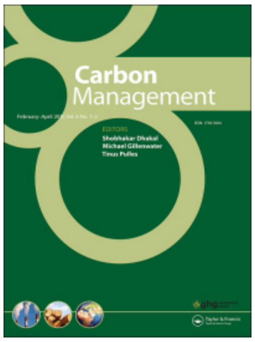

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The contribution of the German building sector to achieve the 1.5 °C target

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ABSTRACT

The melting greenhouse gas emissions budget of the German building sector for the 1.5 °C target requires fast counteraction. In this paper, an analysis of the applicable legal and regulatory framework, the funding situation as well as national and international strategies on a transformation towards climate neutrality elucidates that the suggested approaches do not take a holistic view into account. They neglect, that embodied emissions from construction and emissions from operations phases of buildings must be oriented on the remaining budget, as well as material and human resources associated with the required actions. Therefore a framework to decarbonise the German building sector with eleven recommendations for action, which addresses these findings, is developed with a panel of experts. The results clarify, that the focus must be on adapting the existing building stock since renovation processes release significantly fewer emissions than the construction of new buildings. Stricter legal requirements for building envelopes have no significant effect on the reduction of emissions. Instead, fast-acting measures, such as the usage of district heating, photovoltaics, heat pumps, the optimisation of building operation and digitalisation, must be implemented in a prioritised manner to save resources and maintain the emissions budget longer. To be able to align effective measures it is necessary to engage all Stakeholders and to establish reliable political guidance down to the building level.

HIGHLIGHTS

- A decarbonisation framework for German building sector is developed.
- An emissions budget is required as a benchmark for measures in new buildings and stock.
- Focus on fast-acting measures in existing buildings to maintain the budget and resources.
- Establish a buildings database to evaluate the state, plan resources and monitor effects.
- The energy sector has to decarbonise simultaneously, due to increasing interconnection.

KEYWORDS

German building sector; Greenhouse gas emissions budget; embodied and operational emissions; human and material resources; decarbonisation framework

GHG emissions and CO_2

Within the paper, the terms GHG emissions (greenhouse gas emissions) and CO_2 (Carbon dioxide) are used synonymously and refer to all gases contributing to the greenhouse effect. In the German building sector CO_2 accounts for the predominant share of greenhouse gases (98% in terms of energy-related GHG-Emissions [1]) and some terms or labels aligned with the expression CO_2 (e.g. CO_2 avoidance costs). Also, in the context of metric units, just CO_2 (and not the CO_2-equivalent) is being used.

Introduction

The climate debate in Germany has gained momentum since the Federal Constitutional Court's ruling in April 2021. Within a noticeable short period of time, previous political decisions were adjusted and goals redifined. Climate neutrality is now to be achieved by 2045 and a significant reduction in greenhouse gas emissions (GHG emissions) is to be implemented as early as 2030 [2]. The German Federal Climate Change Act 2021 (*Klimaschutzgesetz*) sets out specific and more stringent energy-saving targets for the energy, building, transport, industrial, agricultural, and waste management sectors. In 2020, around 120 million metric tons of GHG emissions were allocated to the building sector under the source principle [3]. Following this principle, only GHG emissions from fossil fuels used directly on site are

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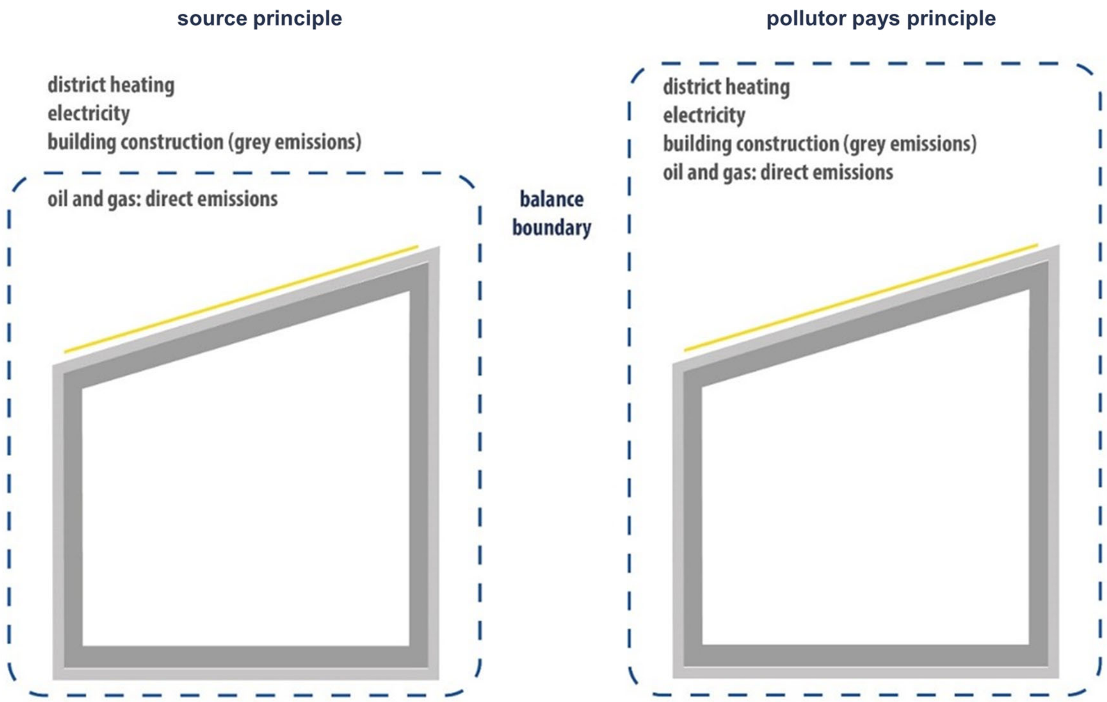

Figure 1. Illustration of emissions assessment framework under source and polluter pays principle for the building sector [4].

included in the emissions assessment of buildings, for example, for heating, water heating or generating electricity from CHP (combined heat and power). However, under the source principle, GHG emissions from generating energy for electricity and district heating are allocated to the energy sector, while GHG emissions generated by producing materials to construct the building are allocated to the industrial and the energy sector.

In contrast to the source principle, under the polluter pays principle all GHG emissions are accounted for where they are initiated. Thus, all building-related GHG emissions are allocated to the building sector and not to other sectors (Figure 1). Under the source principle approx. 16% [3] of the total GHG emissions are allocated to the building sector in 2020, while the share is assumed to be around 40% [5] under the polluter pays principle (Figure 2).[1] This share of 40% explicitly does not include the electrical user-specific applications in non-residential buildings which go beyond heating, ventilation, cooling and lighting [5].

This paper aims to suggest specific recommendations for actions to achieve the climate protection target in the German building sector and uses the polluter pays principle to meet the sector's responsibility as a contributor to emissions. Interactions with other sectors are also considered, as well as the human and material resources required for transformation. Section "Literature review" analyses the existing frameworks and strategies on a national as well as on an international level and show that there are fields, which are not addressed suffienciently. Based on domain expert knowledge and an extensive investigation of the legal framework and the funding landscape applicable in Germany, as well as consideration of available resources, recommendations for action are made in section "Materials and methods". Finally, section "Discussion and conclusion" summarises and discusses the results of this work before presenting the conclusion in consideration of the limitations and a view towards future work.

Literature review

From a German perspective, there currently are national and international approaches to transforming the building sector in the direction of climate neutrality, which will be presented subsequently. Literature was selected that considers a national or international approach, strategy, or framework with climate-friendly and sector-wide measures in the building sector with regard to reducing GHG emissions.

