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Shaping strategies: the impact of assumptions on building retrofit performance and decision-making

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Abstract

To reach decarbonization goals, informed decisions about effective building retrofits are necessary. However, the currently typical 'status quo' assumptions for assessing building retrofits from an environmental perspective are constraining the analysis to limited solution spaces. In the context of ongoing transformations, e.g., the decarbonization of the electricity grid, these constraints could lead to ineffective retrofit decisions. We identify and investigate the impact of five timely and relevant sets of assumptions: The allocation of photovoltaic electricity, the effect of global warming, national decarbonization strategies, choice of the analysis period, and the allocation of biogenic carbon from building materials. We establish a framework to assess, visualize and compare greenhouse gas emissions under different assumptions and boundary conditions. We apply this framework to exemplify the impact of the investigated assumptions using a typical case study building in Switzerland. The results show that the choice of assumptions significantly influences the results, allows for shifting focus, e.g., from operational towards embodied emissions, and can ultimately be used to tailor results and shape strategies. The introduced approach leads to a more comprehensive view, allowing decision-makers to make more robust retrofit decisions. For our case study, we identified four decisive factors which need to be carefully evaluated and transparently communicated when analyzing building retrofit performance: Future decarbonization scenarios, the allocation method of locally produced electricity, the allocation of biogenic carbon, and the analysis period. In particular, the analysis period and the decarbonization play a major role in prioritizing operational over embodied emissions or vice versa. We claim that in the context of the climate emergency, the full life cycle approach, typically based on a period of 50-60 years, should no longer be the only measure for retrofit decisions. Instead, a shorter analysis period in alignment with society's GHG emission reduction goals should be considered.

1 Introduction

1.1 Motivation and background

As the climate crisis worsens, it is clear that the rate of building retrofit must increase to reduce operational greenhouse gas (GHG) emissions of buildings [1]. The European Commission, for example, proposes "A Renovation Wave for Europe" intending to decarbonize and modernize the building stock with goals for 2030 and 2050 [2]. Although research shows that fossil-fuel based heating systems are the most significant contributors to operational emissions of buildings and should thus be avoided, choosing heating and cooling systems, as well as the correct prioritization of measures on the building envelope and the installation of renewable energy in retrofit processes, is an ongoing discussion [3], [4].

In the past, retrofit decision-making was mainly focused on reducing energy consumption. Today's buildings and renovation strategies are increasingly compared in terms of GHG emissions, including the operational and embodied fractions [5]. This adds additional assumptions and definitions to the analysis, which is already highly influenced by underlying assumptions and standardized input values [6], [7]. By defining assumptions and boundary conditions, analysts automatically exclude a significant fraction of the potential solution space. These assumptions, therefore, need careful evaluation.

For example, current impact factors for grid electricity are usually used in standard assessment methods for GHG emissions [8]. Also, design climate data is mainly based on historical observations [9]. Similarly, technological improvements of replaced components are not considered in standard building LCA approaches. Further methodological assumptions, such as how to consider biogenic carbon, what analysis period to consider, or how to allocate emissions of locally produced electricity are also needed.

In summary, one can say that the typically applied assumptions and calculation frameworks lead to a constrained analysis. However, to make informed, robust decisions in times of transformation, it is essential to explore decision options under different scenarios and assumptions. Therefore, an in-depth analysis of different assumptions and an understanding of their impact on building retrofit measures are required.

1.2 State of the art

A life cycle assessment (LCA) is typically carried out to assess the impact of retrofit decisions on GHG emissions to account for the embodied and operational impacts over the whole life cycle. There are three main steps when LCA is connected to building energy assessment in retrofit analysis: 1. Analysis of expected thermal and electrical energy demand. 2. Calculation of operational emissions originating from supplying the expected energy demand. 3. Calculation of embodied emissions originating from materials and constructions required for the retrofit. While some research is focused on energy simulation improvements [10], other work investigates the methods of impact assessment in depth [11], [12].

International and national standards regulate the assessment of building-related GHG emissions. EN 15804, for example, defines which life cycle stages must or can be considered and what data is required [13]. The life cycle phases are split as shown in Figure 1, stages A and C (and B4) are considered embodied emissions, and (the rest of) stage B counts as operational emissions. When looking at building retrofits, often only B6, the impact related to operational energy use, is included in the analysis [6].

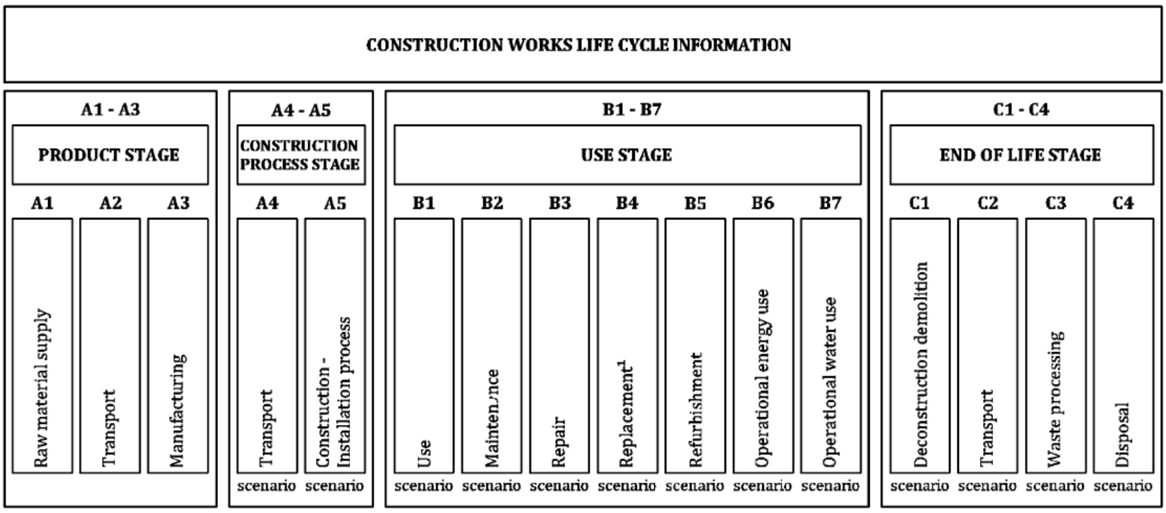

Figure 1: Life cycle stages according to DIN EN 15804 2020 [13]

National databases have been established to aid the assessment containing tabulated industry-representative impacts of different construction materials and energy sources, primarily focused on GHG emissions [14], [15]. Also, the building energy consumption calculation is usually specified in national or international standards. Such norm-based approaches are simple to be applied by a large group of users and make results comparable. However, they are based on typical circumstances and averaged inputs. They, therefore, do not necessarily capture a specific building especially well.

In research articles, we often see that analyses deliberately and rightly deviate from the norms to assess the impact of specific assumptions. Nonetheless, even in the scientific literature related to retrofit decision-making, we observed that the underlying assumptions in the GHG emission calculation are often not discussed in detail.

In the following, we outline boundary conditions and assumptions that are discussed and considered relevant in building life cycle assessment research and are thus relevant for making robust building retrofit decisions.

1.2.1 Climate change scenarios

The effect of climate change on heating and cooling demand and related GHG emissions is highly relevant and assessed in several studies. Robert and Kummert, already a decade ago, claimed that future-oriented weather data needs to be used when designing low-energy buildings to ensure a robust energy performance [9]. For example, it was shown that temperate climates are likely to experience an increase in cooling demand and related cooling energy consumption while the heating energy demand will significantly decrease

[16]. For the European residential building stock, Yang et al. expect that peak loads will be affected and that thermal comfort will decrease for southern Europe [17].

In the context of LCA-informed retrofit decisions, Galimshina et al. perform an LCA of a building retrofit decision under uncertainty using different climate scenarios [18]. They claim that more pronounced global warming leads to higher mean emissions and higher uncertainty. According to their results, using the current climate for the analysis underestimates the life cycle impact. Also, Roux et al. propose to include climate change in building LCA [19]. They conclude that changing climate assumptions can highly influence the analysis outcome.

In most literature related to building energy and emissions, weather files with future projections are taken from respective data providers, not going into detail about how they were created. Those future weather files are based on climate scenarios and projection periods. Older literature refers to the IPCC *Special Report Emission Scenarios* (SRES) [20], and newer publications refer to the *Representative Concentration Pathways* (RCP) projections [21]. Typical projection points are the beginning of each decade up to 2100. Further studies where future climate scenarios are applied to the building energy context can be found in [17], where Yang et al. summarize studies based on the climate scenarios and building context.

1.2.2 Building lifetime / analysis period

Multiple studies investigate the statistical distribution of building components' lifetime. For example, Lasvaux et al. statistically analyzed building components' empirical and literature-based service life assumptions [22]. Despite the high variation, they found that median values are generally close to data given in standards. Goulouti et al. investigate the replacement rate with probabilistic distributions [23]. The building elements they found most influential on LCA uncertainty were facades, windows, flooring, wall coverings, and ceiling coverings. Also, the work by Pannier et al. identifies the building lifetime to be a highly sensitive parameter for building LCA results [24].

