensions—the respective reduction in direct emissions as well as the potential rebound-effect in terms of indirect emissions—and allows for a comparison across different scenarios.

### Deriving the Necessary Renovation Rate

A successful transformation will require both, a reduction of energy use through improved insulation as well as a decarbonization of energy provisioning. As a consequence, our toolbox requires key assumptions on both dimensions. For insulation, we assume that the efficiency level reached by renovated buildings is 60kWh/m<sup>2</sup>. Regarding alternative heating systems, we randomly assign all buildings one of the available emission-friendly heating systems. Specifically, we assume that 25% of all buildings are suitable for district heating (mostly in urban areas<sup>32</sup>), while the remaining 75% of all buildings will be equipped with a heating pump. Heating pumps run on electricity with high efficiency as measured by the coefficient of performance (COP). We set the COP to the average of heating pumps where 1 kWh of electricity can provide 3.1 kWh of heating energy<sup>33</sup>.

Building on these assumptions, we determine the necessary renovation rate within the residential sector by executing our model for different renovation rates and comparing the related emission savings. The relevant climate targets can be extrapolated from policy documents or taken from scientific assessments. For the case of Germany, emissions in the residential building sector need to be lowered to 67 megatons of CO<sub>2</sub>-equivalents until 2030. By 2040, overall emissions need to be reduced by 88% compared to 1990 (Attachments 2 and 3 to §4 Klimaschutzgesetz (Federal Climate Change Act, KSG)). In the residential sector, emissions in 1990 were 210 megatons<sup>34</sup>, that is, until 2040, emissions need to be lowered to 25.2 megatons. Until 2050, climate neutrality needs to be reached. We assume that this can be done by lowering emissions to 90% of their current level. As soon as the necessary renovation rate is determined, the full renovation equivalents can be computed by assessing the share of renovated square meters in our sample.

### Mapping the Costs

To assess the economic aspect of the transformation process, we extrapolate information on current aggregate costs for energy-efficient renovations to the rate of full renovations required to achieve the necessary renovation rate. Specifically, we take into account information on the total costs of energy-efficient renovations, including the change of heating systems, as well as full renovation equivalents for houses and apartment buildings for a given year to extrapolate current costs to later periods. For doing so we employ a flexible framework, that allows for differentiating between fixed renovation costs per building and size-dependent costs, where the latter reflects differences in average size across both types of buildings. The relation between fixed and size-dependent costs can be determined by the user to explore the impact of different assumptions on cost structures in the construction sector. For the German case we assume that a quarter of all costs are fixed costs.

If the information on renovation costs dates a few years back, costs should be adjusted to match the current price level using a price index. For extrapolating costs to future periods, we use the number of renovated houses and apartments as produced by our toolbox to calculate expected costs in prices of 2023—as already indicated, we assume a real annual GDP growth rate of 1% and an inflation rate in the construction sector that corresponds to the overall inflation rate for doing so. As well-insulated buildings that do not yet use a heating pump exist, the number of required heating pumps

might exceed the number of renovated buildings, which could lead to a downward bias in estimates of expected costs. To account for these possible additional costs, we use the share of buildings that get a new heating pump as well as available information on the average cost associated with the installation of such a heating pump to employ a correction if required.

### Assessing the Economic Impact

We analyze the economic impact of our policy suggestion in an input-output model<sup>35</sup> that can be calibrated with the latest available data from the respective country to calculate the value added, workforce requirements, and the required domestic and foreign input factors. In addition to direct effects primarily concentrated in the construction and electrical engineering sectors, the proposed input-output analysis considers indirect effects (additional production in supplying industries) and induced effects (additional consumer demand resulting from the income growth associated with increased production). Since input-output modeling is based on linear extrapolations, potential price changes and scale effects are not accounted for in the model. Therefore, the results of the model need to be compared with current assessments of long-term labor market developments and potential scale effects to realistically assess the actual labor demand.

To employ such a model, we need to estimate (1) the amount of investment *additional* to what is already spent on energy-efficient renovations per year as calculated in the preceding section and, (2) the distribution of costs across economic sectors. For the first step, we simply subtract current costs from expected costs (both for insulation measures and heating pumps) to arrive at the effective additional costs.