International and European perspectives

Ürge-Vorsatz *et al.* [6] deal with a transformation of the entire global building stock towards climate neutrality and emphasise a significant gap and time lag between the apparently already existing advanced professional knowledge and technology on net-zero buildings and the respective scientific documentation. On the whole, the greatest

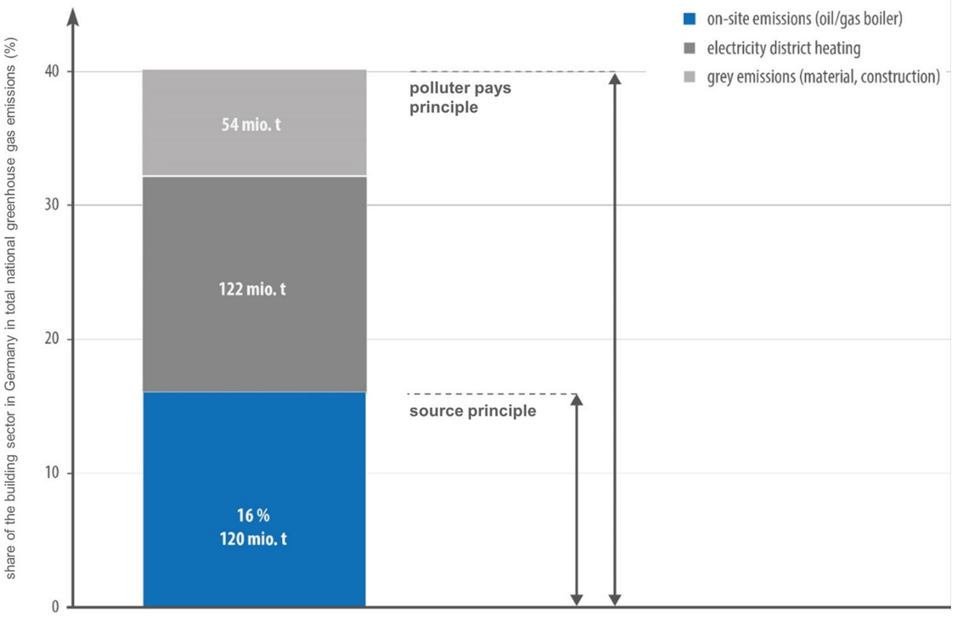

Figure 2. GHG emissions in the building sector differentiated according to the source principle and the polluter pays principle and their share in total national GHG emissions in 2020 [4].

challenges are seen in high-rise commercial buildings in hot and humid climates and for retrofitted historic heritage buildings due to their potentially high energy demand and at present limited possibilities for optimisation [6]. Based on [7] it is highlighted in [6] that embodied emissions in building materials from the construction of necessary new urban infrastructure could consume up to half of the remaining GHG emissions budget for the 1.5 °C target. Thus, strategies for resource-efficient construction are needed [6].

Wolf *et al.* [8] evaluate the European status quo in complementing the emission reduction targets in general and demonstrate correlations to jobs, growth, and price stability. The building sector is responsible for 36% (total of 1,1 billion metric tonnes CO_2) of the EU's energy-related GHG emissions [8, 9]. This refers to the use and operation of buildings, including indirect emissions in the power and heat sector (not their whole life cycle) [9]. Residential buildings alone cause 750 million metric tonnes of CO_2 emissions resulting in an average of approx. 47 kg CO_2/m^2 for about 16 billion m^2 of living floor area in Europe [8]. According to [8], a maximum of around 150 million m^2 is currently getting renovated energetically within one year. For the energy-related renovation of buildings, [8] recommends public investments of annually more than €70 billion between 2021 and 2030 in order to meet climate protection targets. This would trigger a more than fourfold increase in the rate of energy-related renovation and results in additional CO_2 savings in the EU of around 24,5 million metric tonnes each year [8]. Wolf *et al.* [8] highlight the CO_2 reduction potential of digitalisation for emissions reduction through information and communication technology for households. The society-wide reduction potential is estimated to be around additional 30 million metric tonnes each year while public investments of around €30 billion in research and development are proposed in the same field [8]. However, it is not exactly clear how big the corresponding potential is in the building sector alone.

The Buildings Performance Institute Europe (BPIE) [10] declares that solid benchmarks for whole-life emissions in both new constructions and renovations are based on gathered life cycle assessment data and are suitable for benchmarking best practices across different building typologies, are needed [10]. The BPIE [10] also proposes to set mandatory minimum performance thresholds which steadily decrease in the member states, to trigger improvements for buildings with the greatest impact and leverage on the climate. In addition to the holistic life cycle view of [10], another BPIE publication [11] shows the status quo of the European policy framework and indicates existing laws are mainly designed in silos and target only individual phases of the life cycle, without coherent links between the phases.

Saheb *et al.* [12] ask for a shift in the emerging energy-related renovation market. They propose to substitute the currently existing market of step-by-step and shallow energy-related renovation, to one of industrialised and holistic energy-related renovation; ultimately leading to zero energy buildings [12]. Therefore, it is necessary to encourage renovation enterprises to develop and use modern production technics, innovative technologies, and new business models, leading to a reduction in costs, broad availability, and affordability [12].

German perspective

On a national level, the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR) in the Federal Office for Building and Regional Planning (BBR) of Germany proposes necessary developments to achieve a climate-neutral building stock by 2050 (this was the national goal for climate neutrality before the adjustment to the year of 2045, done by the Federal Climate Change Act 2021 [2]) [13]. Any new installations of fossil-fuelled gas and oil boilers – also as hybrid heating – are considered to counteract the achievement of the target in 2030, also taking the overall energy system costs into account [13]. According to [13], the availablility and appropriate training of craftsmen and energy consultants poses a challenge on its own, along with the availability of sufficients production capacities. However, these problem areas are not quantified in [13].

Bürger *et al.* [14] investigate how the German building stock can be transformed into a nearly climate-neutral state by 2050 (at least 80% reduction in non-renewable primary energy demand compared to 2008 level and thus less ambitious than complete neutrality) as well as interactions of the building stock with the energy system as a whole. For the building stock modelling and analysis in terms of final and primary energy demand, GHG emissions and costs, 19 different building types (nine for residential buildings and ten for non-residential buildings) are utilised [14]. Furthermore, impacts of more efficient technical building installations or possible consequences of global warming in 2050 on the target scenarios are investigated [14].

Regarding building constructions and renovations, a report published by the German Property Federation (ZIA) [15] indicated that in non-residential buildings, the energy demand mainly results from the electricity demand for ventilation, cooling and lighting and not from the buildings' heat supply. This emphasises that a steady increase of the building insulation can be counterproductive, as this would even further increase the energy demand, using cooling-intensive buildings as an example.

Kotzur *et al.* [16] propose a bottom-up model of the German residential building stock to estimate the cost-optimal building stock energy consumption in 2050. Furthermore, GHG emissions and grid loads are considered [16]. Heat pumps as well as photovoltaics are suggested to be the most economically and ecologically robust supply solutions for the different residential building types in 2050 [16]. Nevertheless, in rural areas, a doubling of the peak electricity grid is predicted during the winter because the electricity generation and demand temporally do not match, which urban areas can compensate for due to efficient co-generation units [16].

Research gaps and paper contributions

Table 1 gives a summary of the previously conducted literature review. The investigated literature is examined according to their geographical scope, their main indicators used to evaluate the status quo or proposed measures, the scope of the assessment frame concerning buildings and lastly the main contribution concerning the transformation towards climate neutrality. In general, some of the literature focuses on energy consumption and takes GHG emissions only indirectly into account when investigating the building sector. Most literature investigates different energy efficiency developments and energy mix scenarios for the heat and electricity supply of the existing building stock. However, some works also take embodied emissions from construction actions into account. Still, embodied emissions and operational emissions are rarely considered under a holistic budget approach. On a political level, the Buildings Performance Institute Europe (BPIE) already communicates the budget and life cycle concept of GHG emissions without, however, abstracting specific benchmarks for the building sector or for individual buildings referenced to the usable floor area. To summarize, the number of national and international existing approaches, strategies, or frameworks is very high. Yet, these are hardly harmonised. When making assumptions for renovation actions and rates, it is furthermore important to consider material and personnel resources beyond emission reductions. This paper submits measures with recommendations for the transformation of the German building sector

Table 1. Summary of the literature review.

