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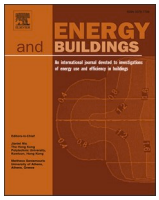

Key challenges for Germany's policy on energy performance upgrades in post-war apartment buildings: an interdisciplinary investigation

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ABSTRACT

Germany needs to sharply upgrade the energy performance of its very large stock of post-war apartment buildings, to meet climate goals and improve the thermal comfort of occupants, especially low-income households. The upgrade rate lags far behind what is needed to reach these goals. The federal government funded a research project in 2022–2024 to explore how the rate and depth of upgrades could be increased affordably. The results of quantitative research in this project are published in 12 peer-reviewed papers. This paper adds a qualitative dimension, by reporting on semi-structured interviews with experts in the field who reflected on the quantitative findings. The interviews mostly affirmed the quantitative findings, but enhanced these with insights into their policy implications, plus a broader social dimension of which actors need to take responsibility for the quality of these buildings and for finance gaps in renovation projects. Policy implications included: acceptance of the financial payback gap, recognition of the prebound effect, subsidy reform, reform of legal fees and taxes in downsizing, and schemes to motivate small private landlords to take more financial responsibility for the energy performance of their properties. The study confirmed the value of interdisciplinary research on a seemingly intractable problem.

1. Introduction

This paper utilizes an interdisciplinary approach to a difficult issue within Germany's energy policy: how the federal government can better support deep energy performance upgrading of the country's large stock of post-war (1946–1978) apartment buildings, affordably and in line with its climate goals. According to the German Energy Agency [1], 28 million of Germany's dwellings, or about 65 % of its total of 43,106,592 dwellings, are rated below the energy performance standards required to meet the country's climate goals.

There is a stream of peer-reviewed literature in relation to energy renovation of these buildings, going back at least 15 years (reviews in [2–4]). After the Second World War there was a concerted rebuilding effort in former West Germany [5], which included the construction of millions of very similar apartment buildings, most of which have 4 storeys plus a basement and roof space with several mansards, flat, non-elegant concrete walls, single-glazed or first-generation double-glazed windows, and heating powered by apartment-specific gas boilers or by central heating, and in some cases district heating. Their building envelopes have high U-values and are notoriously energy-inefficient, averaging around 150–200 kWh/m^2/y for space heating.

Over the past 3 decades the construction industry has optimized its methods of improving these buildings' energy performance. This mostly includes window replacement, external wall insulation, roof and basement ceiling insulation, and more recently a transition to electrically driven heat pumps, often supported by rooftop solar photovoltaics.

The federal government regulates the minimum energy efficiency standard to be reached in renovations of these buildings. Its general principle is that a comprehensive renovation must achieve the highest standard that would pay back, through energy savings, over the technical lifetime of the energy efficiency upgrade measures. In other words, it must at least reach the limit of what is "economically viable" (in

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German legislation *"wirtschaftlich vertretbar"*). From time to time the government commissions think tanks to estimate what this standard is, for a range of different building geometries.

The federal government also offers subsidies, in terms of loan interest reductions or cash handouts, for renovations that go beyond this minimum standard, so that these renovations also become economically viable for the building owner.

In theory, this makes deep energy performance renovation sound like an economically rational approach which building owners would find hard to resist, and even more so since landlords are allowed to pass energy efficiency renovation costs on to tenants via rent increases, so that the landlord, rather than the tenant, gets the payback from the renovation costs.

In fact, however, this policy approach has failed to motivate large-scale energy efficiency upgrading. Analyses based on microeconomics tend to claim that property owners are therefore behaving economically irrationally (e.g. [6–11], most of whom base their claims on theoretical work by [12,13]). In this regard, a slew of academic papers has been published exploring what the non-economic "barriers" might be the cause of this failure (see reviews in [14]).

However, Singhal et al. [15] investigated Germany's CO_2-related policy for buildings, and found that many aspects of these policies were not underpinned by hard empirical evidence. They highlighted "the pressing need for data and modern empirical research to develop targeted and cost-effective policies". Although economists are well-equipped to address questions of cost efficiency and cost effectiveness, "the first major barrier is the availability and quality of data". This study seeks to help fill that gap.

In 2022–2024, the federal government funded a research project (called "INVEST") to explore how the energy performance renovation rate could be increased, specifically aimed at buildings housing low-income households, but also taking the larger picture of energy-inefficient apartment buildings into consideration. The authors of this paper were intensively engaged in that project, via the research institute FCN[1] at RWTH Aachen University, Germany. Their quantitative empirical work has been published so far in 12 peer-reviewed papers, which are referred to in Section 2. This resulted in critiques of certain policy assumptions, and policy strategies, and an agenda for policy changes.

However, there are very few, if any, peer-reviewed reports of actual case studies of this building cohort in Germany by other authors, that would challenge the quantitative findings of the project. Therefore, to provide a check on the credibility of our quantitative findings, we engaged in a parallel process of interviewing key experts in the field. This double-edged approach is in line with a style of interdisciplinary study pioneered mostly in medical research [16,17]. In this approach, a problem or issue is investigated using two or more different methods, such as quantitative and qualitative, or statistical and narrative. The results are then not merely offered separately, as in multi-disciplinary research. Instead, they are brought together and their similarities and differences are explored intensively, with a view to developing further insights that emerge from consistencies and inconsistencies between the different sets of results.

As part of the INVEST project we had already interviewed a set of stakeholders in the state of North Rhine-Westphalia, where most of our hands-on empirical work was done (though some of this work extended throughout western Germany), to help guide us as to what quantitative issues were most in need of investigation (some of the results of this round of interviews are published in [18–22]. The second tranche of interviews was designed to check whether our quantitative findings were balanced and gave a credible picture. These interviews form the empirical basis of this paper.