In the second step, it is required to assign these investments to different economic sectors. While a precise decomposition of costs across sectors is not strictly necessary to arrive at valid estimates, for the *German case* we distribute the costs for different renovation measures as accurately as possible between relevant economic sectors. Specifically, we use data on the relative average size of windows, exterior walls, basement ceilings, and roofs per building<sup>36</sup>, and on corresponding costs for material and installation<sup>36,37</sup> to assign renovation costs according to specific economic sectors such as *Specialised construction works, Chemicals and chemical products, Ceramic products, processed stone, and clay, Glass and Glassware, and Rubber and plastics products*. These micro-adjustments introduce greater precision in the corresponding estimates. Similar, we split up the costs for heating pumps by assuming that 48% are attributable to the sector *Specialised construction works*, 40% to the sector *Machinery*, and the remaining 12% to the sector *Electrical equipment*.

In turn, the input-output model allows for an assessment of input requirements, which helps to identify positive side-effects (e.g. boosts on growth and employment) as well as potential constraints (e.g. bottlenecks or import-dependencies) of a socio-ecological transformation. Our toolbox provides an estimate for the number of required heating pumps, which reaches a maximum of 475,000 heating pumps a year. This amount of required heating pumps is matched by the German production targets set by the respective industry<sup>38</sup>. Calculating the full material impact of increased renovation activities in terms of actual resource use regarding isolation and the construction of district heating is, however, beyond the scope of the input-output model. Future research could extend our toolbox with a material-flow analysis<sup>39</sup> to complement our carbon-focused assessment by an analysis of the material impact of such a transformation strategy.

### Data availability

The required data are listed in Table 1. Access to the relevant data is free, but requires prior registration with third parties.

### Code availability

The source code of the model is [available via GitHub](#).

Received: 9 October 2024; Accepted: 11 February 2025;

