Building renovation passports: an instrument to bridge the gap between building stock decarbonisation targets and real renovation processes

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Abstract
The recast of the Energy Performance of Buildings Directive (EPBD) 2018/844/EU introduced in Article 19a the building renovation passports serving as a complementary document providing a long-term and step-by-step renovation roadmap for a specific building. The step-by-step renovation roadmap should guide and help building owners through the renovation process, therefore addressing barriers such as lack of acceptance and high initial investments, which hinder applying single stage retrofitting measures. This paper aims to study the potential role of the step-by-step renovation measure sequences, as an instrument to achieve ambitious decarbonisation targets in the residential single family house building stock. For this, based on a literature review, first the concept of the step-by-step renovation roadmap has been explored. Then, different exemplary, common step-by-step renovation sequences were developed and determined for different reference buildings, in terms of achieved energy needs for space heating. There are different approaches to define the step-by-step renovation roadmaps, first using multi-objective optimization models, and second, making plausible assumptions based on the common practice of retrofitting projects. In the present study, both methodological approaches are discussed. Finally, by upscaling the exemplary step-by-step renovation sequences for the German single family houses into building stock level, we analysed and discussed the possible impact of these step-by-step renovation sequences, also compared to single stage major renovation measures and a decarbonisation scenario calculated with the Invert/EE-Lab model. The results showed that the concepts applied (step-by-step and single stage) deliver different results, both in line with the total results provided by the Invert-EE/Lab Model. The analysis of the step-by-step approach resulted in lower energy demand in 2050 than the single stage approach. However, to realize a more robust analysis, further sensitivity analysis should be done in order to cover other influencing parameters. Finally, we believe that the step-by-step retrofitting concept is a renovation process taking into account restrictions which are relevant in real-life. Also, we suggest that this concept should be considered, when designing policies and incentives to achieve building stock decarbonisation targets.

Introduction
The building sector has been identified as one of the key sectors for achieving the energy and climate policy targets of the EU, as buildings are responsible for 40 % of energy consumption and 36 % of CO_2 emissions in the EU (European Commission, 2018). Although huge efforts have been made to reduce the energy demand of buildings, recent statistics data about final energy consumption in households (Eurostat, 2018a) and share of final energy consumption per fuel (Eurostat, 2018b) have shown that there is still a long pathway to achieve the EU-targets. Therefore, is it necessary to find alternative deep renovation concepts for the building stock decarbonisation. The EPBD recast 2018/844/EU introduced in Article 19a the possibility of building renovation passports serving as a complementary document, which provide a long-term and step-by-step renovation roadmap for a specific building. This document guides and helps building

owners through the renovation process, therefore addressing barriers such as lack of acceptance and high initial investments, which hinder applying single stage retrofitting measures. The building renovation passport is an important instrument at EU level, to support deep renovation of existing buildings and bridge the gap between real renovation processes and the EU-targets for building stock decarbonisation.

"Deep renovation" is not necessarily restricted to single stage renovation, but can also be achieved by step-by-step renovation measures. Creating a more comprehensive understanding of the reasons and motivation for this alternative retrofitting concept could help accelerating the decarbonisation of the building stock due to suitable and right timing of measures sequence. In the literature, there is no consensus that deep renovation can also be achieved by a sequence of step-by-step renovation measures: e.g. in a study on renovation rates of energy performance activities in the residential building stock in the Netherlands (Filippidou et al., 2017) the results showed that, despite the realization of many building renovation activities, only small improvements on the energy efficiency of dwellings were observed. The authors pointed out the need of packages for deep renovation measures, rather than single measures. Another study (Risholt and Berker, 2013) on the success for energy efficient renovation of dwellings in Norway emphasizes the importance of private homeowners to have access to relevant and reliable advices, to make energy efficient choices in the process of renovation, as a role player in the process of increasing building renovation rates. Fabbri et al., 2018 identified the lack of engagement and knowledge of the homeowners with energy efficiency issues as main barrier to increase energy performance of single-family houses. The authors also stressed the relevance of building passports, which should among other things, foresee the long-term renovation measures, according to building owner's necessity.