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Section 2 reviews and summarizes the findings of our quantitative investigation, referring mostly to our published papers, but also relating these, in places, to findings in other relevant literature. Section 3 explains the method employed in the (second tranche of) interviews. Section 4 gives the results of these interviews. Section 5 discusses these in relation to the quantitative findings. Section 6 concludes and offers policy recommendations.

2. The quantitative findings

Our quantitative findings had brought to light 6 main areas of concern, most of which are interrelated: (1) the large finance gap with energy performance upgrades; (2) the role of prebound effects in this; (3) the mitigating effect of onsite renewable energy; (4) the important differences between energy efficiency and energy performance; (5) the need for cost-efficient CO_2 mitigation; and (6) the impact of energy performance on real estate sales and rental market prices.

2.1. The large finance gap with energy performance upgrades

Galvin [23] used updated engineering and economic data from the Institute for Housing and Environment (*Institut Wohnen und Umwelt* – IWU) on the costs and benefits of energy efficiency renovation for post-war houses and apartment buildings in the city of Augsburg. It found that none of these renovation scenarios would pay back, through energy cost savings and CO_2 tax savings, within the expected technical lifetime of the upgrade measures. Retrofitting to the legal minimum standard of around 70 kWh/m^2/y was the closest to economically viable, while renovating to a higher energy efficiency standard made the costs higher in proportion to the financial benefits, and renovating to an even higher level exacerbated this further.

Galvin [24] extended this using 44 case studies. These included the authors' own hands-on data gathering on two post-war apartment buildings in Aachen, as well as revisiting and updating Germany-wide datasets gathered by think tanks. None showed a payback within 25 years, and payback for most would take over 80 years. The percentage of the costs that would pay back after 25 years averaged around 13 %. This ranged from a worst case of 9.3 % for a country-wide average of Germany's "small" apartment buildings (<300 m^2 of floor area) to a best case of 53.7 % for a particular, medium-sized apartment building in Bavaria. Importantly, the Germany-wide averages for specific sizes and types of apartment building gave among the lowest percentage paybacks.

An uncertain parameter in all these case studies was opportunity costs: the losses incurred by investing in energy efficiency renovation rather than in an alternative, more profitable venture. We then explored this in detail in Galvin and Galvin [25,26], which considered available alternative investments of the same amount of money, under the same loan conditions, as those required for a specified energy performance upgrade on a known building. We found that opportunity costs ranged from a minimum of 8.9 % to a maximum of over 20 %, depending on the level of ambition (but not risk) in an alternative investment. Including these opportunity costs in the cost-benefit analysis would make the benefit-to-cost ratio even worse. None of these alternative investments entailed especially high risk, as they all pertained to the same property market and are not uncommon practice. The issue of balancing risk against return (see, e.g., [27]) was therefore not considered in depth, but this would need to be considered in further studies where alternative investments outside the property market are contemplated.

2.2. The role of the prebound effect

One of the reasons for low return on energy efficiency upgrades is the prebound effect, identified over a decade ago by Sunikka-Blank and Galvin [28]. Occupants of poorly energy-performing homes tend to under-consume, so upgrades often lead to the saving of far less energy

than the engineering calculations predict. In the quantitative part of this research project Galvin [20] found that this effect severely compromises the economic viability of energy efficiency renovation in post-war apartment buildings. Interestingly, the German federal government has never recognized the prevalence of prebound effects or included them in its estimates of economic viability.

2.3. The retrofit cost mitigating effect of onsite renewable energy

Galvin [29] and [30] investigated the economics of installing rooftop solar photovoltaics as part of an energy performance upgrade. Galvin [31] then investigated how this could be used to optimize the benefit-to-cost ratio, since rooftop photovoltaics almost invariably pay back within about one-third of their technical and economic lifetime (of typically 25 years). Building on this, Galvin [32] used a freely available FCN retrofit modeling tool to explore how photovoltaics output in a multi-apartment building could be fairly shared among households. A consistent finding was that including rooftop photovoltaics in a refurbishment scenario substantially improves the economic benefit-to-cost ratio.

Photovoltaics also improved the economics of replacing fossil fuel boilers with electrically driven heat pumps. Terry and Galvin [33] investigated how energy-efficient a building needs to be to make heat pumps viable. They found that if the building envelope's U-value is at least as low as (i.e., at least as good as) about 0.33 $W/m^2/K$, the building will be "heat-pump-ready". Coincidentally, this corresponds to an energy intensity of about 70 $kWh/m^2/y$, which corresponds, on average, to the current minimum standard in Germany. Hence an economic optimum (in terms of percentage return on investment) would be to increase energy efficiency only to the legal minimum standard, replace the boilers with heat pumps, and supplement their energy supply with rooftop photovoltaics. This resonates with recent findings by Hummel et al. [34], that "a combination of thermal renovation and heating system change is often the most cost-effective option to reduce system-wide CO_2 emissions also in more recent buildings." Again, by "the most cost-effective", Hummel and colleagues mean the highest percentage return on investment (not necessarily the lowest cost).

2.4. The differences between energy efficiency and energy performance

The German phrase *"energetische Sanierung"* literally translates as "energy renovation", which at least theoretically includes anything that improves a building's energy performance. However, at government level it is commonly taken to mean "energy efficiency renovation", which tends to marginalise other ways of improving energy performance, such as on-site renewables, replacement of fossil fuel heating systems with electrically driven heat pumps and investing in off-site renewables as part of a larger energy performance investment package. Galvin [31] investigated this issue, using a multi-apartment building in Aachen as a case study. The findings suggest that there needs to be more emphasis on energy performance including all its aspects, rather than a narrow focus on energy efficiency for its own sake.