Published online: 25 March 2025

## References

- Wang, X. & Lo, K. Just transition: a conceptual review. *Energy Res. Soc. Sci.* **82**, 102291 (2021).
- Newell, P. & Mulvaney, D. The political economy of the 'just transition'. *Geograp. J.* **179**, 132–140 (2013).
- Heffron, R. J. *Achieving a Just Transition to a Low-Carbon Economy* (Palgrave Macmillan, 2021).
- Nelson, A. *Housing for degrowth | principles, models, challenges and opportunitie* (Taylor & Francis, 2018).
- zu Ermgassen, S. O. et al. A home for all within planetary boundaries: pathways for meeting england's housing needs without transgressing national climate and biodiversity goals. *Ecol. Econ.* **201**, 107562 (2022).
- Thomas, S., Schüwer, D., Vondung, F. & Wagner, O. Heizen ohne Öl und Gas bis 2035 - ein Sofortprogramm für erneuerbare Wärme und effiziente Gebäude. Tech. Rep., produced on behalf of Greenpeace e.V. <http://nbn-resolving.de/urn:nbn:de:bsz:wup4-opus-79546> (2022).
- BCG. Klimapfade 2.0. Tech. Rep., on behalf of the *The Voice of German Industry* (Bundesverband der deutschen Industrie, BDI). <https://web-assets.bcg.com/58/57/2042392542079ff8c9ee2cb74278/Klimapfade-study-german.pdf> English Summary available here: <https://web-assets.bcg.com/73/e4/dd6da3a34e6ba26e2e5b85e022d9/climate-paths2-summary-of-findings-en.pdf> (2021).
- Federal Ministry for Economic Affairs (Bundesministerium für Wirtschaft). Energieeffizienzstrategie Gebäude. Tech. Rep. <https://www.bmwk.de/Redaktion/DE/Downloads/E/energieeffizienzstrategie-gebäude-kurzfassung.pdf> (2015).
- ifeu, Fraunhofer IEE, and Consentec. Wert der Effizienz im Gebäudesektor in Zeiten der Sektorenkopplung. Tech. Rep., produced on behalf of Agora Energiewende. [https://www.agora-energiewende.de/fileadmin/Projekte/2017/Heat\\_System\\_Benefit/143\\_Heat\\_System\\_benefits\\_WEB.pdf](https://www.agora-energiewende.de/fileadmin/Projekte/2017/Heat_System_Benefit/143_Heat_System_benefits_WEB.pdf) English summary available here: [https://www.agora-energiewende.org/fileadmin/Projekte/2017/Heat\\_System\\_Benefit/163\\_Building-Sector-Efficiency\\_EN\\_WEB.pdf](https://www.agora-energiewende.org/fileadmin/Projekte/2017/Heat_System_Benefit/163_Building-Sector-Efficiency_EN_WEB.pdf) (2018).
- Bürger, V., Braungardt, S., Maaß, C., Sandrock, M. & Möhring. Agenda Wärmewende 2021. Tech. Rep., produced on behalf of Stiftung Klimaneutralität und Agora Energiewende. [https://www.agora-energiewende.de/fileadmin/Partnerpublikationen/2021/Agenda\\_Waermewende\\_2021/2021-06-10\\_Waermewende\\_2021.pdf](https://www.agora-energiewende.de/fileadmin/Partnerpublikationen/2021/Agenda_Waermewende_2021/2021-06-10_Waermewende_2021.pdf) (2021).
- Repenning, J. et al. Folgenabschätzung zu den ökologischen, sozialen und wirtschaftlichen Folgewirkungen der Sektorziele für 2030 des Klimaschutzplans 2050 der Bundesregierung. Tech. Rep., produced on behalf of the Federal Ministry for the Environment (Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit) <https://www.oeko.de/fileadmin/oekodoc/BET2019-Schumacher-Repenning.pdf> (2018).
- dena and geea. Gebäudestudie – Szenarien für eine marktwirtschaftliche Klima- und Ressourcenschutzpolitik 2050 im Gebäudesektor. Tech. Rep., produced on behalf of Deutsche Energie-Agentur (dena) [https://www.dena.de/fileadmin/dena/Dokumente/Meldungen/dena\\_Gebaeuestudie.pdf](https://www.dena.de/fileadmin/dena/Dokumente/Meldungen/dena_Gebaeuestudie.pdf) (2017).
- Prognos, Öko-Institut, and Wuppertal-Institut. Klimaneutrales Deutschland 2045. Tech. Rep., produced on behalf of Stiftung Klimaneutralität, Agora Energiewende und Agora Verkehrswende. [https://www.agora-verkehrswende.de/fileadmin/Projekte/2021/KNDE\\_2045\\_Langfassung/Klimaneutrales\\_Deutschland\\_2045\\_Langfassung.pdf](https://www.agora-verkehrswende.de/fileadmin/Projekte/2021/KNDE_2045_Langfassung/Klimaneutrales_Deutschland_2045_Langfassung.pdf) English summary available here: [https://static.agora-energiewende.de/fileadmin/Projekte/2021/2021\\_04\\_KNDE45/A-EW\\_209\\_KNDE2045\\_Zusammenfassung\\_DE\\_WEB.pdf](https://static.agora-energiewende.de/fileadmin/Projekte/2021/2021_04_KNDE45/A-EW_209_KNDE2045_Zusammenfassung_DE_WEB.pdf) (2021).