literature	geographical scope	main indicator	assessment frame	main contribution
[6]	global	Energy consumption and GHG emissions	Life cycle of a building. Embodied emissions (of necessary new urban infrastructure – not only buildings) are linked to the the budget of remaining emissions for the 1.5 °C target on a global level.	Review of positive international examples buildings, districts or building stocks as well as regulations and policies to draw up an acceleration strategy of building sector transformation towards climate neutrality.
[8]	Europe	Energy consumption and GHG emissions	Building operation. No consideration of remaining GHG emissions budget for the 1.5 °C target.	European status quo in complementing the emission reduction targets in general and demonstrating correlations to jobs, growth, and price stability.
[10]	Europe	GHG emissions	Life cycle of a building. Schematic proposal to a consideration of remaining GHG emissions budget for the 1.5 °C target (no specific numbers). The need for a GHG emissions budget for individual buildings (new constructions and renovations) that incorporates the building operation emissions and the embodied emissions is exemplary pointed out.	Proposal for "whole-life carbon limits" for buildings with presentation of similar existing models in selected member states of the European Union.
[11]	Europe	Energy consumption and GHG emissions	Life cycle of a building. No consideration of remaining GHG emissions budget for the 1.5 °C target.	Review of European regulations and assessment of differences and synergies.
[12]	Europe	Energy consumption and GHG emissions	Mainly building operation. Embodied energy is mentioned to be considered in the future. No consideration of remaining GHG emissions budget for the 1.5 °C target.	Renovation strategy for industrialised and holistic energy renovation with regard to economic aspects and employment in the construction sector.
[13]	Germany	GHG emissions	Building operation. Consideration of annual targets from the Federal Climate Change Act 2019, summarised into an assumed budget. The Federal Climate Change Act 2019 (as well as the amended Federal Climate Change Act 2021) was not oriented on the remaining budget for the 1.5 °C target (see section "Simplify and adjust regulations").	Strategy development based on a scenario for climate neutrality in 2050. Focus on building sector *yet all* sectors are considered. Technological progress and market development at the level of the craftsmen is taken into account.
[14]	Germany	Energy consumption and GHG emissions	Building operation. No consideration of remaining GHG emissions budget for the 1.5 °C target.	Simulation based on a building stock modelling with different target scenarios to achieve a nearly climate-neutral state by 2050. Sensivities of the target scenarios towards more efficient technical building installations or possible consequences of global warming in 2050 are investigated.
[15]	Germany	Energy consumption and GHG emissions	Mainly building operation. Embodied emissions are mentioned to be considered in the future. No consideration of remaining GHG emissions budget for the 1.5 °C target.	Assessment of commercial real estates (office buildings, hotels and shopping malls) regarding the German requirements towards the building envelope (established in 2016) and even more ambitious ones. Representative building types are used for investigations of different variants of energy supply to evaluate their energetic, ecological, and economical effects depending on different requirements for the building envelope.
[16]	Germany	Energy consumption and GHG emissions	Building operation. No consideration of remaining GHG emissions budget for the 1.5 °C target.	Assessment of future buildings' energy supply based on a bottom-up model of the German residential building stock to estimate the cost optimal building stock energy consumption in 2050.

towards climate neutrality with regard to the identified gaps.

Materials and methods

In this section, the approach taken to develop the framework aimed at achieving the climate protection targets in the German building sector is described. Subsequently, the holistic framework consisting of individual recommendations for action will are named and get justified.

Research approach

In this paper, specific recommendations for actions to achieve the climate protection targets in the German building sector are developed. The literature review in section "Literature review" lares bare the lack of holistic approaches oriented on the

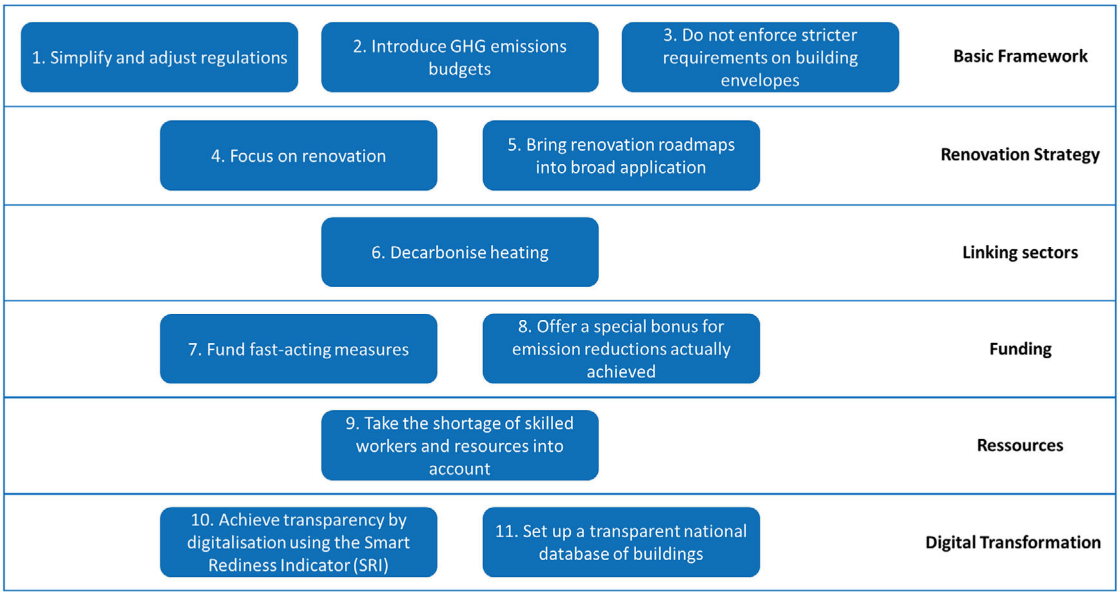

Figure 3. Building sector transformation recommendations for action sorted by their main addressed subjects.

remaining budget of the 1.5 °C target derived for the building sector or on an individual building level. These approaches miss specific recommendations for measures which include necessary material and human resources to enable the building sector's stakeholders allign with effective measures. Therefore, in Germany applicable legal and regulatory framework, the current national funding situation as well as available personnel and material resources were examined through extensive literature research to identify improvement potentials and create the basis for the recommendations for action. Subsequently, the developed framework was discussed and qualitatively refined in (a total of) four two- to three-hours structed workshop sessions. These were joined by experts of the "Task Force Energy" of the German Property Federation (ZIA) with stakeholders from the areas such as engineering companies, real estate investment companies, banking, energy suppliers, housing associations, metering point operators and retail property operators. Those panel meetings were surrounded by an initial kick-off meeting and a subsequent final presentation of the coordinated recommendations which will be presented and justified in the following subsection.

Framework development

This subsection presents and explains eleven recommendations concerning the German building sector, derived from the preceding work. Figure 3 illustrates an overview of the framework designed.

Simplify and adjust regulations

In Germany, the Buildings Energy Act (GEG) primarily regulates the construction of new buildings and major renovations since November 2020. Still, even under this newly enacted legislation, which in principle combines three previously applicable regulations, there has been no significant simplification of regulations. The Buildings Energy Act aims to lead to energy-efficient building operation according to the polluter-pays principle without, however, considering embodied energy or embodied emissions. Figure 4 illustrates the relevant policies and laws stakeholders of the German building sector have to face at the national and EU level. There are more than 3,000 pages of climate protection regulations; none of which include the associated technical annexes. The quantity and complexity of the regulations to be taken into account in the building sector are constantly increasing and are barely manageable, even for experts. Therefore, a simplification of the regulations is urgently required.

Most regulations in the building sector define targets according to the source principle. There is no publication other than the Energy Efficiency Strategy for Buildings [17] which prescribes GHG emissions under the polluter pays principle (without considering embodied emissions) for the German building sector. The Energy Efficiency Strategy for Buildings defines targets for GHG emissions for the entire sector without transferring them into specific usable floor area targets.

Table 2 provides an overview of the currently targeted requirements in Germany. It should be

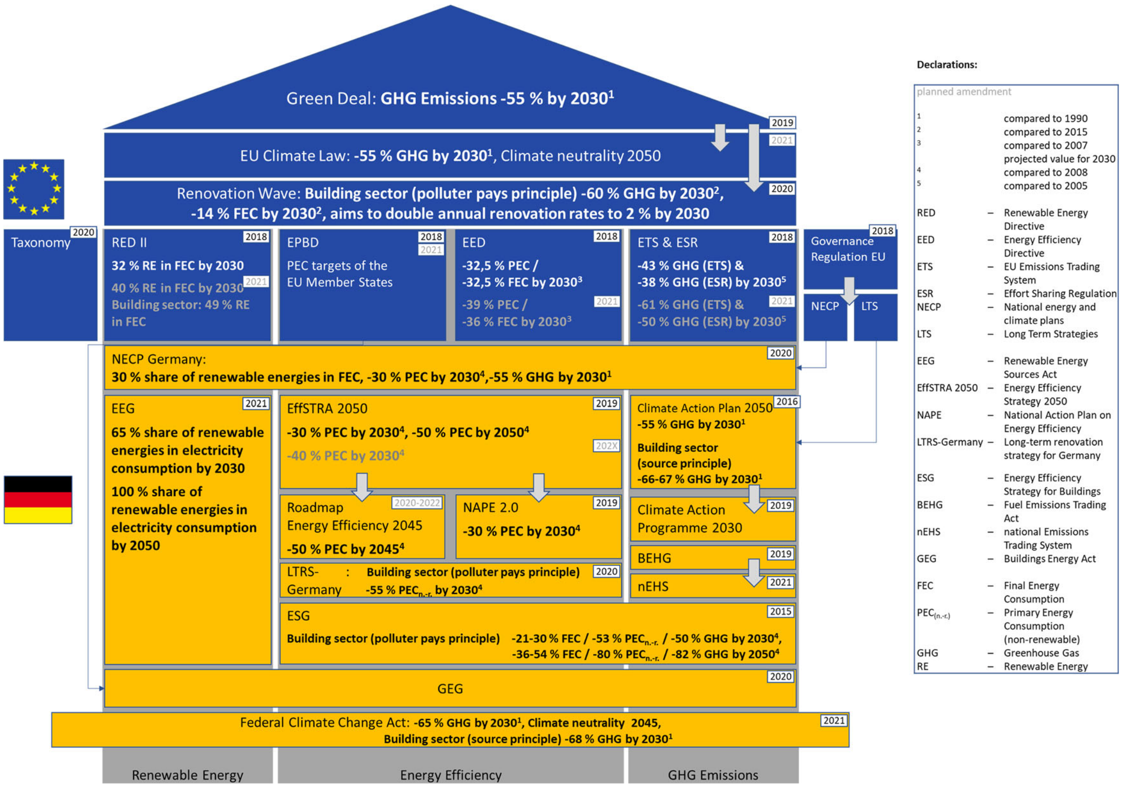

Figure 4. Political house of climate protection with applicable regulations and strategies of importance in Germany with their main targets and requirements [4].