2.5. The need to reduce CO_2 emissions more economically

An important implication of most of the above-mentioned studies was that the aim of energy performance renovation should be to reduce CO_2 emissions as deeply and economically as possible. For example, Galvin [23] found that retrofitting to a modestly high standard of around 70 $kWh/m^2/y$ entails marginal costs of CO_2 abatement that are comparable to current CO_2 prices, but that renovating to a higher energy efficiency standard increases these costs by up to an order of magnitude. The highest standards bring absurdly high marginal costs of CO_2 abatement of over 2,000 €/tCO_2, compared with a current CO_2 market price of around 100 €/tCO_2. Galvin [35] then found that improving energy efficiency just to heat-pump-ready standard and including heat pumps and rooftop photovoltaics brought a lower cost per tonne of CO_2 abated, and almost twice the amount of CO_2 abatement, as the highest energy efficiency standards. For one modestly expensive scenario it reached 100 % abatement.

These studies suggested that policy should support CO_2 abatement directly, rather than supporting energy efficiency for its own sake and assuming this will result in the optimum CO_2 abatement. On a broader level, buying a CO_2 permit will often be much cheaper than renovating to reduce CO_2 emissions. It can therefore be seen as a kind of opportunity cost, to be required to achieve the domestic sectoral CO_2 mitigation target even if it is much more costly (see discussion on this theme, going back at least as far as [36]).

2.6. The impact of energy performance on real estate sales and rental market prices

A number of studies have found that the costs of energy performance renovation are often compensated for, at least to some extent, by increases in a property's market value. Examples are Johnson and Kasserman [37] and Dinan and Miranowski [38] for US housing, Deng et al. [39] for Singapore, Fuerst and Shimizu [40] for Japan, and Brounen & Kok [41] for the Netherlands. More recently, Taruttis and Weber [42,43] and Cajias et al. [44] found that the residential real estate sales and rental markets in Germany also tend to support higher energy performance, though with marked regional differences. These studies suggest or imply that the main reason for regional differences has to do with demand for accommodation. Where demand is low, buyers and potential tenants have more choice, so property owners find it easier to sell or rent out their buildings if they have high energy performance standards, and this gives them a market premium. On the other hand, if demand is high almost any property will sell or attract tenants, thereby reducing the market premium for energy performance.

In our own work, Galvin [19] used data from Immoscout24, Germany's largest rental and sales real estate portal, and found statistically significant correlations between post-war properties' official energy efficiency ratings and their rental and sales asking prices. Although there were substantial regional variations, on average the sales market tended to compensate the cost of energy efficiency renovation, but the rental market generally did not. Further, property owners who renovated and retained their properties would suffer heavy financial losses, since the financial return on energy retrofit investments (through energy costs savings and CO_2 tax savings) is low. However, those who sold their renovated properties were likely to recoup most of their losses, due to the high sales premium for energy performance. Meanwhile those who bought newly renovated properties would suffer heavy losses, again due to the poor financial return on energy retrofit investments. Tenants tended to lose, but not by much, because landlords do not often find it easy to increase the rent by the legally permitted amount after an energy upgrade [26].

Galvin [21] found a similar pattern for pre-World-War-II apartments (built between 1800 and 1944). Also, Galvin [20] found that prebound effects were a major factor in the mismatch between sales values and economic returns on energy renovating – due to the fact that far less energy was being saved, as a consequence of the energy retrofit, than the engineering estimates predicted.

The findings of these quantitative studies have implications for federal policy on energy refurbishment of apartment buildings. We leave discussion of this to Section 5, after considering the findings of the qualitative research.

3. Method for the qualitative analysis

3.1. Selection of interviewees

The interviewees were selected using three main approaches. First, the previous round of interviews, reported in Galvin [18], provided us with insights into who some of the key stakeholders and experts were

among networks and institutions concerned with energy performance upgrades of residential buildings throughout Germany. Second, our quantitative empirical work for the project had brought us into contact and engagement with key actors and experts, helping to build a fuller picture of the personnel who tend to be in the forefront of critique and analysis of Germany's energy renovation policy and practice. This was further refined by a third source, FCN's long experience of investigating energy performance of building issues in a number of research projects in Germany.

We thereby did our best to ensure that our selection of interviewees would give a reasonably balanced picture of how current federal policy on the issue is perceived. However, as in all qualitative interview studies, there is no guarantee that the findings provide a "true" picture of all the relevant issues. We can only claim that they reflect a valid set of concerns and insights as expressed by a balanced selection of players representing Germany's key practitioners in the field.

The University's ethics guidelines were followed for the interviewing, transcribing, coding, analysis and writing up. All interviewees and their institutions were anonymized. Permission was explicitly given for recording, except in one case (interviewees 8#) where themes were allowed to be used but recording was not permitted. The transcripts were permitted to be shared with, and only with, three of the researchers involved in the project (the authors of this paper and one other FCN member).

The interviews were semi-structured, with a series of prompt questions that allowed interviewee narratives to diverge toward issues the interviewees saw as important. The interviews lasted 45–75 min and were conducted by video call.

A list of interviewees, including their types of institutions and the code numbers we have assigned to them, is given in Table 1.

3.2. The process of interview transcription and analysis

The recorded interviews were transcribed and analyzed to identify the main themes and narratives with regard to the INVEST research project's central concern, namely increasing thermal comfort in the homes of low-income households, particularly in post-war apartment buildings, while also supporting Germany's climate goals. The method of analysis was based on a modified form of Grounded Theory [45]. In Grounded Theory we allow the interviewees' narratives to build and shape a conceptual framework, though which we summarize the interviewees' ideas and identify the relevance of this framework and its content to our overall research aim.

In this case, however, we already had an agenda of quite specific issues to explore, based on our quantitative findings (see above). In the interview analysis we therefore listened especially for beliefs, assertions, discourse and experiences among interviewees that related directly to these.