- Nesselhof, L. et al. Klimaneutrales Deutschland. Von der Zielsetzung zur Umsetzung. Tech. Rep. produced on behalf of Agora Think Tanks. English summary available here: [https://www.agora-energiewende.org/fileadmin/Projekte/2023/2023-30\\_DE\\_KNDE\\_Update/A-EW\\_346\\_Climate-neutral\\_Germany\\_EN\\_Summary\\_WEB.pdf](https://www.agora-energiewende.org/fileadmin/Projekte/2023/2023-30_DE_KNDE_Update/A-EW_346_Climate-neutral_Germany_EN_Summary_WEB.pdf) (2024).
- Politico Europe. How heat pumps exploded Germany's ruling coalition. <https://www.politico.eu/article/heat-pumps-exploded-germany-ruling-coalition-green-law/> (2023). Accessed: March 4, 2025.
- dena. dena-Gebäudereport 2022. Zahlen, Daten, Fakten. Tech. Rep. produced on behalf of Deutsche Energie-Agentur (dena) [https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2021/dena-Gebaeudereport\\_2022.pdf](https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2021/dena-Gebaeudereport_2022.pdf) (2021).
- BDEW. Fernwärme: 126 Milliarden Kilowattstunden. [www.bdew.de/presse/presseinformationen/zdw-fernwaerme-126-milliarden-kilowattstunden](http://www.bdew.de/presse/presseinformationen/zdw-fernwaerme-126-milliarden-kilowattstunden) (2021). Accessed: March 4h 2025
- Altermatt, P. P. et al. Replacing gas boilers with heat pumps is the fastest way to cut German gas consumption. *Commun. Earth Environ.* **4**, 1–8 (2023).
- Zika, G. et al. Auswirkung des Strukturwandels für die Bundesländer in der langen Frist. Qualifikations- und Berufsprojektion bis 2040. *IAB-Forschungsbericht 22–2022* (2022).
- Dorffmeister, L. Herausforderungen und neue Ansätze bei der Modernisierung von Gebäuden. *ifo SchnellD.* **73**, 70–73 (2020).
- Drewniok, M. P., Dunant, C. F., Allwood, J. M., Ibell, T. & Hawkins, W. Modelling the embodied carbon cost of UK domestic building construction: Today to 2050. *Ecol. Econ.* **205**, 107725 (2023).
- Drewniok, M. P. et al. Mapping material use and embodied carbon in UK construction. *Resour., Conserv. Recycl.* **197**, 107056 (2023).
- García-López, J., Hernández-Valencia, M., Roa-Fernández, J., Mascort-Albea, E. J. & Herrera-Limones, R. Balancing construction and operational carbon emissions: Evaluating neighbourhood renovation strategies. *J. Build. Eng.* **94**, 109993 (2024).
- Mealy, P., Rio-Chanona, R. M. d. & Farmer, J. D. What You Do at Work Matters: New Lenses on Labour. *SSRN Electr. J.* (2018).
- Grunau, P. & Lang, J. Retraining for the unemployed and the quality of the job match. *Appl. Econ.* **52**, 5098–5114 (2020).
- OECD. Housing taxation in oecd countries. *OECD Tax Policy Studies* **29** [https://www.oecd.org/en/publications/housing-taxation-in-oecd-countries\\_03dfe007-en.html](https://www.oecd.org/en/publications/housing-taxation-in-oecd-countries_03dfe007-en.html) (2022).
- Frick, J. R., Grabka, M. M. & Groh-Samberg, O. Dealing with incomplete household panel data in inequality research. *Sociol. Methods Res.* **41**, 89–123 (2012).
- Dabla-Norris, E. et al. Public perceptions of climate mitigation policies: Evidence from cross-country surveys. *IMF Staff Discussion Notes* **2023/002** (2023).
- Fuest, C. et al. Wege aus der stagnation - (wie) kann die wirtschaftspolitik bessere rahmenbedingungen schaffen? Tech. Rep. produced on behalf of ifo Institut, München. <https://www.ifo.de/publikationen/2024/aufsatz-zeitschrift/wege-aus-der-stagnation-wirtschaftspolitik-bessere-rahmenbedingungen> (2024).
- Krieger, O. Vorbereitende Untersuchungen zur Erarbeitung einer Langfristigen Renovierungsstrategie nach Art 2a der EU-Gebäuderichtlinie RL 2018/844 (EPBD). Tech. Rep., produced on behalf of the Federal Ministry for Economic Affairs (Bundesministerium für Wirtschaft) [https://www.bmwk.de/Redaktion/DE/Downloads/Studien/vorbereitende-untersuchungen-zur-langfristigen-renovierungsstrategie-ergaenzung.pdf?\\_\\_blob=publicationFile&v=6](https://www.bmwk.de/Redaktion/DE/Downloads/Studien/vorbereitende-untersuchungen-zur-langfristigen-renovierungsstrategie-ergaenzung.pdf?__blob=publicationFile&v=6) (2019).
- Statista. Distribution of electricity generation worldwide in 2022, by energy source. <https://www.statista.com/statistics/269811/world-electricity-production-by-energy-source/> (2022). Accessed: January 31th 2024.
- Gerhardt, N. et al. Transformationspfade der Fernwärme in Rückkopplung mit dem Energiesystem und notwendige Rahmenbedingungen. Tech. Rep., Fraunhofer IEE. Produced on behalf of the Federal Ministry for Economic Affairs (Bundesministerium für Wirtschaft) <https://www.iee.fraunhofer.de/>