Typically in LCA, the expected product lifetime is assumed as the analysis period (temporal system boundary). For buildings, it is often given in national standards. Frischknecht et al. compare different values chosen in different national standards [6]. They find typical values to be 50 or 60 years. However, considering the climate crisis, which requires fast decarbonization, the entire life cycle of a building may not be the appropriate time scale for analysis. The IPCC special report chapter "Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development", for example, states that it is critical to reach peak emissions and a high degree of decarbonization before 2030 and to completely decarbonize over the following decades, achieving net-zero by 2050 [25]. Further, Röck et al. conclude in their analysis that considering expected GHG emission reduction of energy carriers and replacement materials makes the embodied emissions of the initial construction the most important source of GHG emissions in a building's life cycle [5].

So, when considering embodied emissions, the combination of lifetime assumption and analysis period becomes essential. Especially the choice of analysis period because it reflects the weighting of embodied and operational emissions.

1.2.3 Electricity grid decarbonization and PV electricity exports

With increasing global efforts to turn away from fossil fuels, electricity grid decarbonization is en route in most countries. Electricity for building operation results in indirect carbon emissions. Therefore, the decarbonization of the electricity grid has been identified as an influential parameter regarding building life cycle emissions.

In a previous study, we demonstrate that the assumption on grid decarbonization can impact the performance robustness of building system choices [26]. Further, Pannier et al. identify the grid carbon factor as one of the most sensitive parameters of building LCA with a future-oriented view [24]. Similarly, Roux et al. stress the importance of the grid carbon intensity and compare calculation with a marginal grid mix to an average mix [19]. They conclude that these methodological approaches highly influence the outcome of a building life cycle assessment. Also, the time resolution of grid carbon intensity data can affect the life cycle performance results since the grid intensity can vary with seasonality [27].

In the analysis of a low-energy, all-electric building, Asdrubali et al. propose a dynamic LCA methodology for grid carbon intensity and show that the fraction of embodied emissions gains importance when decarbonization over the life span is considered [28]. At the same time, they raise the issue that different approaches on allocating the emissions of locally produced electricity exported to the grid are highly sensitive.

Independent of the approach used, the future decarbonization rate is highly uncertain since it depends on many boundary conditions. However, political targets can be used for orientation, such as the goals defined by the European Union [29].

1.2.4 Biogenic carbon

Biogenic carbon is carbon stored in biomaterials, absorbed from the atmosphere during plant growth. There is no general agreement on how to allocate biogenic carbon over the different life cycle stages. Hoxha et al. compare three biogenic carbon accounting methods: they distinguish between the 0/0 approach where biogenic carbon is not accounted for, the -1/+1 approach, where biogenic carbon is accounted for negatively in production and positively in the disposal, and the dynamic approach based on a more detailed analysis [30]. They point out that workflows using the -1/+1 approach and only considering certain life cycle stages can end up with net negative impact, which could potentially misinform decision-makers.

Further analysis of low-energy buildings with a focus on biogenic carbon is carried out by Fouquet et al. [31]. They conclude that the end of life strategy is crucial when assessing timber structures.

1.2.5 Occupant behavior and preferences

Occupancy schedules and occupant preferences are highly researched topics in the building systems simulation and controls domain [32]. It is also widely evident that occupancy preferences and behavior can influence building energy demand [33]. Energy-intensive occupant behavior, for example, can reduce energy savings from a building retrofit [34]. Since assumptions on occupant behavior and preferences influence building energy performance, they also directly impact the environmental performance and thus are relevant parameters of building life cycle analysis. Rodrigues and Freire show that occupant preferences, particularly heating set-points, are sensitive parameters for an LCA analysis of a residential building [35]. Also, Pannier et al. show an impact of temperature and ventilation set-points [24] on the life cycle performance.

1.3 Hypothesis, research questions, and objectives

In the context of increasing the retrofit rate based on well-informed retrofit decisions, and at the same time expecting changes in terms of climate and energy infrastructure over the anticipated building lifetime, an analysis comparing the effect of assumptions and boundary conditions on retrofit decision-making is highly relevant. However, we identify a lack of studies that systematically investigate the impact of such assumptions with a future-oriented point of view. We define the term 'future-oriented assumption' as a combination of assuming global warming and decarbonization taking place throughout the building's lifetime. If we want to make a robust decision, meaning to take better decisions under deep uncertainty, we should consider what we currently know and investigate future pathways to anticipate uncertainty and expected developments.

We hypothesize that the current practice of using static models and data mainly representing the status quo for building retrofit decision-making introduces bias and does not represent the entire solution space with respect to the ongoing transformation. At the same time, we suggest that potential retrofit solutions should always be investigated under different scenarios and assumptions for robust decision-making. Within this work, we address the following research questions:

1. How does the choice of assumptions influence the calculated performance and the choice of retrofit options?
2. How do future-oriented assumptions regarding global warming and energy decarbonization affect retrofit choices?

We focus on four main assumption categories and boundary conditions in this work: 1. The allocation of photovoltaics (PV) and electric power exported to the grid, 2. Climate change scenarios and decarbonization pathways, 3. Different analysis periods, and 4. the allocation of biogenic carbon. From the literature, we identified these 4 points as relevant and expect them to have the most impact on decision-making.

2 Method

To demonstrate the impact of different assumptions, we use a case study of a typical single-family house in Switzerland where a set of retrofit strategies is compared. We analyze and compare these strategies using operational and embodied GHG emissions calculated with standard values. In a second step, we systematically vary assumptions and boundary conditions and assess their effect on the choice of building retrofit measure.

2.1 Case study description

The single-family house is located in Zurich, Switzerland. Average thermal properties of the pre-retrofit state are derived from a statistical analysis of the Swiss building stock [36] and according to standard values given in SIA380-1 [37]. They are listed in Table 1.

Table 1: Average thermal properties of the pre-retrofit state of a typical existing single-family house in Zurich, Switzerland.

Parameter		Parameter	
Energy reference area (ERA)	250m^2	U-Value roof	0.6 W/m^{2}K
Wall areas	138m^2	U-value window	2.0 W/m^{2}K
Roof area	56m^2	U-value to ground	0.7 W/m^{2}K
Total window area	4x 10m^2	Window g-value	0.5
Footprint area	56m^2	Mechanical ventilation	No
Area per person	60m^2/P	Installed heat emission system	Radiators
Thermal mass per ERA	0.15 kWh/m^{2}K	PV	No
U-value wall	0.9 W/m^{2}K	Cooling	No

The assessed retrofit strategies include typical measures currently applied in the Swiss context and are investigated in all combinations. The single measures are listed and described in Table 2. The choices of added insulation are based on typical values in Switzerland and represent the insulation material thickness added to the envelope cross-section [38]. For this investigation, we distinguish between cellulose or mineral wool-based insulation material. In terms of windows, the decision is either keeping the existing windows or replacing them with new, state-of-the-art products, i.e., a triple-glazed window. Technical parameters of the envelope materials are tabulated in Appendix A.

For the replacement of the heating system, the following options are considered: natural gas burner, wood pellet heating, air source heat pump (ASHP), ground source heat pump (GSHP), or pure electric heating. If cooling is required, split units are assumed to be installed when combustion-based systems or pure electric heating is chosen. For PV, the analysis is limited to choosing full roof coverage or no PV at all. Performance parameters of the system choices are also listed in Appendix A.

Table 2: Typical retrofit measures for single-family houses in Switzerland, separated by envelope measures and system choices

	Parameter	Choices investigated
Envelope measures	Additional wall insulation	0, 0.21m
	Additional roof insulation	0, 0.26m
	Additional insulation to ground	0, 0.19m
	Insulation material choice	Cellulose/Mineral wool
	Window replacement	Yes/No
System Choices	Heating system	Natural Gas, Pellets, ASHP, GSHP, pure electric
	PV	Yes/No

2.2 Performance simulation

The performance evaluation of each retrofit option includes an energy demand simulation for heating and cooling energy, domestic hot water use, and further electricity consumption to assess the operational GHG emissions connected to energy use. Further, the material-related embodied emissions of the retrofit measure are assessed. The simulation workflow is presented in Figure 2 and has been previously described in detail in [26].

In the first step, we calculate energy demand using standard values from SIA2024 [39] and SIA380-1 [37] as inputs. Heating and cooling energy demand are simulated according to SIA380-1 [37] and to EN ISO 52016-1 2017 [40], respectively. We model the combustion-based systems with conversion efficiencies and the heat pump systems with dynamic COPs. Electric heating is considered with a conversion efficiency of 1 as all the electric energy ultimately converts into thermal energy. Solar irradiance on the PV array is simulated with the PV lib package [41], and PV yield is derived from the irradiance value with an efficiency term and a performance ratio factor. Due to the monthly approach, the self-consumption ratio is calculated with a surrogate method (for further details, see [26]).