We first identified all the **"themes"** in each interview relevant to these issues, using multiple Word docs with a cross-reference system, which made it easy to share the data analysis with colleagues in the research team. We found 20-29 relevant themes per interview.

We then interrogated the themes in light of our existing and developing quantitative findings. From this we identified a small number of **"relevant discourses"** that straddled between the interviews and drew on the themes. These discourses stood out because they acted as bridges between the material, technical, quantitative world of what is economically and physically possible with renovation, and the social-political, qualitative world of how these material realities are understood, misunderstood, liked, disliked, promoted, suppressed, etc.

Finally, we considered the relevance of the main issues that arose in the analysis, to the overall research question: How can Germany increase thermal comfort in the homes of low-income households economically, while supporting the country's climate policy goals.

Table 1
Interviewees.

Identifier	Background
1#	Policy expert in a Germany-wide association representing large corporate and other institutional rental housing providers
2#	Leading civil servant in one of Germany's federal agencies that offers subsidies for energy efficiency renovation
3#	Leading academic involved in the EU's research on funding mechanisms for energy efficiency renovation
4#	Germany-based finance and real estate market expert in a multinational corporation that buys, renovates and re-sells old buildings, also in Germany
5#	Leading civil servant in one of the federal ministries dealing with energy efficiency and CO_2 emissions reduction in buildings
6#	Exemplary young couple with long experience of low income and more recent experience of middle income and their own energy-efficient house
7#	Economist and house purchaser with first-hand experience of energy efficiency renovation
8#	Energy and buildings think tank researchers (two together)
11#	Europe-wide real estate and sustainability consultant, Finance expert
12#	Researcher, economy and environment think tank
13#	Expert on the attitudes and practices of small private landlords in Germany

4. Results of interview analysis

We identified 16 "relevant discourses" – discourses that were closely relevant to the key findings of the quantitative empirical work. 13 of these either reinforced or were compatible with the quantitative findings but 3 were at odds with these findings. We report both these sets of findings here, together with the numerical identifiers of the interviewees who expressed them most strongly or clearly. In a separate document, for our own reference, we have recorded the transcript lines and/or time stamps of these expressions within the cited interviews. In many cases the same narratives were also expressed by interviewees additional to those explicitly noted, since we report here only those who expressed these with the utmost clarity, vigor or intensity.[2]

Sections 4.1 and 4.2 report the opinions of the interviewees. Some of these are given verbatim, in quotes, and some in summary form, but all are expressions of the interviewees, not our own views or input from existing literature, *except where clearly stated*.

4.1. Discourses that accorded with or built on our quantitative findings

1. How best to balance energy efficiency standards with costs and CO_2 savings

Most interviewees asserted that the most sensible, economically efficient way to renovate the homes of low-income households (and in fact all old homes) is to do limited energy efficiency renovation, i.e., to a standard of about 70–80 kWh/m^2/y (currently labeled EH140 – EH160 in Germany's building code) then replace fossil fuel boilers with heat pumps and add photovoltaics if possible (e.g., 4#; 6#). Interviewees maintained that it does not make economic or technical sense to renovate to higher energy efficiency standards (e.g., 1#). Even renovating only to a standard of 70 kWh/m^2/y does not pay back (3#, 2#), but we have to do it to make heat pumps viable. This enables a transition from fossil fuels to renewable energy, at minimum cost.

2. The need to align energy efficiency policies with CO_2 goals

Interviewees associated with large rental housing firms maintained that the government needs to be more consistent in its aim for net-zero CO_2 emissions by 2045 and avoid confusing this with the aim for higher energy efficiency. Although increasing energy efficiency generally does reduce CO_2 emissions, the marginal costs of increasing it sufficiently to reach zero CO_2 emissions are prohibitively high. Only renewable energy

[2] An example of what we mean by clarity, vigor or intensity is the interviewee comment: "It is sensible to prioritize installing PV over energy efficiency upgrading".

will lead to climate neutrality (1#). These interviewees claimed that large rental housing firms already know this and act on it, but that current regulations and subsidies do not support it. Interviewees maintained that housing firms should be allowed to deviate from a rigid energy efficiency plan so as to achieve net-zero CO_2 more economically.

3. The need for reform of federal subsidies

Almost every interviewee expressed strong opinions on the need for reform of federal subsidies. Six features of current federal subsidies were said to be in need of reform.

(a) Renovation of low-rent apartments (<7 €/m^2/month) should be explicitly subsidized, because landlords cannot legally increase the rent sufficiently in these apartments to get their investment back (1#; 13#).

(b) Subsidies need to be based on CO_2 reduction rather than energy efficiency (1#).

(c) Subsidies also need to reward quick, cheap wins for building owners, such as with intelligent thermostats and predictive building automation systems (4#; 99–102; 111ff).

(d) Subsidies need to be extended to *basic* energy performance renovations for the worst-performing buildings (2#; 12#), i.e., renovation to the minimum legal standard. This is important because, as these interviewees pointed out, the main federal subsidies, those from the KfW (*Kreditanstalt für Wiederaufbau* – German Development Bank) are currently available only for renovations to energy efficiency standards that go well beyond the legal minimum [46]. Also, interviewee 12# noted that "there is a definite correlation that low-income households tend to live in the older buildings". The authors note that this accords with studies on the incidence of low-income households living in older and badly performing buildings (e.g., [47]).

(e) Subsidies should be extended to low-income homeowners (2#) and to landlords of classes of apartment buildings that are typically rented to low-income households (2#; 12#). Low-income households cannot improve their dwellings' energy performance, or move to a better performing dwelling, as they are below a certain threshold of income that is needed just for survival. It is only if and when they get above this threshold that they can act to improve their heating energy performance (6#;). "If you have money, it's easy to get money. But if you don't have any money, it's always difficult" (6#). The authors note that this insight has recently been extensively affirmed and explored (e.g., [48]). Also, an anomaly with the KfW subsidies is that these are given only as interest rate reductions and capital repayment reductions on bank loans, while low-income households often do not qualify for bank loans (5#). Therefore, there needs to be strong subsidy intervention where households are on low income (5#; 7#; 3#) and a corresponding reform of the subsidy regime (5#; 2#).