- [content/dam/iee/energiesystemtechnik/de/Dokumente/Veroeffentlichungen/2019/2021\\_Jun\\_Bericht\\_Fraunhofer\\_IEE\\_Transformation\\_Waerme\\_2030\\_2050.pdf](#) (2021).
33. Günther, D. et al. Feldmessung von Wärmepumpenanlagen. Tech. Rep., Fraunhofer ISE <https://wp-monitoring.ise.fraunhofer.de/wp-monitor-plus/german/index/ergebnisse.html> (2013).
  34. Statista. Entwicklung der Treibhausgas-Emissionen des Gebäudesektors in Deutschland von 1990 bis 2023. <https://de.statista.com/statistik/daten/studie/1411542/umfrage/treibhausgas-emissionen-von-gebaeuden-in-deutschland/> (2024). Accessed: April 18th 2024.
  35. Miller, R. E. & Blair, P. D. *Input-Output Analysis: Foundations and Extensions* (Cambridge University Press, 2009).
  36. Patrick, J. et al. Dämmbarkeit des deutschen Gebäudebestands. Tech. Rep. Institut für Energie- und Umweltforschung Heidelberg [https://www.ifeu.de/fileadmin/uploads/Beuth\\_ifeu\\_Daemmbarkeit\\_des\\_deutschen\\_Gebaeudebestands\\_2015.pdf](https://www.ifeu.de/fileadmin/uploads/Beuth_ifeu_Daemmbarkeit_des_deutschen_Gebaeudebestands_2015.pdf) (2015).
  37. Frahm, T. Was kosten Einbau & Montage von einem neuen Fenster? <https://www.daemmen-und-sanieren.de/fenster/preise/kosten>. Accessed: February 1st 2024.
  38. Weinhold, K., Cornils, M. & Pilgram, I. Branche bereit für großflächigen Rollout von Wärmepumpen, [https://www.waermepumpe.de/fileadmin/user\\_upload/waermepumpe/08\\_Sonstige/Filedump/2022-06-29\\_PI\\_WP-Gipfel\\_BWP\\_ZVEI\\_ZVEH.pdf](https://www.waermepumpe.de/fileadmin/user_upload/waermepumpe/08_Sonstige/Filedump/2022-06-29_PI_WP-Gipfel_BWP_ZVEI_ZVEH.pdf) (2022). Accessed March 4th 2025.
  39. Meglin, R., Kytzia, S. & Habert, G. Regional circular economy of building materials: Environmental and economic assessment combining Material Flow Analysis, Input-Output Analyses, and Life Cycle Assessment. *J. Ind. Ecol.* **26**, 562–576 (2022).
  40. Bundesverband der Energie- und Wasserwirtschaft, e.V. Wie heizt Deutschland? Tech. Rep. [https://www.bdew.de/media/documents/BDEW\\_Heizungsmarkt\\_2023\\_Langfassung\\_final\\_28.11.2023\\_korrigiert.pdf](https://www.bdew.de/media/documents/BDEW_Heizungsmarkt_2023_Langfassung_final_28.11.2023_korrigiert.pdf) (2023)
  41. Bettgenhäuser, K. & Boermans, T. Umweltwirkung von Heizungssystemen in Deutschland. Tech. Rep., produced on behalf of the Umweltbundesamt <https://www.umweltbundesamt.de/sites/default/files/medien/461/publikationen/4070.pdf> (2011).
  42. Icha, P. & Lauf, T. Entwicklung der spezifischen Treibhausgas-Emissionen des deutschen Strommix in den Jahren 1990 - 2022. Tech. Rep., Umweltbundesamt [https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2023\\_05\\_23\\_climate\\_change\\_20-2023\\_strommix\\_bf.pdf](https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2023_05_23_climate_change_20-2023_strommix_bf.pdf) (2023).
  43. Gornig, M., Kaiser, C. & Michelsen, C. Bauwirtschaft: Sanierungsmaßnahmen ohne Schwung, Wohnungsneubau mit zweiter Luft. *DIW Wochenbericht* **49/2015** [https://www.diw.de/documents/publikationen/73/diw\\_01.c.521395.de/15-49-2.pdf](https://www.diw.de/documents/publikationen/73/diw_01.c.521395.de/15-49-2.pdf) (2015).
  44. Federal Statistical Office of Germany (Statistisches Bundesamt) Baupreisindizes: Deutschland (Instandhaltung). <https://www-genesis.destatis.de/datenbank/online/table/61261-0005/table-toolbar> (2023). Accessed: January 29th 2024.
  45. Federal Statistical Office of Germany (Statistisches Bundesamt) Input Output Tables for Germany (2019). [https://www.destatis.de/DE/Themen/Wirtschaft/Volkswirtschaftliche-Gesamtrechnungen-Inlandsprodukt/Tabellen/\\_tabellen-innen-in-output.html](https://www.destatis.de/DE/Themen/Wirtschaft/Volkswirtschaftliche-Gesamtrechnungen-Inlandsprodukt/Tabellen/_tabellen-innen-in-output.html) (2023).
  46. RWI Leibniz-Institut für Wirtschaftsforschung RWI Real Estate Data - Apartments for Sale - suf. RWI-GEO-RED. Version: 9. (2022). Dataset.
  47. RWI Leibniz-Institut für Wirtschaftsforschung RWI Real Estate Data - Apartments for Rent - suf. RWI-GEO-RED. Version: 9. (2022). Dataset.
  48. RWI Leibniz-Institut für Wirtschaftsforschung RWI Real Estate Data - Houses for Sale - suf. RWI-GEO-RED. Version: 9. (2022). Dataset.
  49. RWI Leibniz-Institut für Wirtschaftsforschung RWI Real Estate Data - Houses for Rent - suf. RWI-GEO-RED. Version: 9. (2022). Dataset.