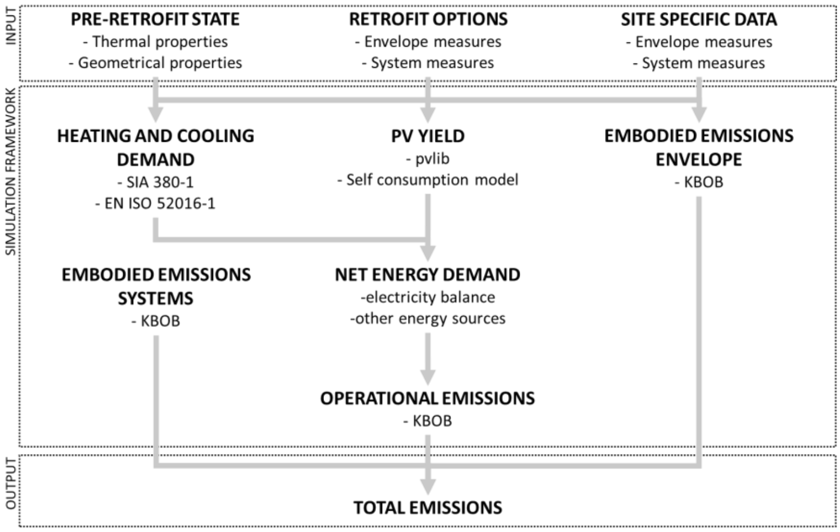

Figure 2: Overview of the simulation framework. The input data on the building's pre-retrofit state, the retrofit options, and site-specific data are processed through several models for the final calculation of total GHG emissions.

In the second step, GHG emissions are calculated as the sum of operational and embodied emissions from building systems and envelope materials. Only materials related to the retrofit measures are considered. For the base case, emissions are calculated according to Eq. 1 and Eq. 2.

$$I_{operational} = \sum_{source} \sum_{year} E_{source,year} \times f_{source} \times f_{decarb,year} \quad \text{Eq. 1}$$

Where $I_{operational}$ is the operational emissions in $kgCO_2eq$, $E_{source,year}$ the annual energy demand per energy source in kWh/a, f_{source} the respective energy source's GHG intensity in $kgCO_2eq/kWh$, $f_{decarb,avg}$ the decarbonization factor for the given year.

$$I_{embodied} = \sum_{material} \sum_{year} C_{material,year} \times f_{material} \times f_{decarb,year} \quad \text{Eq. 2}$$

Where $I_{embodied}$ is the embodied impact in $kgCO_2eq$, $C_{material,year}$ the material quantity (e.g., m2, kg, etc.) installed or disposed in the given year, $f_{material}$ the GHG emission intensity per material quantity for production and disposal in kgCO2eq/unit, and $f_{decarb,year}$ the decarbonization factor for the given year. Eqs. 1 and 2 may change depending on the assumption as described in the following sections.

2.3 Assumptions

The performance simulation presented in Section 2.2 is repeated using a set of different assumptions and boundary conditions to assess their effect on total GHG emissions.

2.3.1 PV allocation

We assume that unused on-site gererated PV electricity is exported to the grid. Local storage options are not considered. Additional electricity demands are covered through electricity imports from the grid. Different approaches to allocating embodied and operational emissions of PV installations and electricity exports to the grid are investigated. In this work, we consider the following three:

Grid displacement

PV electricity exported to the grid is assumed to replace electricity being supplied to the grid elsewhere. These 'potentially avoided emissions' are accounted as negative operational emissions. Consequently, Eq. 1 is extended with an export term, as shown in Eq. 3. Embodied emissions of the PV installation are fully allocated to the building, i.e., Eq. 2 remains unchanged.

$$I_{operational} = \sum_{source} \sum_{year} E_{source,year} \times f_{source} \times f_{decarb,year} - E_{export,year} \times f_{export} \times f_{decarb,year} \quad \text{Eq. 3}$$

Where, $E_{export,year}$ is the energy amount exported from local production in kWh/a, and f_{export} the GHG intensity of the grid exported to in CO2eq/kWh (here $f_{source} = f_{export}$)

Pro-rata

The underlying assumption of this approach is that PV-related emissions are allocated on a pro-rata share [42]. I.e., only the fraction of the embodied emissions proportional to the self-consumption ratio is allocated to the building while the rest is attributed to the electricity exports. For PV, the material emission factor in Eq. 2, $f_{material}$, is redefined as shown in Eq. 4.

$$f_{PV,effective} = f_{PV} \times SC \quad \text{Eq. 4}$$

Where $f_{PV,effective}$ is the GHG emissions per material quantity of PV allocated to the building, f_{PV} is the GHG emissions per material quantity of from the database, and SC the annual self-consumption ratio of the produced PV electricity. For the operational emissions, Eq. 1 is used without changes.

Fully allocated to the building

Here, the assumption is that embodied emissions of PV installations are fully allocated to the building. Self-consumed electricity generated by PV is emission-free, but exporting electricity to the grid does not reduce the operational emissions of the building. Eq. 1 and Eq. 2 are used without any change.

2.3.2 Future-oriented assumptions

Grid and material decarbonization

The decarbonization of energy and materials is key to reaching the goals set out by the Paris agreement [43]. Multiple decarbonization goals exist, but pathways are highly uncertain because they depend on political decisions and socio-economic development. We use a simplified approach in which we assess two different assumptions. For the first scenario, we calculated the results based on current emission factors of the electricity grid and construction materials given in the KBOB database [15]. For the second scenario, we assumed linear decarbonization over the first 30 years of the building life according to EU goals for the power sector to a remaining four g-CO2eq/kWh by 2050 [44]. When considering decarbonization, operational and embodied emissions are for each year in which they occur, with the respective decarbonization factor weighted as shown in Eq. 1 and Eq. 2. The decarbonization factor for each year is calculated according to Eq. 5

$$f_{decarb,year} = f_{target} + \frac{\left(f_{start} - f_{target}\right) \times t_{year}}{t_{target} - t_{start}} \qquad \textit{Eq. 5}$$

Where f_{target} is the impact factor after the decarbonization has happened in $kgCO_2eq$/unit, f_{start} the current impact factor in $kgCO_2eq$/unit as tabulated, t_{year} the year for which the decarbonized impact factor is calculated, t_{target} the target year for the full decarbonization (here 2050), and t_{start} the current year or the starting point of the decarbonization process (here 2021).

Global warming

We rely on current and projected future weather data for climate change by meteonorm [45]. They provide EnergyPlus (EPW) weather files following the different IPCC scenarios [46]. We use the current weather file and the RCP8.5 projection for 2050 as simulation inputs for this analysis. For simplicity, we do not interpolate data for the years in between, but we use either the current or projected data.

2.3.3 Analysis period

The analysis period is another necessary choice in the impact assessment of a building retrofit decision. Generally, the uncertainty on operation, replacement, and disposal increases with longer analysis periods.

This is particularly true in transformative times. We, therefore, examine three different time spans: 60 years as it is often used in standards, 30 years because this is approximately the time that we have left until we should have decarbonized entirely according to the IPCC 1.5°C goal [25] and EU targets [47], and 20 years because this is the typical lifetime of building system components and thus of the decision cycle. Figure 3 qualitatively visualizes GHG emissions with uncertainty over time for the three chosen analysis periods.

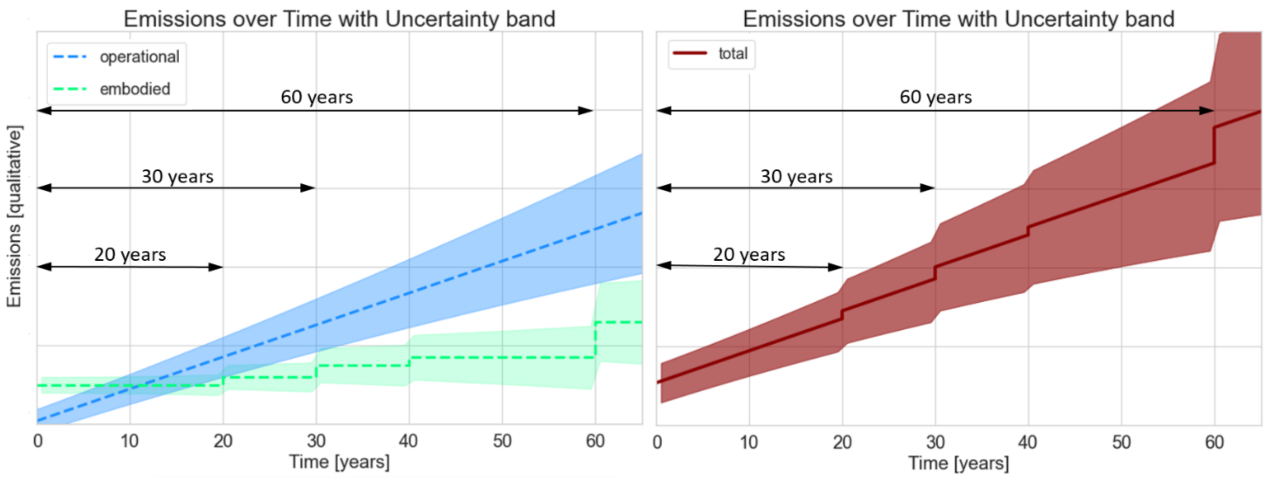

Figure 3: Qualitative growth of cumulative emissions over time with increasing uncertainty. Only materials related to the retrofit are considered. L: total emissions, R: embodied and operational emissions. The shorter the analysis period, the higher the fraction of embodied emissions.

60 years

Sixty years is the assumed lifetime of insulation materials, the longest-living component of the considered retrofit measures. For calculating embodied GHG emissions, emissions due to replacement and disposal of all components are considered. Therefore, this analysis period is the closest to a typical life cycle approach. However, it also comes with the biggest inherent uncertainty, as emissions due to replacement and disposal are heavily influenced by future developments and challenging to predict.