In Europe, there are already some demonstration projects, which focus on the key concept of building passports, as an initiative to increase awareness about building's energy performance, and to encourage homeowners to conduct deep renovations. One example is the concept of renovation roadmap (Sanierungsfahrplan – SFP) in Germany, which was launched in 2015 as an energy audit instrument (Baden-Württemberg, 2015). In France, the roadmap Passeport Efficacité Énergétique (P2E) provides a set of solutions ("performance combinations"), which enable the building to reach low energy or n-ZEB levels (Expérience P2E, 2018). In this context, the iBRoad EU-funded project works on eliminating the barriers between house owner and building energy performance, by developing tools to create building passports and long-term step-by-step renovation roadmaps for single-family houses. The step-by-step renovation roadmap is at its core a home-improvement long-term plan, which considers the occupants' needs and specific situations and avoids the risk of lock-in effects, if future renovation measures are not considered in current activities. Taking into consideration that in real life, most retrofit activities are performed step-by-step sequences (EuroPHIT project, 2016), the main goal of the present paper is to analyse the effects of step-by-step renovation on the building stock decarbonisation targets. This analysis will focus on the German single-family houses building stock.

Method and data

The method was carried out in different steps: literature review, parameter definition, data collection and synchronization between the databases, plausibility proof of the first assumptions, set of step-by-step measures sequences and finally, calculation of the effects of step-by-step renovation concept on the building stock decarbonisation targets. As this analysis involves many phases before the main goal (last step) was achieved, this chapter also presents the results and main conclusions of each intermediate step to increase understanding about the method and chosen steps. The chapter "results" focuses on the main results, delivered from the last step.

PREPARATORY ANALYSIS

The first step of this paper was to carry out a literature review, to understand how building retrofits are modelled in building stock decarbonisation scenarios and if the step-by-step concept has been approached by other authors. We observed that the multi-objective optimisation is a commonly applied method to calculate cost optimized retrofits by maximizing energy savings and minimizing the investment costs – (Wu et al., 2017), (Steinbach, 2016), (Asadi et al., 2012), (Antipova et al., 2014) and others. Although this method delivers optimized results, it does not cover the timing aspect when the renovation measure should be performed, by considering that the optimized measures are applied at the same time (single stage renovation).

In the step-by-step concept, the time variable plays an important role besides energy savings and investment costs, because it determines how fast the decarbonisation targets will be achieved. Therefore, the second step of this study deals with the question about historical and expected future timing of different retrofit measures. During a building's life cycle, maintenance and operation activities constantly happen to avoid first stages of degradation and failure of building elements (Flores-Colen and de Brito, 2010). At the same time, usual maintenance activities and/or material replacement provide an opportunity for increasing building element's energy efficiency, and consequently improving building's energy performance. These activities can be induced by unpredictable damages, as breaks, leakages and cracks, or predictable parameters, as material's durability, which defines the material's lifetime. Because of its predictability, the parameter material's lifetime was used in the present study to determine when the retrofit measure should happen.

In the third step, we defined a set of selected reference single family buildings in Germany and prepared the building-related data by synchronizing information regarding the building vintage with the material lifetime (Pfeiffer et al., 2010). For each building vintage typically used construction materials (wood, cement, brick, insulation etc.) of the building elements (windows, floor, roof, external wall) were identified (EPISCOPE project, 2016). In this paper, we focus on the energy efficiency improvement measures in the building envelope, as they provide the highest energy savings in a retrofit project. Naturally, the heating system also plays a relevant role regarding energy efficiency and energy demand of buildings. Therefore, we will include the effects of the heating system and its replacement in the next activities of this study. A building is composed of different construction material layers with thermal and other

Table 1. Characterization of the reference buildings – building elements, building material and material lifetime (for each building vintage, a reference buildings for single family houses in Germany).