## Acknowledgements

We thank Sophie Hieselmayer, Laura Porak, Ulrike Röhr, Immanuel Sties, Florian Wagner, Isabelle Wappelhorst and Rafael Wildauer for their input and support in the course of this project. Financial support from *Dezernat Zukunft* is gratefully acknowledged. JK, BS, and JDW also received financial support from the *Hans Böckler Foundation* under grant number 2021-544-2. AH acknowledges funding by the Austrian Science Fund (FWF) under grant number STA80-G. This paper uses data from the *Eurosystem Household Finance and Consumption Survey*.

## Author contributions

Conceptualization: J.K., A.H.; data curation: J.K., J.D.W., A.H., B.S.; formal analysis: A.H., J.K., J.D.W., B.S.; funding acquisition: J.K.; investigation: A.H., J.K., J.D.W., L.C., B.S.; methodology: A.H., J.K., J.D.W.; project administration: J.K., A.H.; software: J.K., A.H., J.D.W., B.S., L.C.; supervision: J.K.; validation: J.D.W., L.C.; visualization: J.K., J.D.W.; writing—original draft: A.H., J.K., J.D.W.; writing—review & editing: J.K., A.H., J.D.W., L.C.

## Funding

Open Access funding enabled and organized by Projekt DEAL.

## Competing interests

The authors declare no competing interests.

## Additional information

**Correspondence** and requests for materials should be addressed to Jakob Kapeller.

**Reprints and permissions information** is available at <http://www.nature.com/reprints>

**Publisher's note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

© The Author(s) 2025

# DuEPublico

Duisburg-Essen Publications online

UNIVERSITÄT  
DUISBURG  
ESSEN

*Offen im Denken*

ub

universitäts  
bibliothek

This text is made available via DuEPublico, the institutional repository of the University of Duisburg-Essen. This version may eventually differ from another version distributed by a commercial publisher.

**DOI:** 10.1038/s44168-025-00229-2

**URN:** urn:nbn:de:hbz:465-20251118-112701-9



This work may be used under a Creative Commons Attribution 4.0 License (CC BY 4.0).