30 years

Assuming that energy and materials will be maximally decarbonized within 30 years, additional energy and material-related emissions can be considered free of emissions after 2050. Consequently, no replacement, disposal, and energy use emissions will occur after 30 years. For calculating embodied emissions, emissions due to replacement and disposal are only considered for components with a lifetime of less than or equal to 30 years.

20 years

20 years is the timespan where the system configuration remains unchanged. After 20 years, the first components, such as heating and cooling systems, will reach the end of their nominal service life. Typically a new decision will be made to either prolong the components' life or dispose of and replace it. For calculating

embodied emissions, emissions due to replacement and disposal are only considered for components with a lifetime of less than or equal to 20 years.

2.3.4 Biogenic carbon

As described in Section 1.2, there are three main approaches for allocating biogenic carbon; the 0/0, the -1/+1, and the dynamic. While the 0/0 and the -1/+1 approaches lead to the same results when the whole life cycle is assessed (i.e., including all replacements and disposal), this changes when the analysis period is shorter than the assumed lifetime. Taking a -1/+1 approach and combining it with an analysis period shorter than the component lifetime leads to a -1 approach. Nonetheless, it can be argued that it is not yet clear how biogenic materials will be disposed of in the future but that it will likely be connected to carbon capture and storage technologies, which justifies this approach. Since the KBOB database uses the 0/0 approach, for the -1/+1 values, we rely on data based on environmental product declarations collected by Ökobaudat [14], where negative biogenic carbon is accounted for in the production (life cycle stage A).

3 Results

We use nested heat maps to visualize the results, as presented in Figure 4. We chose nested heat maps because they are well-suited to identify patterns and visualize multiple parameters in two dimensions. For example, in Figure 4, the retrofit combination of cellulose insulation with window replacement, an air source heat pump, and PV is marked with a green rectangle. The performance in terms of GHG emissions is indicated using a color scale, which is adapted for the different figures. The darker the color, the higher the respective CO2 emissions and the less desirable the retrofit combination. For simplicity and readability of the graph, we only show and discuss selected results. We do not show all combinations of opaque envelope insulation. Either all insulation measures or none is applied (see Table 2). Further, we present results that do not include cooling demand because it appeared irrelevant for the assessed case study. More detailed results looking at insulation combinations in detail and including cooling are shown in Appendix B.

The assumptions behind Figure 4 are closest to current Swiss standards, considering a 60 years timespan including emissions due to replacement and disposal, allowing negative emissions when exporting PV electricity to the grid (grid displacement) but not considering future-oriented assumptions, i.e., potential impacts due to decarbonization and climate change. As expected, configurations with natural gas heating clearly lead to the highest GHG emissions. All retrofit measures, including a natural gas heating system, perform comparatively poorly in GHG emissions for all investigated assumptions (See Appendix B). Natural gas is therefore excluded from further analyses. With the current assumptions, pure electric heating can result in moderate emissions with a retrofitted envelope (wall insulation and window replacement). The heat pump-based configurations tend to have low GHG emissions, particularly when combined with an envelope retrofit. The installation of PV generally reduces overall emissions as a consequence of the negative emission accounting. Differences between the choice of insulation (mineral wool or cellulose) and benefits from window replacement are marginal for the investigated case study.

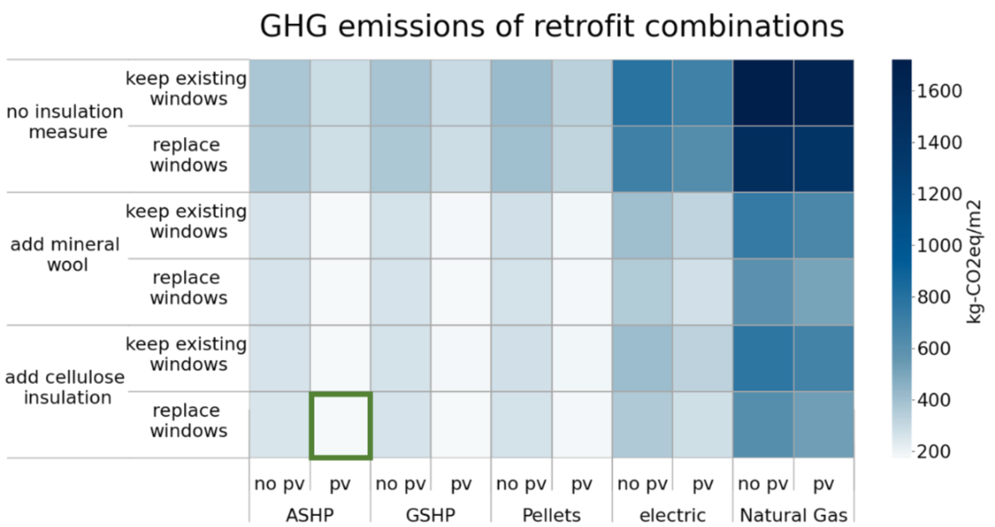

Figure 4: Cumulative emissions of the retrofit decision summed up over 60 years with the grid displacement approach for PV electricity and no future-oriented assumptions on decarbonization and climate change.

3.1 Effect of PV electricity allocation

The PV electricity allocation methods described in Section 2.3.1 can significantly impact the overall GHG emissions. Figure 5 shows a comparison of the three PV electricity allocation approaches. The remaining assumptions are identical to those presented in Figure 4, a 60-year analysis period, and no future-oriented assumptions. For the investigated case study and overall GHG emissions, the installation of PV is favored when allocating negative operational emissions to grid exports or using the pro-rata approach according to the self-consumption ratio. Allocating all emissions to the building leads to the preference of no PV. We consider the pro-rata approach the most suitable since it allocates the embodied emissions to the actual energy consumption and reduces the risk of double accounting [42]. Therefore, we use the pro-rata approach for allocating PV emissions in the following sections.

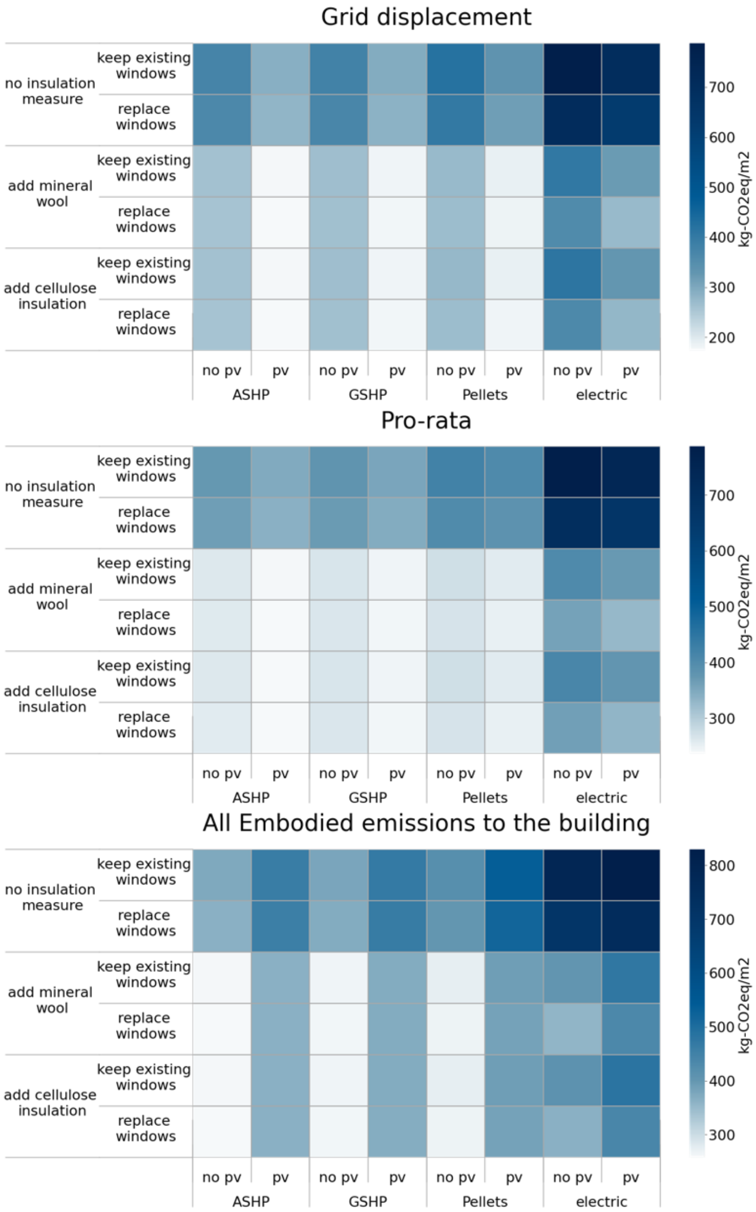

Figure 5: Calculated GHG emissions of retrofit combinations for different PV allocation methods. The GHG performance of the PV installations is highly dependent on these assumptions. Other assumptions are kept constant: 60-year analysis period, no future-oriented assumptions.

3.2 Effect of future-oriented assumptions

Two significant changes can be expected within the lifetime of a currently built or renovated building: 1. Rising outdoor temperatures and 2. decarbonization of energy sources and materials. The effects of grid decarbonization, global warming, and the combination are shown in Figure 6 for a 60 years analysis period and pro-rata PV allocation. The most evident change can be observed in the color bar legend, indicating the range of calculated GHG emissions. Using the linear decarbonization assumption reduces the emissions to less than half compared to the results with current carbon intensities. In comparison, the effect of global warming is less significant. Overall a slight reduction in GHG emissions is observed due to lower heating demands. The effect of including global warming also did not significantly change when cooling was included in the assessment (see Appendix B).