(f) Subsidies should be provided for low-income households to install photovoltaics, whether or not there is an energy performance upgrade, as there is always a good monetary return on this for general electricity use (6#).

4. Renewable energy (photovoltaics) and heat pumps

Almost all interviewees asserted the value of rooftop photovoltaics as part of an energy performance upgrade. Interviewee 1# noted that many people find renewable energy sensible and exciting, but are sceptical about insulation, a point also affirmed by interviewee 2#. Interviewee 6# maintained: "It is sensible to prioritize installing PV over energy efficiency upgrading". Others pointed out that this accords with the high-cost, low return of energy efficiency and the low-cost, high return of renewable energy (e.g., 2#; 3#; 6#; 12#; 13#). The government should use the attractiveness of renewable energy as a lever to get moderate-level energy efficiency renovation done. Interviewee 2# noted that "homeowners really want renewable energy as they are afraid of future energy prices", a point also noted by 5# and 12#. Interviewee 2# cautioned, however, that "a property owner should not install a heat pump if the building is not energy-efficient enough to make it work efficiently: the motor has to fit the chassis" (#2; 3:25). This accords with discourse 1 above. More generally, other interviewees maintained that while both energy efficiency and heat pumps with rooftop PV are desirable, the cost-benefit-ratio of photovoltaics is far better than for energy efficiency (e.g. 6#).

5. A long-term CO_2 budget

Interviewee 1# maintained that policy should support the idea of a long-term "CO_2 budget" for each property owner's "portfolio" (their combined set of properties), for example, 20 tonnes of CO_2 per m^2 between now and 2045, a point also implied by 4#. (Authors' comment: This was a novel idea within the context of the research project, though it has been explored in some depth in studies such as Habert et al. [49], Almeida and Ferreira [50] and Priore et al. [51].

6. Tax and photovoltaics

Interviewee #4 suggested that the regulations for photovoltaics in multi-apartment buildings need to be reformed to avoid the disincentives of extra taxation and over-complication of PV electricity sharing. This theme also emerged among other interviewees, often as a complaint bordering on anger. We comment that this resonates with recent studies on tax and compliance for household rooftop photovoltaics in Germany. For example, Fleiter et al. [52] found that tax requirements for units greater than 10 kW-peak led to "bunching", i.e., a high proportion of units just smaller than this, which often wasted available roof space. Similarly, Klimsa et al. [53] found that Germany's photovoltaic tax structure caused "the most inefficient use of rooftop space in areas with the most sunshine hours." More generally, Kuckshinrichs et al. [54] offered an analysis of levelized costs of electricity from photovoltaics in relation to the impact of different fiscal options available to households who were seeking to install photovoltaics systems with storage batteries.

The authors also note that, interestingly, the fact that this issue emerged in interviews but not in the research project's quantitative studies strengthens the idea that interdisciplinary, quantitative–qualitative research can sometimes provide a fuller picture than one type of research alone.

7. Energy efficiency and the real estate market

Two interviewees were professionally qualified to speak on the effects of energy efficiency on property market prices. Interviewee 4# suggested that doing energy efficiency renovation increases the market value of a property, but only for the first 10 years, as the whole job will need to be done again after 25 years. Interviewee 4# also pointed to the strategy of a large, international property firm that profits from buying old buildings, refurbishing them and selling them within 10 years. Interviewee 11# spoke of a downward spiral in market value of buildings with poor energy performance: these are harder to sell, and banks are less likely to lend on them, driving the market value down further, making them even harder to sell.

8. The EU's energy performance of buildings directive

The authors note that a recent update of the EU's Energy Performance of Buildings (EPB) directive focuses on compulsory renovation of the worst-performing buildings (European Commission [55]). Interviewee 2# maintained that this is appropriate, as it brings the largest CO_2 reduction. This interviewee noted, however, the problem that bringing these buildings up to the minimum standard does not qualify for KfW subsidies. Interviewee 12# had explored this in depth, and suggested various subsidy changes, such as bonuses for low-income households: "The current subsidies help the high-decile income earners more than low-decile income earners, not least because it's usually the high-decile income earners who have their own homes."

9. Expenses in downsizing

Several interviewees noted the problem that many older people in Germany are owner-occupiers in large homes that are too big for them and therefore over-expensive to heat. Further, interviewee 2# pointed out that in Germany, real estate transaction costs are far too high to enable old people to downsize to smaller dwellings: up to 25 % of the value of the property (12.5 % for selling, plus 12.5 % for buying). The interviewee was referring to a specific type of transaction cost, namely taxes, legal fees and real estate agent fees. The interviewee maintained that these need to be reformed urgently by the housing ministry. The authors note that this was a point that had not been picked up in the

quantitative studies, which dealt mostly with the material features of buildings and the costs and financial benefits of energy renovation, and that it therefore deserves further research. Interviewee 12# further reported a scheme under consideration among large rental housing providers in Berlin, to enable people on low rents to downsize by taking their rent with them to their next apartment.[3]

10. The classic problem of the economics of energy efficiency upgrades

All interviewees except 2# and 5# maintained that energy efficiency renovation to the basic standard (approx. 70 kWh/m^2/y) or better does not pay back, through energy and CO_2 tax savings, over the technical lifetime of the energy efficiency renovation measures. Interviewees 12# and 8# had a more nuanced view on this – see below under the heading "*The proportionality fallacy*".