Table 2. Building sector-related targets according to the Energy Efficiency Strategy for Buildings [17] and the Federal Climate Change Act 2021 [2].

Year	Final energy consumption Polluter pays principle [PJ]	Primary energy consumption non-renewable Polluter pays principle [PJ]	GHG emissions Polluter pays principle [million t CO_2]	GHG emissions Source principle [million t CO_2]
2030	$<$ 2,453 – 2,757 and 24-32 % share of renewables	$<$ 1,997 – 2,008	$<$ 152 – 153	$<$ 67
2040	$<$ 1,966 – 2,465 and 30–43 % share of renewables	$<$ 1,299 – 1,309	no specification	"Across all sectors -88 % compared to 1990." No specific target value for building sector.
2050 / 2045	$<$ 1,597 – 2,243 and 34-50 % share of renewables	$<$ 827 – 840	$<$ 55 – 57 and "nearly climate-neutral building stock"	"Net greenhouse gas neutrality."
	Residential building 74 – 104 kWh/(m²a) Non-residential building 100 – 139 kWh/(m²a)	Residential building ~40 kWh/(m²a) Non-residential building ~52 kWh/(m²a)	No building-specific targets declared.	No building-specific targets declared, but net greenhouse gas neutrality can be assumed.

noted that all the targets from the polluter pays principle (the first three columns illustrated in Table 2) were published in the year 2015. They no longer meet the current requirements under the 2019 Green Deal and the amended Federal Climate Change Act 2021, whose requirements for the building sector are shown in the 4th column of Table 2. Already the Federal Climate Change Act 2019 did not align with the remaining budget for the 1.5 °C target [18]. With the Amendment in 2021, the annual targets became more ambitious but the intended GHG emissions reductions in total still do not align with the remaining budget for the 1.5 °C target [19]. Furthermore, it should be noted that there are no specific targets for the building sector in the current 2021 Federal Climate Change Act for the years subsequent to 2030.

Until now, the national overall targets for GHG emissions are neither transferred to the building sector nor to individual buildings (Table 2). Without transferring building sectoral targets related to GHG emissions under the polluter pays principle regarding the embodied emissions to specific square metres (usable floor area pursuant to the Buildings Energy Act), including a corresponding adaption of the regulatory framework, clear and climate-compliant action will not be possible.

Introduction of GHG emissions budgets

The Intergovernmental Panel on Climate Change (IPCC) has calculated a remaining global GHG emissions budget in order to achieve the Paris climate protection target of 1.5 °C.

The Environmental Report 2020 of the German Advisory Council on the Environment (SRU) [18] takes this into account and criticises the fact that the current political framework, which is solely based on annual targets (for example 2030 and 2045/2050) is not sufficient if requirements of the Paris Agreement are to be met. Focusing on target values ignores the absolute GHG emissions budget, which must not be exceeded if climate protection intends to be successful.

According to the German Advisory Council on the Environment [18], Germany has a GHG emissions budget of approx. 4,200 million metric tons in total to meet the 1.5 °C target.[2] Assuming that the building sector continues to emit 40% of national GHG emissions, a budget of approx. 1,680 million metric tons would remain under the polluter pays principle. Figure 5 illustrates with a linear reduction (variant 1) of the 296 million metric tons of GHG emissions (Figure 2) incurred in the building sector in 2020 that climate neutrality would have to be achieved as early as 2032 in order to meet the GHG emissions budget of 1,680 million metric tons (shown in the graphic in dark blue) for the 1.5 °C target set by the Paris Agreement.

The temperature target cannot be accomplished by merely defining targets to reduce GHG emissions for the years 2030 and 2045 (variant 2). Variant 3 shows that extending the climate neutrality deadline beyond 2032 requires a stringent reduction of GHG emissions in the years up to 2030. This explicitly highlights the necessity of "fast-acting measures", which means a frontloading of the strongest and most immediate emission-reducing actions.

In order to meet the budget targets under the Paris Agreement, a usable floor area-related target value up until 2045 for the GHG emissions budget for operations (label CO_2-B) and for construction (label CO_2-A) could be derived, that is oriented on the remaining budget. End-of-life emissions (label

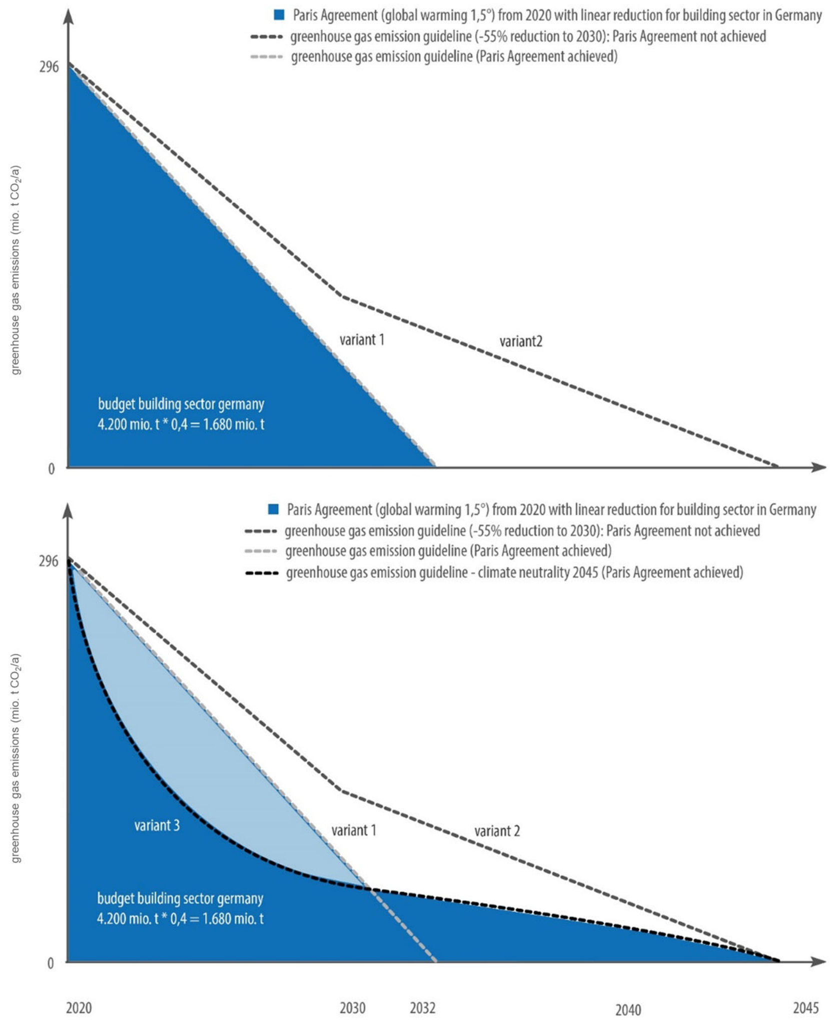

Figure 5. GHG emissions paths to comply with Paris climate protection targets in Germany (schematic) ([4] based on [18]).