Next to the changes in absolute values, a change in the pattern can be observed for the decarbonization assumption. On the one hand, the installation of PV no longer seems to be preferred when the grid is decarbonizing. On the other hand, replacing the windows switches from slightly advantageous to clearly unpreferred. Both PV and windows are responsible for a comparatively large fraction of the embodied emissions. Assuming decarbonization, the operational benefits decrease and can no longer outperform the added embodied emissions. In contrast, adding insulation always lowers GHG emissions regardless of the investigated assumption combinations. This indicates that mineral wool or cellulose insulation gets more out of its carbon investment than the windows. Compared to windows, the investigated insulation materials have substantially lower embodied emissions and more considerable leverage on reducing operational energy emissions. We expect this to change with a higher window to wall ratio or high-emission insulation materials such as PUR and PIR insulation.

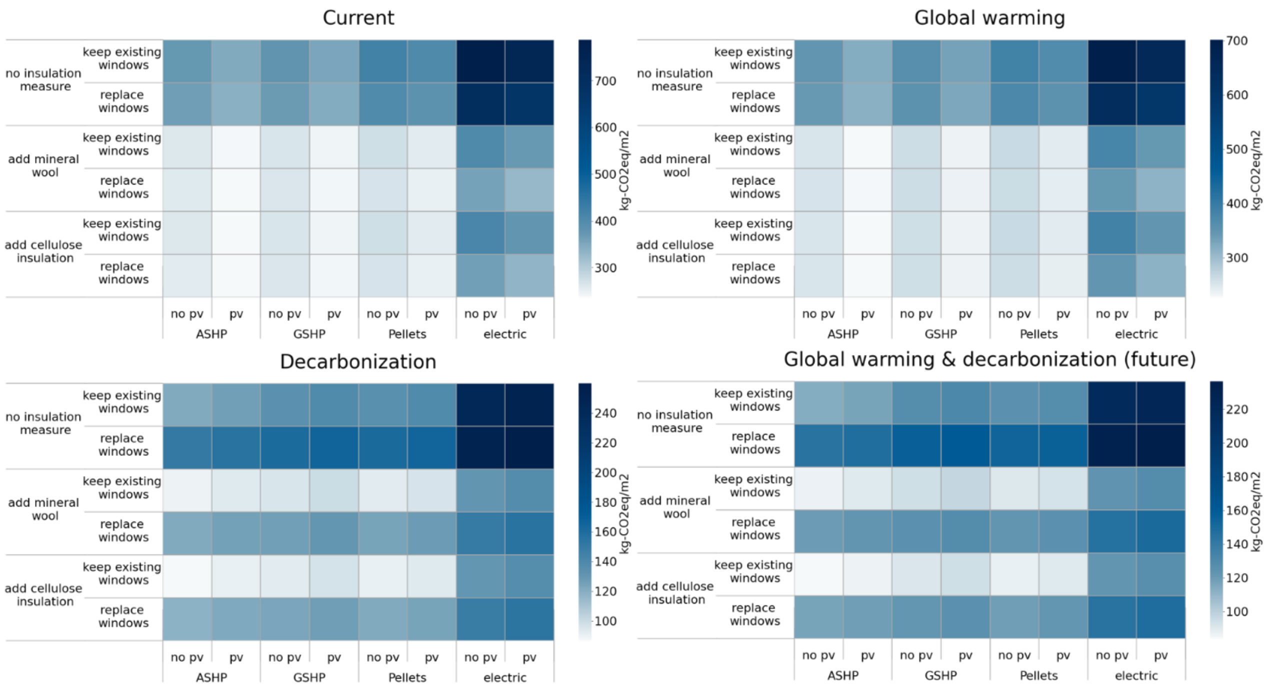

Figure 6: Calculated GHG emissions of retrofit combinations for different assumptions on future developments in terms of decarbonization, global warming, and the combined effect. Decarbonization has a significant impact, while global warming does not strongly impact the presented case study. Other assumptions are kept constant: 60-year analysis period, pro-rata PV allocation.

3.3 Effect of the analysis period

Figure 7 shows the analysis periods of 60, 30, and 20 years with non-future-oriented assumptions. Similar to the decarbonization assumption, with a shorter analysis period, PV becomes slightly less preferred, and keeping existing windows becomes slightly more preferred. Again, the high embodied emissions of PV and windows are difficult to offset through operational GHG emission savings, particularly if the analysis period is shorter than the components lifetime. Looking at insulation, adding a low or medium-emission-intensive insulation material such as cellulose or mineral wool is always the preferred solution, independent of the analysis period. Overall, a shorter analysis period shifts the focus from operational towards embodied emissions. Further, the preference of heating systems does not change significantly with different time horizons.

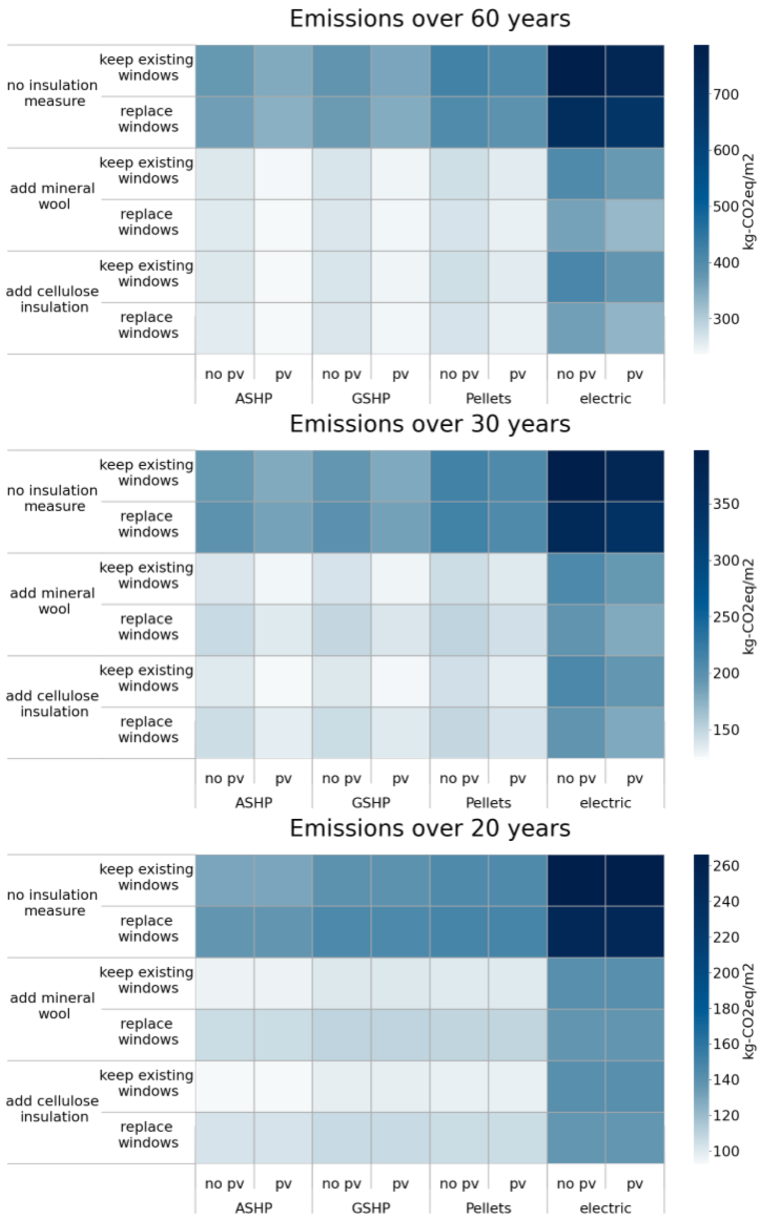

Figure 7: Calculated GHG emissions of retrofit combinations for the three different analysis periods of 60, 30, and 20 years. Other assumptions are kept constant: pro-rata PV allocation and current assumptions. A slight shift towards lower-emission materials can be observed with shorter analysis periods.

3.4 Effect of biogenic carbon accounting

The 0/0 and -1/+1 approaches for biogenic carbon as described in Section 2.3.4 result in the same GHG emissions over a 60-year analysis period because this is the assumed lifetime of the biogenic insulation material. Therefore, it is interesting to see how the results change when introducing the -1/+1 assumption at a 20 or 30 year analysis period. Figure 8 shows for a 30 year analysis period that when using the -1/+1 approach, the cellulose choice shows slightly lower GHG emissions than the mineral wool, despite its slightly lower thermal resistance. This is mainly because the disposal is not considered within the shorter analysis period, making the -1/+1 approach more favorable for biogenic materials. However, the overall effect for the presented case study is relatively small.