11. Small private landlords

Interviewees generally agreed it would be good if Germany created an institutional framework for small private landlords to get loan credits (etc.) for investing 20–30 % of the basic rent each month in a fund dedicated to increasing their buildings' energy performance (especially 13#). This type of investment is compulsory in some countries (7#). More generally, the government could institute a voluntary Code of Practice for small private landlords comparable to the Scottish model, where landlords commit to supporting social and climate goals in the upkeep of their properties (5#). Interviewee 12# found this an "exciting idea". He suggested promoting "a culture of responsibility". "To those who have the money, (we need to) say, 'you simply have to make your contribution and you can also bear these additional costs.'" He added "I think that would be important, to initiate a bit of a cultural change." The authors note that the relevance of this idea in relation to Germany's need to increase the rate of deep energy renovation has recently been explored and affirmed in a study by Galvin and März [26].

12. The danger of stranded assets

Interviewee 11#, an EU-wide banking expert (interviewed in English rather than German), maintained that residential buildings that are not upgraded for energy performance risk becoming stranded assets on the real estate sales market, as EU banking rules are moving toward restricting mortgage lending based on energy performance ratings. Also, she had found that banks are becoming less inclined to lend on energy efficiency upgrades that do not pay back. "It has to be feasible financially. We (banks) cannot possibly commit to something that is not making financial sense. If it doesn't make financial sense, we just put it to one side (meaning "we avoid considering it)." She reported that the two issues are interrelated, and also that banks are increasingly seeing energy-inefficient properties that already have mortgages on them as "brown assets" and are keen to divest from them.

13. Uncertainty about future energy and construction prices

None of the interviewees suggested future energy prices would increase so steeply as to make energy efficiency renovation substantially more economically viable. However, some reported that popular belief in high future energy prices is helping to increase the rate of rooftop PV installations (see above).

Regarding construction and renovation costs, 12# suggested that the energy transition itself will put increasing upward pressure on these: "If we are really serious about the heat transition and we really want to increase the renovation rate, then construction prices will simply have to rise, because the labor alone will become much more expensive and there will be much more competition for construction companies, etc."

[3] The authors also note that the discussion on transaction costs can be extended to cover a broader range of costs, including, for example, travel costs and time off work for viewing properties (search costs), costs of extra maintenance to bring a dwelling up to saleable standard, purchasing of new furniture to suit the new, smaller property, and installing a new kitchen – since in Germany the kitchen units are generally removed when a property is sold. However, the interviewees' concerns were that the taxes, legal fees and real estate agent fees need regulatory review.

4.2. Discourses that contradict or challenge the peer-reviewed quantitative findings

1. The economic viability of energy efficiency renovation

Interviewees 2# and 5#, both civil servants associated with the federal subsidy programme, maintained consistently that energy efficiency renovation to the basic standard (about 70 kWh/m^2/y) is economically viable, and that federal subsidies cover the extra costs of renovating to higher standards. Interviewee 2# suggested that homeowners who reject this are economically irrational. The authors note that this view is consistent with the website of the KfW, as is further discussed below. It is interesting that this view was strongly opposed by all the private sector interviewees.

2. The proportionality fallacy

Interviewees 12# and 8# asserted what can be called the "proportionality fallacy": that renovating a building to a very high energy efficiency standard is more economically viable than renovating to a modest standard if the losses are smaller *in proportion* to the costs. The authors note that this can be seen as problematic, since the losses may be far greater in *absolute* terms. For example, most building owners would probably be happier with a €50,000 loss, for a renovation to 70 kWh/m^2/y, than a €100,000 loss, for a renovation to 20 kWh/m^2/y, even if the former loss represented 30 % of the costs while the latter loss represented only 20 % of the costs. In both cases the effect on thermal comfort is the same: a warm apartment. A proportionately smaller loss does not necessarily indicate a smaller loss in real terms.

3. Energy efficiency as a social good

Interviewee #3 maintained that even though efficiency renovation to the basic standard (about 70 kWh/m^2/y) or better does not pay back, we should still do it, because "energy efficiency in itself is a good thing". She maintained that energy performance renovation of the homes of low-income households needs to be framed as a social good, and therefore commonly-held considerations of economic payback do not fully apply. Other interviewees expressed similar ideas but less directly. Interviewee 13#, for example, spoke of how landlords need to be more responsible for the social and climate impact of their properties' poor energy performance – quite apart from considerations of cost.

The authors reflect that this view contained the germ of a profound insight that the quantitative findings had perhaps pointed towards but not been suited to explore. The need to achieve Germany's climate and social goals for the built environment will not be met simply by reporting that energy performance renovation to these standards does not pay back. Interviewee 3# accepted that only a portion of the energy performance upgrade costs pay back through energy savings, and even when a further portion is covered by subsidies, that this leaves a gap which somebody has to pay. We discuss this further below.

5. Bringing the qualitative and quantitative findings together

In this section we discuss the qualitative findings in relation to the quantitative findings, and reflect on this in terms of interdisciplinary theory.

Fig. 1 offers a simplified mind-map of how the quantitative and qualitative findings relate to each other. The solid arrows indicate quantitative findings that were reinforced by or directly reflected in the qualitative interviews, and vice versa. For example, the quantitative finding of persistently large finance gaps with energy performance renovation was reflected in the affirmation of the classic problem of the economics of energy efficiency upgrades, by all but two of the interviewees.

The dotted arrows indicate qualitative findings that both reinforced and went beyond the quantitative findings. For example, the quantitative finding of a positive real estate market impact of energy performance standards was supplemented by an interviewee's observation that energy-inefficient properties could become stranded assets.