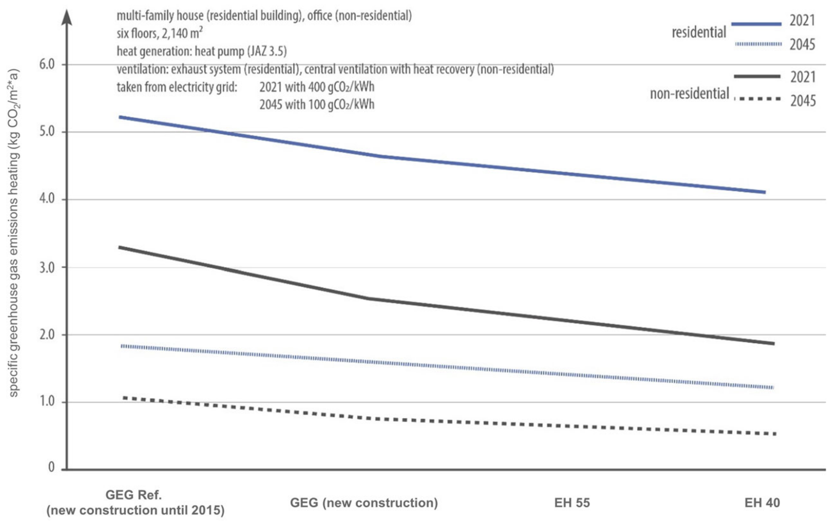

Figure 6. Usable floor area-related GHG reductions for new buildings with different energy levels [4].

CO2-C) for deconstruction to disposal and beyond life emissions for reuse and recycling (label CO2-D) are not taken into account. This is because an evaluation under the current circumstances seems too inaccurate for buildings with an average life-span of 50 years or more.

A comparison of the different implementation strategies from new construction to renovation is only possible by considering GHG emissions from construction and operation. At the same time, only by taking a GHG emissions budget up until 2045 into account, it will be possible to see the effects of the implementation date of the different measures has. Different measures may lead to the same target value in 2045 due to changing GHG emission factors but differ significantly in the total emissions emitted up to that point, for example.

If the derived budget of 1,680 million metric tons according to the polluter-pays principle for the building sector is distributed equally over the usable floor areas of German residential and non-residential buildings, we obtain a budget of approx. 243 kg CO_2/m.[2] The total usable floor area in Germany assumed were 6.9 billion m^2 composed of 3.9 billion m^2 of living floor area for residential buildings according to the German Energy Agency (dena) [20] and 3.1 billion m^2 net floor area for non-residential buildings according to the Institute for Housing and Environment (IWU) [21]. Ideally, the budget of 243 kg CO_2/m^2 would have to be further divided among different building clusters (residential and non-residential buildings and even further down) to do justice to the heterogeneity in the national building stock. Any new buildings would obviously reduce the budget, and this should also be taken into account by making an assumption for future building stock and adjusting the budget accordingly. If the 242 million metric tonnes of CO_2 for the German building stock operation (not the grey emissions from construction) in 2020, shown in Figure 2, are broken down to the 6.9 billion square metres of usable floor area in German buildings, this results in around 35 kg CO_2/m^2 per year. This would exceed the previously derived German budget benchmark of 243 kg CO_2/m^2 after about seven years without conducting intervention measures and illustrates the ambitious requirements that the crucial budget approach sets for the building sector.

Do not enforce stricter requirements on building envelopes

With a theoretically statutory lowering of the required building envelope level to efficiency house level 55 (approx. 25% less primary energy demand compared to the German New Construction Standard) or 40 (approx. 45% less primary energy demand compared to the German New Construction Standard), there are only minor reductions in heat-related GHG emissions when supplying heat a 100% by a heat pump (Figure 6).

When comparing 2021 and 2045, it becomes clear that decarbonising power and not the tightening of thermal insulation requirements will be the decisive factor in achieving the climate protection targets. The building envelope will have less influence due to decreasing GHG emission factors. This also applies to heat supply *via* district heating, whose GHG emission factor decreases over time.

The following assumed calculation suggests the same. Scaled to the year 2030 and an assumed additional capacity of approx. 25 million square metres per year for non-residential buildings and approx. 30 million square metres per year for residential buildings, GHG emissions for heating will increase by roughly 4 million metric tons per year. Calculations are based on the minimum standard for thermal insulation for all buildings under the Buildings Energy Act and a supply structure covering half of the requirements with gas boilers and the other half with electric heat pumps. If all buildings were constructed at the efficiency house level 55 instead of the legal standard, an arithmetic savings potential of only 0.5 million metric tons of CO_2 per year could be achieved. Further 1.0 million metric tons of CO_2 per year could be achieved through constructing at the efficiency house level 40. The scale is not significant compared to today's GHG emissions in the building sector of 296 million metric tons, calculated according to the polluter pays principle (Figure 2). Therefore, a steady tightening of the requirements for building envelopes (i.e. set lower maximum tresholds for the transmission heat loss of the building envelope for new buildings and renovation of existing buildings) should be left aside, as this will only lead to marginal benefits in operation but higher human and material resource consumption during the construction phase.

Focus on renovation

The new construction and renovation of buildings generate more than 18% of national, building-related grey GHG emissions, accounted for according to the polluter pays principle (Figure 2).

Figure 7 compares the embodied GHG emissions of new construction and renovation and regards the respecting usable floor area. Embodied GHG emissions in new constructions of around 44 million metric tons of emissions per year indicate a level which corresponds to over two-thirds of the Federal Climate Change Act 2021 [2] reduction targets in 2030 which are according to the source principle. According to the polluter pays principle, embodied GHG emissions in new constructions accounted for 15% of the building sector's annual emissions. A significant part of the entire potential of annual savings by optimising operations, expanding renewable energies, or reducing consumption will be wiped out by the embodied emissions of new construction.

Nevertheless, the funding of new construction is an important goal for the Federal Government and necessary for socio-political reasons due to the higher investment costs caused by politically required energy levels. KfW's 2021 Funding Report [22] indicates approx. 150,000 funded, energy-efficient new buildings or new units for the first half of 2021, while renovations made up roughly two-thirds of the projects with around 99,000 funded projects in the form of individual and systemic measures.

Figure 8 shows the development of KfW's annual investment volume concerning residential buildings for the years 2018 to 2020. This refers to the funding's sum granted, as well as th sum of the loans issued. Compared to 2018, the level of investment more than doubled in 2020. Approx. 80% of the €26.5 billion funds have gone into the funding of new buildings.

This trend continued in the first half of 2021. Despite considerable redemption grants, the renovation funding of €3.2 billion only reached approx. one fifth of the funding for new buildings of around €16 billion [22]. The focus and strengthening of activities and funding must be on renovating existing buildings. This is where the biggest potential lies due to a broad applicability of

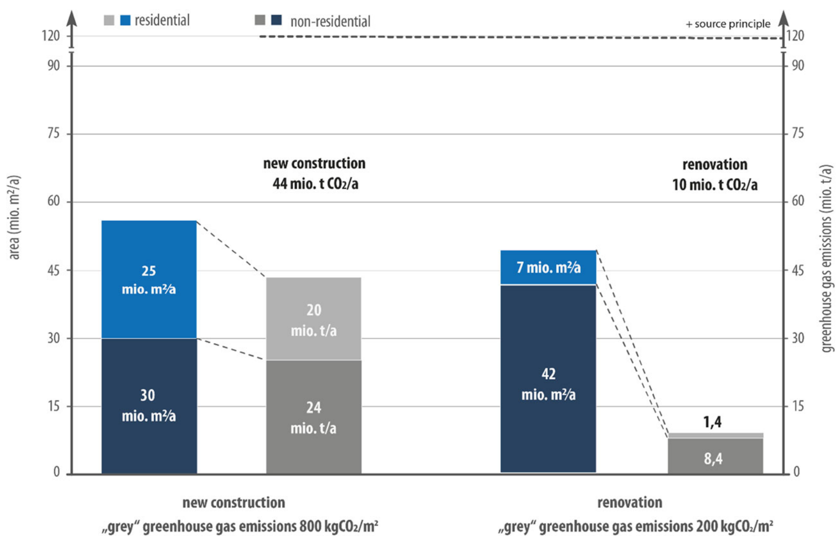

Figure 7. **Grey GHG emissions in the building sector in 2020, comparison of new buildings and renovation [4].**

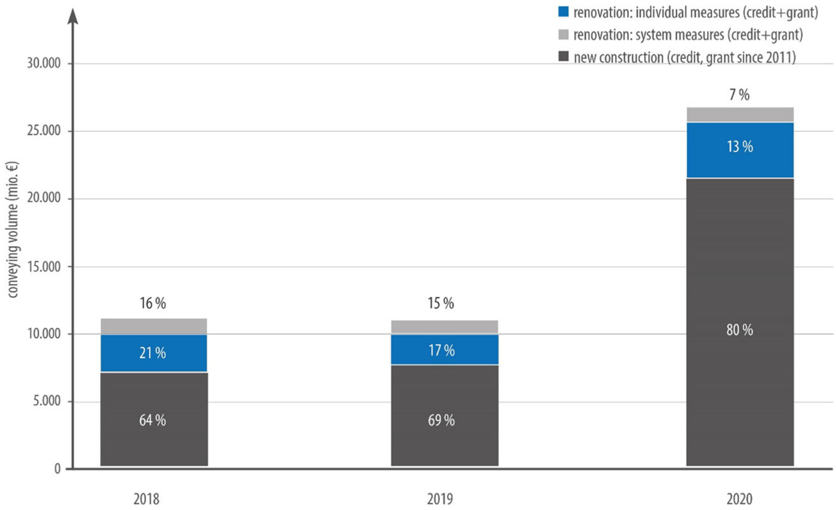

Figure 8. **Development of annual investment volume for energy-efficient buildings (systemic measures) for renovated, new buildings and individual measures in renovation ([4] with data from [23–25]).**

measures and a lower GHG emissions impact per attacked usable floor area.