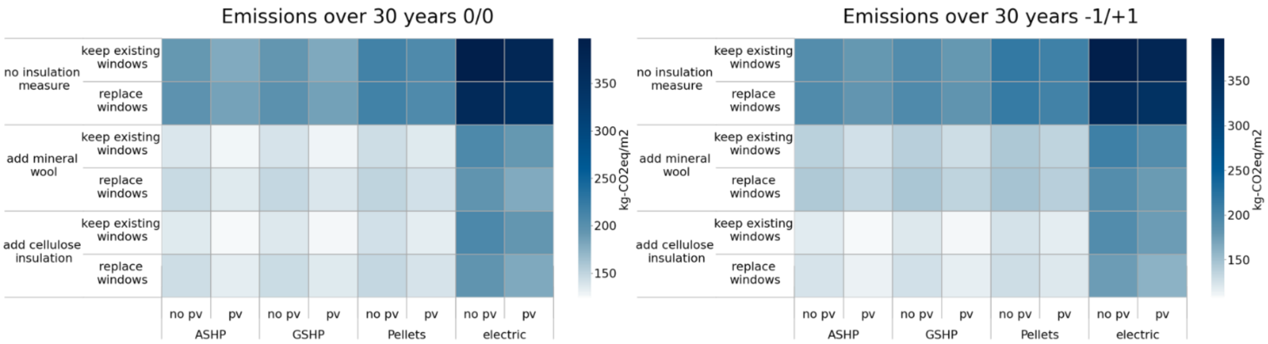

Figure 8: Calculated GHG emissions over 30 years for the 0/0 and the -1/+1 approach. Other assumptions are kept constant: pro-rata PV allocation and current assumptions. The -1/+1 approach leads to a preference for cellulose insulation over mineral wool insulation.

4 Discussion

We present an approach to study and visualize the impact of assumptions on GHG emission calculations for a building retrofit. The nested heat maps allow us to compare absolute GHG emission values. More importantly, the heat maps enable us to identify changes in patterns, e.g., switching from PV preference to no PV or from keeping windows to replacing them. Observing these pattern changes can further shed light on how assumptions can shift focus. E.g., using a shorter analysis period or assuming decarbonization will shift focus from operational towards embodied emissions and generally allow to report lower emission values. Vice versa, these findings can also be used to tailor results for decision-makers and hence be used to shape strategies. For illustration, we have selected two sets of assumptions. The first one represents the 'status quo', i.e., the assumptions are merely following the norms: an analysis period of 60 years is considered, PV electricity is awarded through the grid displacement approach, future changes in climate and decarbonization are ignored, and potential benefits of temporal biogenic carbon storage are not accounted for. The second set of assumptions is what we would call the response to 'climate emergency', i.e., focusing on the immediate impact in a highly transformational world. Here we consider an analysis period of 20 years, PV is allocated on a pro-rata basis, global warming and decarbonization are taken into account, and temporal biogenic carbon storage is enabled. The corresponding results for the 'status quo' and the 'climate emergency' assumptions are shown in Figure 9.

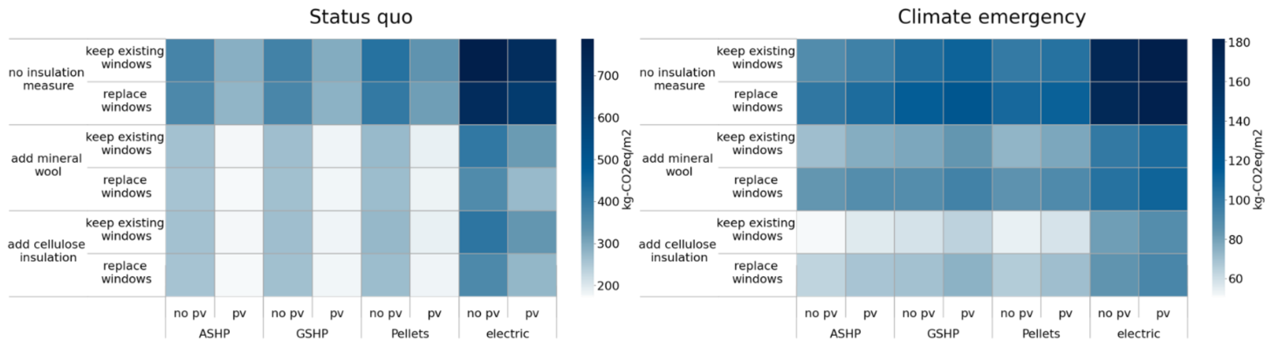

Figure 9: Calculated GHG emissions of retrofit combinations according to a status quo and a climate emergency perspective. Status quo: 60-year analysis period, grid displacement PV allocation, current assumptions on climate and decarbonization, 0/0 approach for biogenic carbon. Climate emergency: 20-year analysis period, pro-rata PV allocation, future-oriented assumptions on climate and decarbonization, -1/+1 approach for biogenic carbon.

The results demonstrate that choice of assumptions is decisive for retrofit strategy recommendations. For the given case study, we can for example, see a shift from 'pv' using 'status quo' assumptions to 'no pv' using 'climate emergency' assumptions. This highlights the need to investigate further and, if possible, reduce embodied emissions of PV. However, this has to be put into context: On the one hand, the Swiss electricity consumer mix already has a low average carbon intensity of 102 g-CO_2eq/kWh [15]. On the other hand, the analysis is based on the KBOB database of 2016, which includes relatively high embodied emissions for PV compared to more recent publications, which show a reduction of embodied emissions by half [48]. Nevertheless, it shows that the embodied emissions of PV are an important emission source that needs to be addressed. With the latest PV technologies having lower embodied emissions than the values used in this study, PV will likely become favorable under 'climate emergency' assumptions.

No significant pattern changes can be observed in the heating system choice. Heat pumps and pellet systems generally perform best, while pure electric heating performs relatively poorly under all assumption sets. Even when using future-oriented assumptions, i.e., decarbonization of the electricity grid, pure electric heating still shows higher emissions overall. Therefore, the heating system choice can be considered to be a robust choice for the given case study. While ASHP, GSHP, and Pellet perform similarly well with the 'status quo' assumptions, the advantage of the ASHP and Pellet slightly increases with the 'climate emergency' assumptions, based on a shorter analysis period and future-oriented assumptions. This is mainly due to the high embodied impact of the boreholes required for a GSHP.

The choice of not replacing the windows is pretty robust in combination with heat pumps and pellet heating over most assumptions for this case study. On the one hand, the embodied emissions of windows are quite high, requiring high operational benefits to make up for it. While window replacement could have been a good choice with fossil heating or, for some assumptions, with pure electric heating, it does not seem to pay off with the low-emission heating systems in terms of GHG emissions. On the other hand, the pre-retrofit U-value of the windows in this study is defined with 2 W/m^2K. It could be significantly higher for other cases, especially for older buildings. A higher pre-retrofit U-value could potentially increase operational GHG emission savings and make window replacement a more suitable choice.

We see that adding mineral wool or cellulose insulation is a robust choice as it shows lower GHG gas emissions compared to not insulating for almost all assumptions investigated. The difference in GHG emissions between cellulose and mineral wool insulation is relatively minor but becomes visible when choosing 'climate emergency' assumptions, i.e., a -1/+1 approach for biogenic carbon combined with an analysis period of 20 years. The thermal performance of both materials is similar, but cellulose insulation offers biogenic carbon storage, which is positively acknowledged with the 'climate emergency' assumptions. It has to be noted that mineral wool shows quite a low amount of embodied emissions compared to other insulation materials. PUR/PIR insulation, for example, one of the most used insulation materials, has roughly seven times the embodied impact of mineral wool [15] and would perform worse than 'no insulation' for cases with the climate emergency assumptions.

Overall, we can summarize for the given case study that the decarbonization assumption of the electricity grid and the PV allocation method significantly influence the results. In contrast, global warming had a relatively small influence, even when considering cooling. However, this should be put into perspective: the study investigates a residential building with a relatively low fraction of glazed façade located in the Swiss climate where heating is also dominating with global warming.

Taking one or the other assumption is not necessarily right or wrong, but it can influence the calculated GHG emissions and thus the decision-making. The findings clarify that assumptions taken in the assessment process must be communicated clearly and transparently to make the results interpretable. It also encourages considering dynamics of boundary conditions throughout the building's lifetime and including them in the analysis to increase the decision robustness.

Also, our study comes with several limitations which need discussion. We present the results based on a case study of one building in the specific context of Swiss climate. They should, therefore, not be generalized. Further assessments are required to justify more general conclusions. Nonetheless, the presented method is not case-specific and can be applied in other cases. We look at different assumptions and show how they affect the result. While previous studies did detailed analyses on particular assumptions, we use several simplifications but look at many assumptions to compare the different approaches.

The energy model is based on a monthly simulation approach. It can only limitedly represent the system's dynamics. We have, however, shown that the model can compete with an hourly assessment in terms of GHG assessment in [26].

On the subject of decarbonization, we only distinguished between 'no decarbonization' or 'linear decarbonization' within the next 30 years (net zero 2050). We also applied the same decarbonization factors to electricity and construction materials. However, the speed and the extent to which electricity and materials will be decarbonized are unclear. We argue that our approach is suitable for showing that it is a significant assumption to be looked at in the environmental assessment of retrofit decisions.

Further, to investigate the impact of climate change assumptions, we distinguish between two different RCP scenarios. We are confident that 2050 RCP8.5 is a good choice to show the potential impact climate change could have on the environmental performance of retrofit decisions, even if it did not highly affect the presented case study building.

Furthermore, the results were calculated using a Swiss LCA database. Not only is the climate different for different sites, but also LCA databases for materials and energy carriers differ regionally [49]. Especially the electricity mix plays a key role. Further analysis of the potential impact of the respective assumptions for different regional contexts would be highly interesting. Similarly, it would be interesting to include other impact categories beyond GHG emissions.