The plus signs indicate findings in the interviews that did not emerge

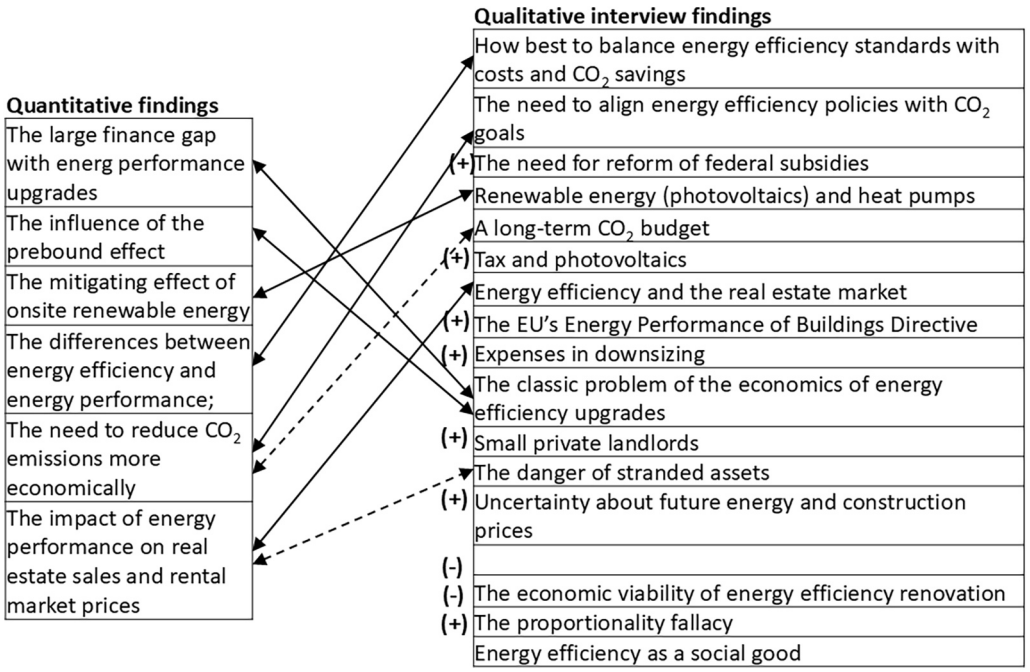

Fig. 1. Intersections, reinforcements, differences and enhancements between the qualitative and quantitative findings.

in the quantitative work. Six of these directly extended the quantitative findings toward their policy implications: the need for reform of federal subsidies; the need for tax reform with respect to onsite photovoltaics; the emphasis on renovation of worst-performing buildings in the EU'S Energy Performance of Buildings Directive; the heavy tax, legal and real estate agent expenses of downsizing, i.e., selling a large old house to buy a small energy-efficient apartment; the need to motivate small private landlords to take more financial responsibility for their properties' energy performance upgrading; and how uncertainties in future energy and construction prices frustrate renovation planning.

The final plus sign, on the last line of Fig. 1, represents interviewee 13#'s insight: rather than assess energy performance renovation primarily in terms of its economic viability, we can start by affirming it as worthwhile for a number of other reasons. The interviewee pointed out that it enhances societal wellbeing and supports climate protection, and she maintained that we should therefore discuss economic viability within this framework. Her remark, of course, points to an expanding literature on the co-benefits of energy performance renovation (see review in [56]).

This offers a fundamental rationale and motivation for the very expensive, complex, often fraught project of energy renovation, and underlines the value of interdisciplinary research that uses qualitative findings to reflect on quantitative findings. It reminds us, as researchers, that the efforts and expense we give to quantitative research are motivated not just by curiosity or the accumulation of knowledge for its own sake, but by basic human and societal needs, aims and goals.

A further conceptual insight from the matrix of quantitative–qualitative findings is that each side of the matrix provides an essential part of a fuller picture. Without the quantitative findings, we would not have had the means to judge the soundness of the interviewees' assertions on factual matters, such as the (lack of) economic viability of energy efficiency renovation or the way the real estate market responds to it. At the same time, the qualitative findings were able to take us further than the quantitative findings alone could have. This is especially so in terms of policy recommendations, which we summarize in the next section.

The qualitative findings also include some rather simple but profound insights into the human, social side of energy performance renovation. For example: some interviewees maintained that small private landlords should take more pride in their properties, be more socially responsible, and be prepared to pay a significant portion of their rental profits to fill the finance gap in non-economically viable energy performance renovation – a view that has recently been explored in depth by Galvin and März [26]. Another example: Property owners face the problem of too much uncertainty about future energy and construction prices, and this hinders them from being able to make wise decisions on when and how deeply to renovate. This can be seen as a form of market failure. A further example: Elderly people need to be able to downsize to small, energy-efficient homes without having to pay up to 25 % of their equity as transaction costs in Germany's uniquely styled bureaucracy.

The qualitative findings with minus signs in Fig. 1 also bring insights. The two interviewees who claimed that energy efficiency renovation to the minimum standard is economically viable were associated with the federal government. This puts them at odds with the entire tranche of quantitative findings, and opposed to a solid consensus among private sector experts. The "proportionality fallacy" was also an interesting finding, suggesting that even among building sector experts the mathematics of finance can be daunting.

6. Conclusion and policy recommendations

This study used qualitative interviews among 13 carefully selected experts associated with energy performance upgrades of western Germany's post-war apartment buildings, to critique and supplement the peer-reviewed findings of a large set of quantitative investigations carried out in 2022–2024. It utilized an interdisciplinary approach in which a topic is explored from two different perspectives using two different methods, and the results are brought together to enhance understanding of the issues that emerge (see reviews of interdisciplinary methods in [16]. Here, two or more studies investigate the same phenomena from their own unique perspectives, then bring their findings together to reflect on commonalities, contradictions, and emerging new insights. The research question was: How can Germany increase thermal comfort in the homes of low-income households economically, while supporting the country's climate policy goals.