Funding targeted at preserving and further developing the fabric of the building may reduce the use of materials and substantially increase resource efficiency. It would also offer the chance to upgrade and improve culturally meaningful urban developments.

Bring renovation roadmaps into broad application

Renovation roadmaps specifically show the technical and construction measures along with related costs needed to achieve optimised energy consumption and emission reduction in an individual property or property portfolio. They form the basis for making decisions about implementation measures and thus create planning security for property owners. Both, owners of individual buildings with the holders of larger real estate portfolios profit from renovation roadmaps.

However, to date, no uniform legal requirements have been imposed on the framework for drawing up renovation roadmaps in Germany. Thus, there is no comparability between renovation roadmaps.

To be able to compare renovation roadmaps in the future a clear structure and definition of the assessment limit and the key performance indicators for residential and non-residential buildings is needed.

In general, renovation roadmaps could be linked to the energy performance certificate. In particular, the rules for having to prepare an energy performance certificate in Germany (new build, significant renovation, sale, leasing, and public accessibility) could also be applied to the drawing up of renovation roadmaps. The basis for renovation roadmaps should always be the energy demand orientated certificate. This is based on standardised usage profiles and thus enables a user-independent comparison of buildings, in contrast to the energy consumption-oriented certificate, which is based on the actual consumption of the last three years. Specific GHG emissions in [kg CO_2/(m^2·a)] should be shown as the primary key performance indicator in the energy performance certificate and the corresponding renovation roadmap. By integrating the CO_2-A construction and CO_2-B operation labels, it can be ensured that implementation measures will also take grey GHG emissions into account in the future and that renovation roadmaps are GHG emissions budget-oriented, open to different technologies and thus aligned with the Paris climate targets. In addition to this, specific final energy demands and the non-renewable primary energy demands, if applicable within the context of European conformity, should also be displayed on the certificate. The corresponding figures on the certificate should be amended and should anually be updated on the basis of real GHG emissions or actual consumption. With the renovation roadmaps to be planned by energy experts, the stakeholders in the building sector will be able to implement measures in a scheduled and target-oriented manner in the future. Also, conversions could be carried out more easily through extensive planning. In general, as mentioned in chapter 3.2.4, it is important to focus all actions (not only funding, but also the general implementation) on the renovation of existing buildings. If an urgent need for new spaces arises, which cannot be provided or conversed by the existing building stock, then the new construction should strictly comply with the requirements of the derived budget benchmark that incorporates limits on the permissible sum of emissions from construction (label CO_2-A) and operation (label CO_2-B) to meet the remaining budget for the 1.5 °C target (see section "Introduction of GHG emissions budgets").

Decarbonise heating

The aim of decarbonising heating can be mainly achieved by two system strategies that can be standardised and are transferrable. Just like systematically expanding local and district heating networks, the transition to power-based heating systems using electric heat pumps is of great relevance in ecological and energy efficiency terms. Heat pump systems additionally offer the benefit of increasing the proportion of solar energy coverage with decentralised photovoltaic installations and stepping up the expansion of renewable energy use in buildings. Based on simulations mainly in the area of single-family houses and multi-family houses, the study entitled *future:solar* [26] from 2015, comes to the conclusion, that in general the best results in terms of renewable energy supply with up to 100% can be achieved with photovoltaics in combination with heat pumps and district heating. While calculating a 100% renewable supply in an annual assessment in a scenario for the example of the renovation of multi-family houses, it is further shown that, apart from ecological criteria, the economic efficiency is also in favour of district heating and heat pumps in comparison to other heating systems like gas boilers, combined heat and power (CHP) plants or biomass based power plants [26]. The pricing of GHG emissions (which, in Germany, mainly started for emissions in the areas of heating and transport in 2021) has not yet been considered within [26]. Consideration of this pricing would have an even greater impact on the decarbonisation of power grids by 2030 initiated by the energy sector for both variants. For gas variants, emissions are offset by feeding electricity generated by photovoltaics into the public grid for comparability [26]. This offsetting mechanism becomes increasingly ineffective as the GHG factor in Germany's electricity mix decreases, to which the energy sector must foremost contribute to. This appears to be another argument against new or continued operation of gas-based systems. This core message is transferrable to non-residential buildings and applies in the same way for new construction projects. Besides putting an end to the installation of new oil boilers as of 2026 (according to the Buildings Energy Act), the next step today should be to specify an exit scenario for gas appliances. In this context, building a grid-based infrastructure to supply gas to new urban districts should be ruled out as an option as soon as possible.

Fund fast-acting measures

Depending on four different assumed scenarios according to Fraunhofer Institute for Solar Energy Systems ISE [27], the installed photovoltaics capacity in Germany must increase annually by approx. 12.7 to 25 GW_{el} (electric power) between 2020 and 2045. Since the assumed German GHG emissions budget in [27] is even higher (derived from annual targets of the Federal Climate Change Act 2021) than the underlying budget for the framework in this paper (adopted from the German Advisory Council on the Environment [18] and oriented on the wordwide budget - see section "Introduction of GHG emissions budgets"), the annual increase in installed photovoltaics capacity should be even higher. In Germany, overall, there were around 59 GW_{el} installed photovoltaics (approx. 75% on roofs and 25% on open spaces [28]) up until 2021 [29, 30]. Since about 5,3 GWel (approx. 240,000 plants) were being installed in 2021 alone [29], at least a threefold increase in annual installations is required to meet the budget-oriented target. According to [30], there are solar modules which do not require raw materials for which limited availability would be foreseeable. Thus, considerable potential for reducing GHG emissions can be tapped by a fast and broad adoption of solar units, especially on roof surfaces. Optimising building operations also has great potential in reducing GHG emissions. In the case of commercial properties, for example, up to 30% of the final energy for room conditioning per year can be avoided just by optimising operations [31]. Due to a generally favourable cost-benefit ratio, low CO_2 avoidance costs and prompt implementation options of building optimisations, the current funding rate of 20% for energy efficiency measures in facility technology should be substantially increased in the Federal Government's Efficient Buildings Funding (BEG). The implementation of technical monitoring should be connected to the funding to enable faulty facility functions to be digitally identified and corrected in the future.

Currently, photovoltaic installations can only be funded within the framework of federal funding if