5 Conclusion and outlook

Performing an environmental assessment of a building retrofit decision requires multiple modeling and input assumptions. We go through various assumptions and show that changing them can impact a retrofit decision based on GHG emissions. The approach introduced leads to a more comprehensive view of the solution space, potentially enabling decision-makers to make more robust decisions.

The methodological approach is supported with a case study example. The results show that an approach based only on current data does not do justice to the expected future changes. In the results of this study, especially the assumption on the decarbonization of energy carriers and materials turned out to be a decisive factor. This emphasizes how vital cross-sector decarbonization is for the construction industry.

Typically, to assess building-related GHG emissions, a full life cycle assessment with an analysis period of 50-60 years is carried out. However, analysis periods shorter than the typical life cycle are also relevant. In our opinion and the context of a climate emergency, the full life cycle should no longer be the only scale for retrofit decisions. Our results show that the analysis period plays a significant role in prioritizing operational over embodied emissions or vice versa. Therefore, the choice of analysis period should be further discussed and aligned with energy and material decarbonization pathways. In particular, longer analysis periods that suffer from high uncertainties due to hypothetical replacement and disposal scenarios should be critically reviewed.

Further, in terms of reporting GHG emissions, lower emission values can be reported when future-oriented assumptions for decarbonization and global warming or shorter analysis periods are used. Therefore, when comparing reported values, it should be transparently communicated what assumptions on future changes are included. Results where assumptions are not aligned, should not be directly compared.

Ultimately, assumptions in norms and standard calculations manifest in the preference of certain retrofit measures. If poorly defined, these assumptions pose a risk to systematically choosing non-robust solutions. However, specifying the assumptions according to expected developments and society's decarbonization goals can be used as a powerful instrument for policymaking.

This study could be extended in multiple ways to create a deeper insight into assumptions and their impact on retrofit decision-making. The model could be further refined to investigate the impact of storage technologies or advanced control strategies. Additionally, the analysis should be extended to other locations and buildings, climate scenarios, and decarbonization scenarios to study the sensitivities of the assumptions under different boundary conditions. Additionally, other impact categories should be looked at. This would allow for a more comprehensive view and potentially more generalizable results.

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Appendix A Embodied Emissions and Performance Parameters of Systems and Envelope Materials

Table A. 1: Embodied impact and lifetime assumption of building systems.

System Component	reference	GHG impact total [kgCO2eq/ref]	GHG impact without disposal [kgCO2eq/ref]	lifetime	Source / Comment
Pellet heater	kW	111.3	111.3	20	UVEK Data, furnace, pellets, 50kW
ASHP	kW	363.8	232.5	20	[15]
GSHP	kW	896.5	816.2	30	(incl. borehole) [15]
electric heater	kW	51	50	20	KBOB 2016, based on spec power 30W/m2
natural gas burner	kW	38.4	37.8	20	UVEK Datensatz, gas boiler (~10kW)
split unit	kW	363.8	232.5	20	Same as ASHP for cooling
PV (m-Si)	m^2	2080.0	2080.0	30	[15]
hydronic heat distribution office	m^2	7.6	6.6	60	[15]
hydronic heat distribution residential	m^2	3.1	2.4	60	[15]
floor heating	m^2	5.1	3.0	60	[15]
radiator	m^2	5.5	5.4	60	[15]

Table A. 2: Performance data of the systems investigated.

System Component	Conversion efficiency [-]	Exergetic efficiency* [-]	Comment
Pellet heater	0.70		
ASHP	-	0.55	
GSHP	-	0.55	
electric heater	1.0		
natural gas burner	0.88		
split unit	-	0.55	Same as ASHP for cooling
PV (m-Si)	0.18		with a performance ratio of 80%

* see [26] for calculation of dynamic COP

Table A. 3: Required supply temperatures for hydronic heating and cooling.

Supply Temperature	$T_{Heating}$	$T_{Cooling}$	Source
floor heating	40	12	[50], [51]
radiator	50	-	[50], [51]

Table A. 4: Greenhouse gas impact of different energy carriers per kWh.

Energy Carriers	GHG impact [kgCO2eq/kWh]	Source
Natural Gas	0.228	[15]
Pellets	0.027	[15]
Electricity	0.102	Swiss consumer mix [15]

Table A. 5: Envelope measures and their performance parameters.

Envelope Measure	U-Value [W/m2K]	thermal conduc-tivity [W/mK]	Insulation thickness [m]	GHG impact total [kgCO2eq/m2]	disposal [kgCO2eq/m2]	«-1» impact* [kgCO2eq/m2]	Lifetime [y]	Source, Comment
new windows	0.9	-	-	122.80	16.46	-	30	from [52] 1.75x2.0m, 3 panes
Add 21cm mineral wool to wall	-	0.032	0.21	7.12	0.07	7.11	60	[14], [15]
Add 21cm cellulose insulation to wall	-	0.039	0.21	2.57	0.42	-17.77	60	[14], [15]
Add 26cm mineral wool to roof	-	0.032	0.26	8.81	0.08	8.80	60	[14], [15]
Add 26cm cellulose insulation to roof	-	0.039	0.26	3.18	0.52	-22.00	60	[14], [15]
Add 19cm mineral wool to ground	-	0.032	0.19	6.44	0.06	6.43	60	[14], [15]
Add 19cm cellulose insulation to ground	-	0.039	0.19	2.32	0.38	-16.07	60	[14], [15]

* impact with -1/+1 approach for biogenic material without disposal

Appendix B Extended results

B.1 Natural gas and future-oriented assumptions

Complementary to Figure 4, we show in Figure B. 1 that including natural gas becomes unnecessary when future-oriented assumptions are used.

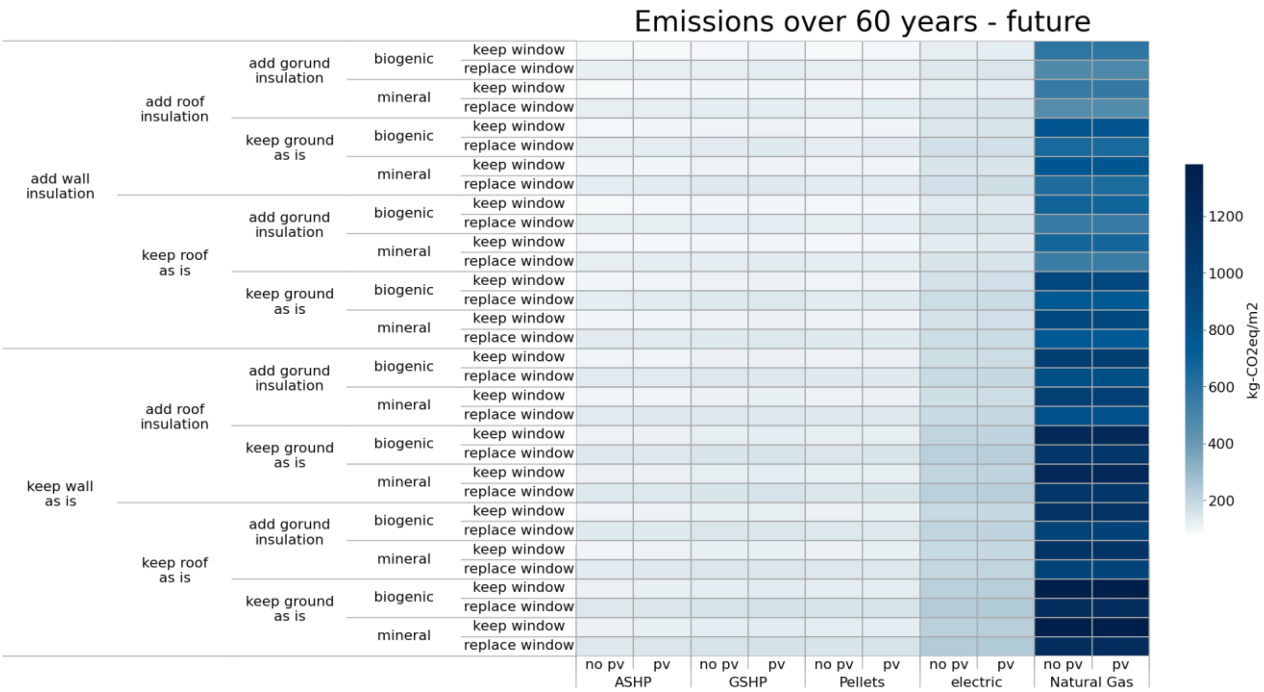

Figure B. 1: Cumulative emissions of the retrofit decision summed up over 60 years with the pro-rata approach for PV electricity and future-oriented assumptions on decarbonization and climate change. Higher-resolution for insulation measures.

B.2 More detailed steps of insulation

The results presented in Section 3 only show insulated or non-insulated combinations. Figure B. 2 and Figure B. 3 additionally show a higher resolution of the results where adding insulation to the walls, the roof, and areas exposed to the ground are shown individually. This is demonstrated for a 60-year analysis period for current and future-oriented assumptions.