The qualitative interview findings largely supported the numerically based quantitative findings, and vice-versa, but the qualitative findings

added further dimensions. At a basic level, the interviews brought to light the motivation and implications of energy performance renovation and the human, social consequences when it goes wrong, such as through economic non-viability or policy clashes. They also identified a set of stakeholders who need to act more responsibly regarding the energy performance and climate impact of their properties, namely small private landlords.

Perhaps more importantly, the qualitative insights extended into policy implications for Germany's federal government. The main ones are as follows.

(a) The government needs to accept the finding, now supported by overwhelming empirical evidence, that energy efficiency renovation even to only the minimum standard – the least ambitious legally permissible standard – generally does not pay back, through energy and CO_2 tax savings, over the technical lifetime of the renovation measures – at least among post-war apartment buildings. This may not be easy to accept, as there is considerable legislation, regulation, bureaucracy and funding law associated with the view that such renovation always pays back. The payback is even worse for higher energy efficiency standards, and this could be even harder to accept.

(b) One of the reasons this renovation does not pay back is the prebound effect (though our quantitative research shows that even without the prebound effect, economic viability is seldom achieved). The German federal government has long ignored the prebound effect, but needs to take it fully into consideration in its estimates of the economics of actual, real-world energy upgrades.

(c) The government should take seriously the recent, consistent finding that an optimal renovation strategy is to increase energy efficiency only to heat-pump-ready standard, replace fossil fuel boilers with electrically driven heat pumps and supplement their electricity supply with rooftop photovoltaics. The government has not yet begun to speak positively about this approach or consider it as a model to be explored, due to longstanding government emphasis on achieving the highest possible energy efficiency.

(d) The government needs to make CO_2 abatement the main criterion for federal subsidies for energy performance renovation. Currently energy efficiency is the decisive policy criterion, leading to excessive costs per tonne of CO_2 abated. Changing this would enable the building and renovation industry to work out, for each upgrade case, the most economical way to reduce CO_2 emissions in accordance with the government's climate goals. The cost per tonne of CO_2 abated would come down substantially, and far greater amounts of CO_2 would be abated.

(e) In support of the EU EPB, the government needs to investigate the possibility of allowing worst-performing buildings to qualify for subsidies even if renovated only to the minimum standard – since this would represent a major reduction in CO_2 emissions for these buildings and a considerable improvement in occupant comfort.

(f) The government should begin investigating how to motivate small private landlords to take responsibility for closing the finance gap in energy performance renovation at their own expense – possibly along lines proposed in Galvin and März [26], but a wide-ranging investigation is needed.

(g) The government should review the regulations that lead to extremely high transaction costs for selling one's dwelling and buying a new home. We refer here to legal fees, taxes and estate agents' fees. This would make it far easier for households in large, old, energy-inefficient homes to transition to more appropriate-sized dwellings with high energy performance.

(h) The federal subsidy system needs to be reformed to better serve the interests of low-income households. There are so many aspects to subsidy reform (see topic 3 in Section 4) that a new research project on this may well be justified.

It is important to note that the findings and recommendations apply specifically to Germany and may not be extrapolated to other EU countries, since energy prices, architecture, subsidy and regulatory structures differ from country to country.

We note, also, that the issue of ventilation was not explicitly covered in either the quantitative or qualitative sections of the study.Most of the renovation scenarios in the quantitative research assume that the renovation provides adequate ventilation. A more specific focus on ventilation, in relation to Germany's renovation regulations, would be an interesting topic for future research.

The quantitative and qualitative research for this paper have an economic viability focus, in light of the government's concern to see more low-income households benefiting from deep energy performance renovation. Further research could build on this by investigating, for example, psychological factors in renovation decision-making and post-renovation behavior [57] in view of the economic issues this study has brought to light. Other possible research frameworks would be social practice theory [58], and technology diffusion theory (e.g., [59]), which can provide important frameworks for research on the topic.

There are, of course, limitations to this study. The research institute that organized and conducted the qualitative interviews had also performed the quantitative investigations. However, all the quantitative studies were peer-reviewed by anonymous experts, providing critique from outside, disinterested sources, and the resulting published papers had taken their comments on board.

Further, it is possible that a different research institute would have selected a different group of interviewees, and their emphases may have been different. It does seem interesting, however, that no private sector experts we could find disagreed with the most basic, consistent quantitative finding, namely that deep energy efficiency renovation seldom if ever pays back.

A further limitation is that all the quantitative studies were performed by the same research institute. The main reason is that there were simply no peer-reviewed, empirically grounded case studies on costs and benefits of energy efficiency renovation of western Germany's post-war apartment buildings – or of any subsector of Germany's older buildings. It would be very beneficial if other research institutes would begin systematic, peer-reviewable studies on this topic. Peer review is essential, because without it there is far less reason to trust findings, and entrenched viewpoints can sometimes color methods, assumptions, results and their interpretation. We note the findings of Galvin [24] on assertions from non-peer-reviewed literature on this topic in Germany. There were, however, peer-reviewed studies on real estate markets and on rooftop photovoltaics (referred to above), and the findings of these accorded with our institute's findings. Hopefully new studies will continue to be pursued on all these topics, and we look forward to well-grounded, peer-reviewed critique of our own findings.

CRediT authorship contribution statement

Ray Galvin: Writing – original draft, Validation, Methodology, Investigation, Data curation, Conceptualization. **Reinhard Madlener:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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Author declaration on AI

No AI was used in the planning, execution, analysis or write-up of the research for this paper.

Author roles

Ray Galvin performed the empirical work, including the interviews and their transcription, analysis and investigation of their implications for the previously published quantitative research. He shared in the writing of the manuscript with Reinhard Madlener. Reinhard Madlener supervised the research project, set the empirical work within a broader context of microeconomic theory, and shared in the writing of the manuscript.

Data availability

The authors do not have permission to share data.

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