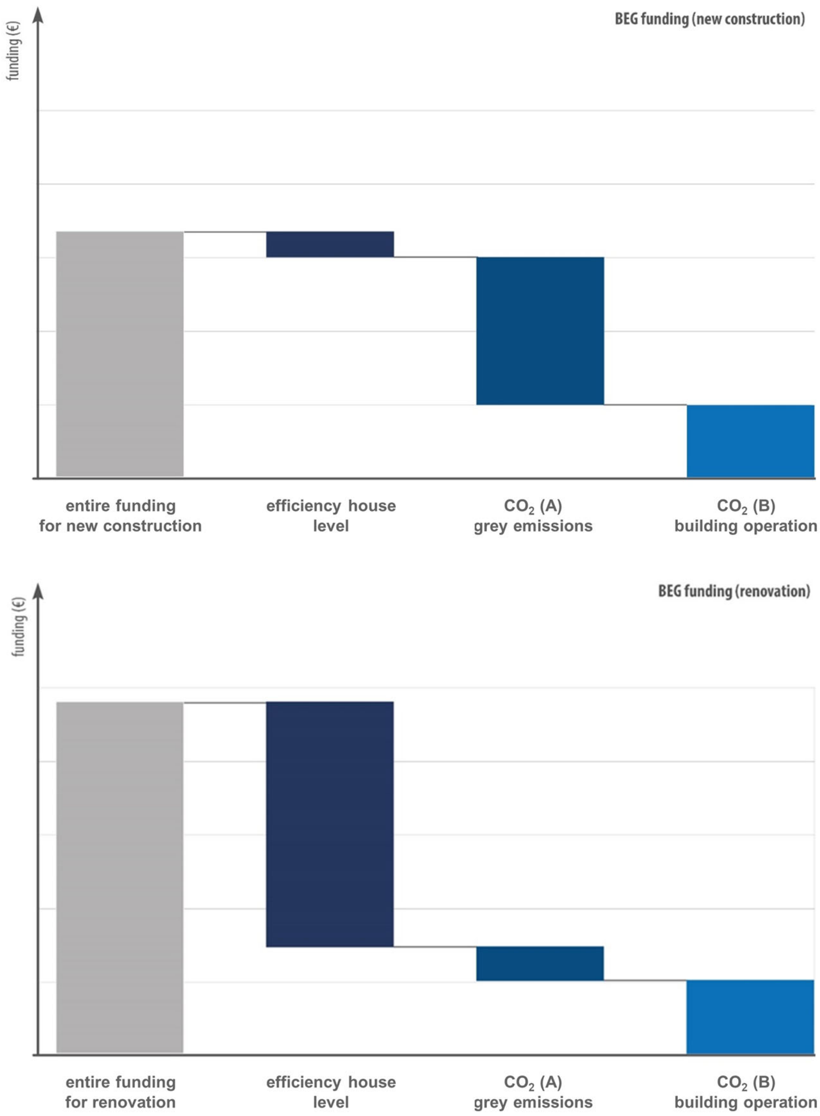

Figure 9. Proposal for a funding methodology for renovations (above) and new buildings (below) [4].

further systemic measures are implemented. However, photovoltaic installations also contribute to the decarbonisation of the building sector as a single measure and should therefore be eligible for funding without any further preconditions. Due to the unavoidable grid feed-in because of installing as many solar units as possible, binding regulations are necessary. A long-term, fixed feed-in tarif for solar energy will guarantee budgeting certainty for owners and operators.

Offer a special bonus for emission reductions actually achieved

The current Efficient Buildings Funding (BEG) grant in Germany supports the theoretical achievement of the targeted efficiency house level, which is assessed based on pre-calculated primary energy demand and transmission heat loss in operation. Yet, there can be significant differences between the theoretically calculated and in practice measured values [32]. The real savings or GHG reductions of the building operation are not taken into account by the national funding framework. This also applies to the construction of buildings and the respective share of grey emissions. In the future, there will be a need for an emissions budget-oriented funding system which includes the avoidance of GHG emissions, that are achieved in reality. However, since it takes time to measure and evaluate (at least one year has to be covered) the real improvements after the construction of a building or after undertaking renovation actions, funding should continue to be granted for the theoretically achieved efficiency levels in order not to inhibit ambitions.

Figure 9 shows a schematic proposal for a future funding system for construction and renovations. Besides the theoretically achieved efficiency house level (in the future to be measured by GHG emissions instead of primary energy demands and transmission heat losses) it also includes the embodied GHG emissions of the construction and

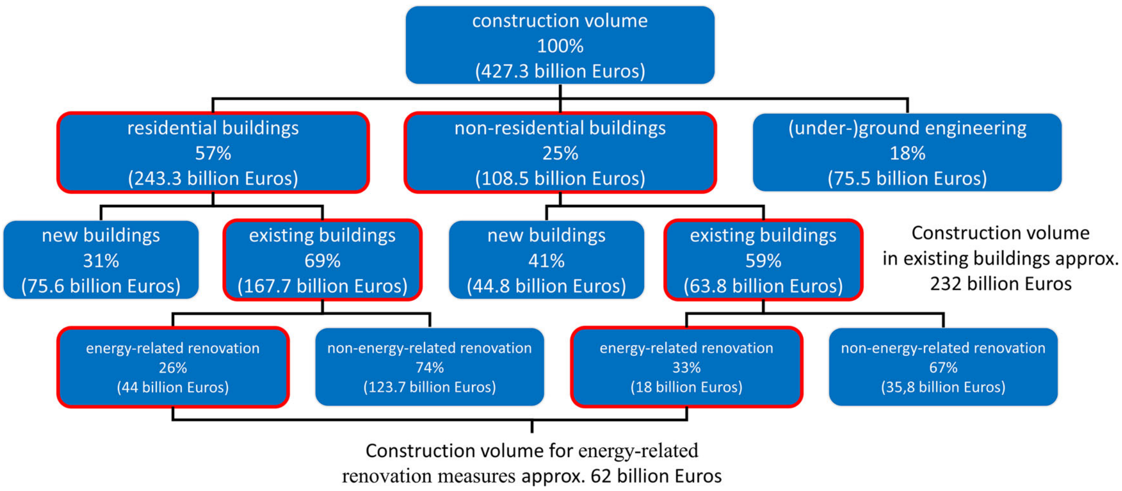

Figure 10. Structure of the German construction volume [33, 34].

the emission reductions met in reality (to be measured in operation). In new buildings, grey emissions (construction) predominate which is why there should be a higher share of funding grant oriented on avoidance in this category. In renovation, the effort required to achieve lower theoretically calculated GHG emissions in operation is higher. Thus, the achieved efficiency house level has to be the highest part of the funding. The real operation of the building, designated as the CO_2-B label, could be generally integrated as a third component, and will be paid out if the measured consumption value is within the pre-calculated efficiency house level range. Funding could also be complemented in a meaningful way by aspects of ecological construction.

Take the shortage of skilled workers and resources into account

According to the Federal Institute on Building, Urban Affairs and Spatial Development (BBSR) construction volume in Germany amounted approx. €427 billion [33] in 2019. This can be taken from Figure 10, as well as a further subdivision. Approx. €352 billion (around 82%) of the construction volume in Germany belong to residential and non-residential buildings; of which approx. 69% in terms of residential buildings and approx. 59% in terms of non-residential buildings refer to construction work in existing buildings [33]. This corresponds to a total volume of approx. €232 billion for construction work in existing buildings. In 2019, only €62 billion of the €232 billion were attributable to energy-related renovation measures, approx. €44 billion to residential buildings and approx. €18 billion to non-residential buildings [33]. Thus, the approx. 1% energy-related renovation rate can be assigned to a construction volume of approx. €62 billion per year in Germany, which is roughly 14.5% of the total German construction volume.

If the construction industry's employees (main construction and finishing trades: approx. 2.118 million employees [33]) were allocated on a pro-rata basis to energy-related renovation activities (approx. 14.5% of the German construction volume), then approx. 310,000 employees would be needed for these activities. Doubling the 1% renovation rate thus requires an additional investment of at least €62 billion and an additional 310,000 employees. In addition, there will be a higher demand for workers from related fields such as the manufacturing sector like steel and light metal construction, or further services like construction planning, public sector bureaucracy, etc., as the mentioned numbers concern only the construction industry which was narrowed down above.

The main problem is posed by the current shortage of skilled workers in Germany. According to the 2021 study [35] carried out by the Competence Centre for Securing Skilled Workers at the German Economic Institute in Cologne, there currently exists a shortage of skilled workers in craftsman trades in the building sector. According to this study, several building-related professions already have a shortage of skilled workers in the thousands and tens of thousands (headed by electricians with a shortage of 14,000 skilled workers and sanitation, heating, and air-conditioning with a shortage of around 10,500 skilled workers). The workforce is expected to decline by about 10% by 2035; thereby aggravating the situation [36]. In order to fully transfer existing buildings in Germany over the next 25 years towards climate neutrality a 4% renovation rate – as proposed by the Wuppertal Institute [37] – is needed. This in turn entails the need for around one million additional employees.

Furthermore, a shortage of materials in 2021 particularly affected steel and wood, but also synthetic insulation materials, sewage pipes as well as other plastic components which led to enormous price increases in building materials in 2021 [38].

Using the example of maintaining residential buildings [39], data from the Federal Statistical Office shows that the prices of building materials and services have increased disproportionately in comparison to the usual inflation rate of 2% per annum. Since the beginning of 2021, this development has further intensified. In August 2021, the price of constructing conventional new residential buildings in Germany was shown to have risen by 12.6% within one year. Compared to a previous year since November 1970 (13.1% increase compared to November 1969), this is highest increase in building costs [40].

Considering the current shortage of human and material resources, cost-effective GHG measures for emissions optimisation, with low costs per avoided metric tonne GHG emission, such as optimising operations and decarbonising the energy supply must be promoted and implemented.