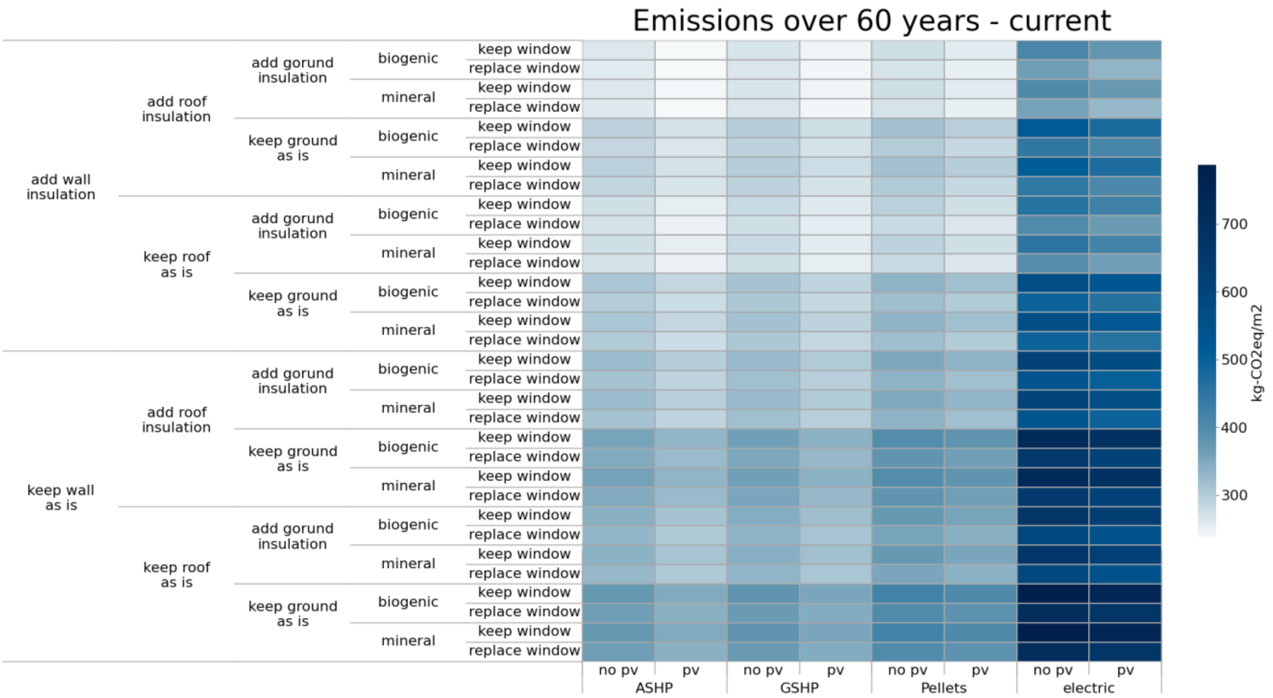

Figure B. 2: Calculated GHG emissions of retrofit combinations for 60 years under current assumptions and with pro-rata PV allocation. Higher-resolution for insulation measures.

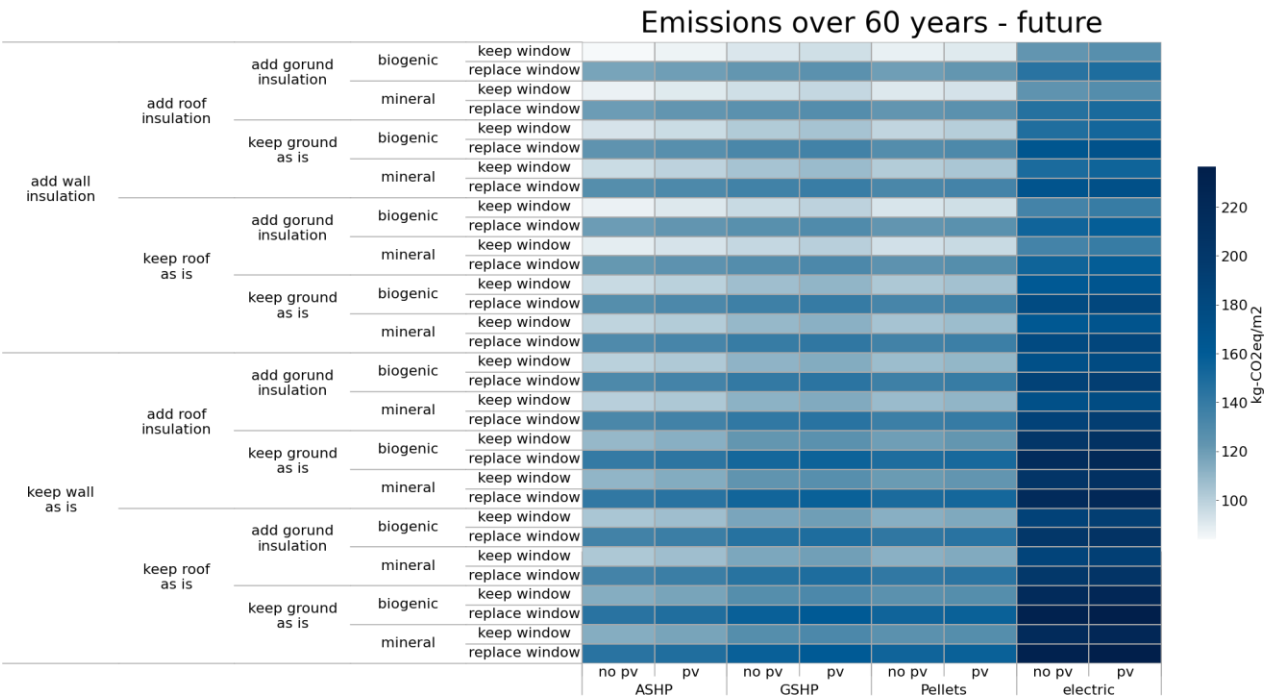

Figure B. 3: Calculated GHG emissions of retrofit combinations for 60 years under future-oriented assumptions and with pro-rata PV allocation. Higher-resolution for insulation measures.

B.3 Effect of Cooling

Figure B. 4 shows the GHG emissions of the retrofit combinations when cooling is added for current and future-oriented assumptions. The analysis is fixed at 60 years, and the pro-rata PV allocation is used. We can see that using future-oriented assumptions does not significantly change the ranking in terms of GHG emissions for the given case study. This result should not be generalized as this could look differently for buildings with larger window to wall ratios and in locations where space cooling is generally more relevant.

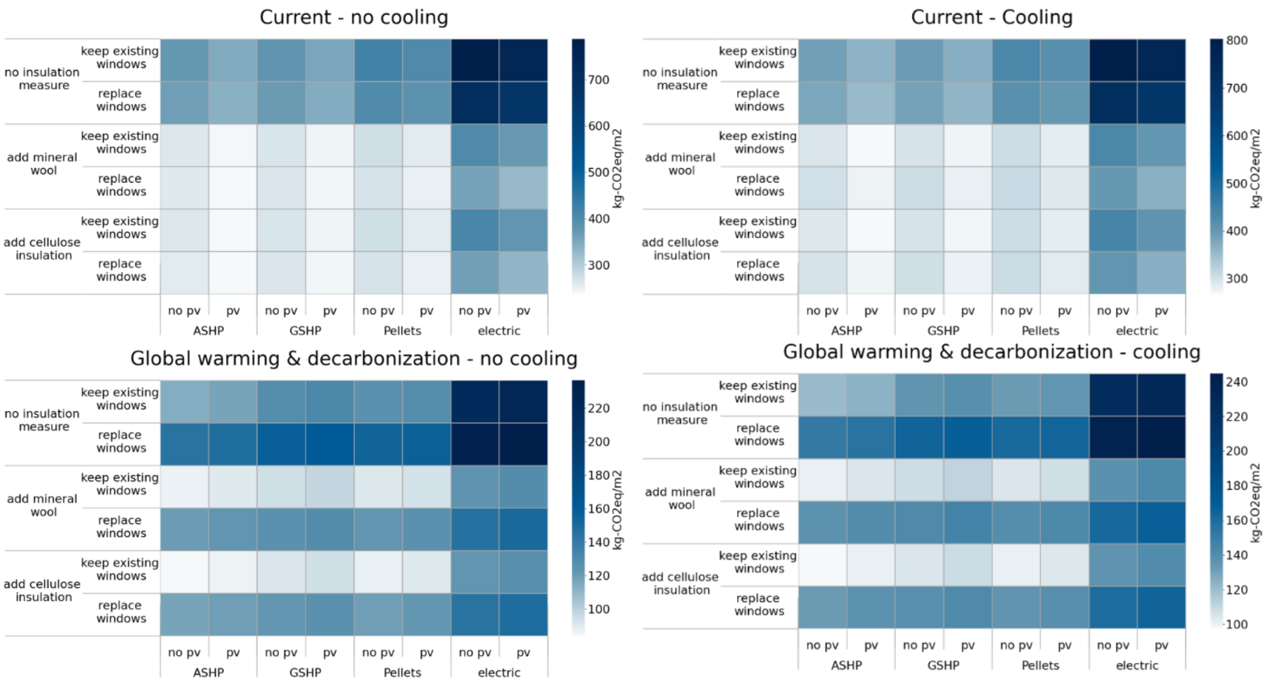

Figure B. 4: Calculated GHG emissions of retrofit combinations for current and future-oriented assumptions comparing the effects of cooling excluded or included in the analysis. Other assumptions are kept constant: 60-year analysis period, pro-rata PV allocation.