In order to not only counteract personnel and material shortages but also to take the GHG emissions associated with producing building materials into account, building materials should be used more efficiently in general. Urban mining can help to put durable building materials back into the circular economy. According to the German Environment Agency (Umweltbundesamt) [41], around 55% of the anthropogenic materials are tied up in structural engineering alone. To a large extent, these are minerals but also metals, which generate large amounts of GHG emissions during production. A sustainable circular economy could be ensured through integral planning using the urban mining approach or the cradle-to-cradle principle. In order to increase the current energy-related renovation rate in a realistic manner despite all the current obstacles, the following measures will be needed:

1. Vocational training and further education initiatives
2. Qualified immigration
3. Creation and use of innovative construction methods (such as serial renovation)
4. Increase in building technology efficiency through standardisation and system solutions.
5. Development of additional resources

Achieve transparency by digitalisation using the smart readiness indicator (SRI)

Digitalising the recording of heat and electricity consumption in form of digital and remote measurement and data technology already is technically feasible and should be introduced across the board significantly earlier than provided for in the existing regulations. The European Energy Efficiency Directive (EED) prescribes remotely readable metering systems (smart meters) for buildings' heat supply. For electricity meters, the German Metering Point Operation Act (MsbG) goes hand in hand with an obligation to convert to digital meters (according to the MsbG: "meters which reflect the actual electricity consumption and actual utilisation period and can be integrated into a communication network *via* a smart meter gateway). Smart meters are only prescribed under certain conditions. The planned introduction of digital measurement technology alone does not generate any added value for property owners or users. In the future, only smart meters in combination with intelligent communication units and the associated possibilities of providing a live display of consumption and GHG emissions should be used. This way, actions and their effects will become tangible for users. To create an awareness of consumption and GHG emissions and encourage energy savings, comparative figures should also be displayed.

Beyond digital metering, the general digitalisation of buildings also offers a huge savings potential. The Smart Readiness Indicator (SRI) is recommended as an option in the Energy Performance of Buildings Directive to benchmark the digitalisation potential of buildings. This offers possibilities to evaluate buildings' intelligence capabilities. European benchmarks are possible using a standardised assessment method. By increasing a building's SRI, in Germany (Western Europe) the estimated savings potential of thermal energy can be quantified up to 60% and electrical energy up to 16% depending on the type of building and the underlying SRI value [42]. Introduction of the European SRI should be reviewed within the framework of revising the Buildings Energy Act.

Set up a transparent national database of buildings

In comparison to other EU Member States, when registering Energy Performance Certificates (EPCs), Germany does not collect any information beyond simple building-related data (name and address of issuer, federal state, zip code of location of building, date of issue, type of energy performance certificate, consumption/requirements, type of building - residential building/non-residential building, new or existing building). Data that can be used for the climate-relevant assessment of buildings, such as specific energy demands and GHG emissions, are not stored in the centrally maintained database at the Deutsches Institut für Bautechnik (DIBt). On the other hand, other EU Member States collect this climate-relevant and other data [43]. This is compounded by the fact that rudimentary data from the central database is not accessible to the general public in Germany.

The need for a proper and transparent database is illustrated by the fact that the Federal Government's long-term renovation strategy [44] is based on data from random checking of the EPC data containing less than 200,000 datasets taken between 2014 and 2018 [45]. This reflects less than 1% of the building stock in Germany. From a statistical point of view, this is not sufficient to make valid statements about the entire building stock.

Furthermore, tailored renovation roadmaps could be integrated in the database to create a transparent view on to expected developments of GHG emissions in the building sector. It is conceivable in the future to include building materials in this national database of buildings as a reliable data source for urban mining. Enormous stocks of materials are accumulated in buildings over decades, which hold great potential as a future source of secondary raw materials.

Setting up such a comprehensive national database of buildings would enable stakeholders not only to reliably evaluate the existing building stock, but also monitor the effects of achieved climate protection measures in the building sector.

Discussion and conclusion

Like all sectors, the German building sector itself and all its interdependencies to other sectors, must rapidly reduce greenhouse gas emissions in order to counteract the changing climate. After reviewing German and international approaches and strategies in literature which aim to transform the building sector towards climate neutrality, it can be concluded that embodied emissions and operational emissions caused by buildings, are rarely considered under a holistic point of view while taking into account the remaining GHG emissions budget for the 1.5 °C target. There is no approach abstracting specific budgets at the individual building level and attempting to publish appropriate budget targets that stakeholders of the building sector can align effective measures to. Beyond this, the requirement of material and personnel resources for necessary actions and measures must also be worked out extensively.

This paper aims to submit a holistic framework with measures and recommendations for the transformation of the German building sector towards climate neutrality with regard to the identified gaps i.e. to the remaining GHG emissions budget for the 1.5 °C target as well as necessary material and personnel resources. For this purpose, section "Materials and methods" presents a list of eleven recommendations for action in the German building sector. Domain expert knowledge, an extensive investigation of the legal framework and the funding landscape applicable in Germany, as well as consideration of available resources complemented the literature review's foundation and led to the holistic framework presented.

To halt the progress of global warming at the maximum temperature of 1.5 °C specified by the Paris Agreement, it is necessary not to limit the German building sector and other sectors to an emission target for the year 2045. Instead, all the GHG emissions generated up to that date shall be taken into account. Given the melting GHG emissions budget, only measures which can be quickly realised and whose effects act immediately regarding the available material and human resources, will help to reach the climate protection goals. A sustainable circular economy and new building techniques will function as the key to transformation as they increase the potential of resource conservation. Also, detailed numbers about the costs, including assumptions on inflation, material and personnel provision for specific measures (e.g. increase in photovoltaics) within the necessary fast transition are to be developed and published.

There also are emissions from End-of-life for deconstruction to disposal as well as beyond life emissions for reuse and recycling. Due to today's uncertain predictive value on future emissions of these two late life cycle phases of buildings, they are not taken into account in the course of this paper. If reasonable assumptions are made, such phases could also be included in the budget consideration when evaluating buildings and related measures.

On a private level, a lack of financial resources can of course inhibit investments at the moment. Nevertheless, this paper assumes that it is not the general availability of financial resources (because they are available at the macroeconomic level and only need to be made accessible to the individual), but rather the availability of skilled workers as well as material resources which are inescapable necessary preconditions for improvements in the building sector.

The reduction of energy consumption must be cost-effective (low costs per avoided metric tonne GHG emission) and make efficient use of renewable energies. In the years to come, new construction will massively increase the consumption of resources and the associated grey GHG emissions. To achieve the climate protection targets, the focus must be on renovating existing buildings in a manner which is cost-effective and open to different technologies and measures which aim to not only reduce operational emissions but also embodied ones. This can be reached through funding programmes oriented on the GHG emissions budget and without legal prescriptions of technology or measures like the tightening towards building envelopes. Future work should also be intensified in order to obtain reliable and quantifiable statements on the necessary balance between renovation and raising demand for new residential and non-residential buildings.

It is crucial to accelerate the decarbonisation of the buildings' energy supply including electricity and heating networks. Yet, decarbonising infrastructures in general is also a commitment of the energy sector due to the increasing link to the building sector. The necessary transformation process towards climate-neutral operations also offers the possibility of a holistic consideration of economic, design and ecological criteria.

This paper focuses its measures on the potential for action on the part of owners, operators and policy-makers. The electrical user-related applications that go beyond heating, ventilation, cooling, and lighting were mainly not addressed within the developed recommendations. Owners and operators lack influence in this segment. However, these emissions could also be taken into account in the future, as they are caused in the building, and thus the building's users could also be further involved in transformation strategies. As a first step, digitalisation and making emissions-relevant data accessible to all those affected, can help to achieve this. In the future, strategies must also be developed and implemented at the individual building level, which above all do justice to the heterogeneity of the building stock and the different building types with their particularities.

Involving property owners, investors, architects, engineers, and the approving authorities as well as the users of a building is a socio-political task. The degree necessary for change, offers the opportunity to combine the increase in efficiency obtained by upgrading real estate with improving amenity value and utility. Decisive and fast action must be taken at all levels.

Notes

1. The share of the building sector in total national GHG emissions of around 40% according to the polluter pays principle was determined by the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR) [5] for the year 2014 and adopted here because there is no such detailed derivation available for later years.
2. The German Advisory Council on the Environment only considers CO_2 emissions in its report for calculations and graphics, as these represent the majority of the GHG emissions. In Germany, CO_2 emissions accounted for almost 89% of all GHG emissions in 2021 [1]. In the case of energy-related GHG emissions, the share of CO_2 was nearly 98 percent [1].

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Data availability statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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