Building element	Building material	Material's lifetime [yr]	until 1918	1919-1948	1949 - 1957	1958 - 1968	1969 - 1978	1979 - 1983	1984 - 1994	1995 - 2001	2002-2009
windows	multi glazing	25	y	y	y	y	y	y	y	y	y
floor	insulation	30	n	n	n	y	y	y	y	y	y
external wall	insulation	30	n	n	n	n	y	n	n	y	y
roof	insulation	30	n	n	n	y	y	y	y	y	y
floor	wood (load bearing)	60	y	n	n	n	n	n	n	n	n
external wall	cement	70	n	n	n	n	n	n	y	n	n
external wall	wood	70	n	n	n	n	n	n	n	n	n
windows	single glazing	80	n	n	n	n	n	n	n	n	n
external wall	brick (load bearing)	90	y	y	y	y	n	y	n	n	n
roof	cement reinforced	100	n	n	n	n	n	n	n	n	n
floor	natural stone (load bearing)	100	n	y	y	n	n	n	n	n	n
roof	wood chairs	120	y	y	y	n	n	n	n	n	n

Source: own table, based on (EPISCOPE project, 2016) and (Pfeiffer et al., 2010).

Table 2. Building elements' renovation cycle until 2017, for each building vintage.

Construction period	until 1918		1919-1948		1949 -1957		1958 -1968		1969 -1978		1979 -1983		1984 -1994		1995 -2001	
Construction year	1875	1918	1919	1948	1949	1957	1958	1968	1969	1978	1979	1983	1984	1994	1995	2001
Building age until 2017	142	99	98	69	68	60	59	49	48	39	38	34	33	23	22	16
Roof	1	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0
Floor	3	2	2	0	0	0	1	1	1	1	1	1	1	0	0	0
External wall	2	1	1	0	0	0	0	0	1	1	0	0	0	0	0	0
Window	5	3	3	2	2	2	2	1	1	1	1	1	1	0	0	0

Source: own table.

specific properties. For this study, we focused on the materials with thermal properties – thermal mass and insulation as they have high influence on the energy performance of the building, and on materials with load bearing function. Table 1[1] summarizes the characterization of the reference buildings, where the abbreviation "y" indicates that the building element contains the specified material and "n" indicates that the building element does not contain the specified material for the selected reference building.

The characterization of the reference buildings and specification of material's lifetime allowed us to develop, in the fourth step, a step-by-step deep renovation sequence for each building vintage since the construction year. Assuming a strictly deterministic lifetime as specified above, the retrofitting measure's frequency is determined by the lifetime of the building material. If the building element includes insulation, its maintenance activity happens more frequently than a non-insulated building element, because insulation has a comparably shorter lifetime than the other materials (besides glazing) according to Pfeiffer et al., 2010. Also, with the material replacement, a new life-cycle starts. To make a first calibration and plausibility verification of the chosen approach, possible renovation cycles until 2017 were calculated based on the data and assumptions presented above. Table 2 shows the number of renovation cycles per building element, for two reference buildings per building vintage. The age of the building in the year 2017 is also showed.

From Table 2, it is possible to observe that buildings older than 120 years (in 2017), should have at least completed one renovation cycle of each building element (not implying to which extent this renovation measure had an impact on the energy performance of the building). Buildings of around 100 years (in 2017) still not performed renovation of all building elements as, for example, roof renovation is still pending. Buildings, with an age of 60–70 years (in 2017) only completed the window renovation cycle, according to the assumptions made. Most reference buildings constructed between 1958–1983 would have complemented at least one renovation cycle of all building elements, with exception of the buildings constructed between 1969–1978. These building did not include insulation on the external walls, and therefore did not complete until 2017 all their first renovation cycles. In general, windows replacement is the most frequent measure for all buildings. Up to the construction year 1994, the buildings are relatively "young", which means that none of the building elements reached the end of its lifetime.

It is important to highlight that the frequency of the renovation cycle is not directly connected to an improvement on the energy performance, as already observed by (Risholt and Berker, 2013) and others. In a study about energy performance and deep renovation trends in the German residential building stock, the authors concluded that 70–75 % of old buildings[2]

1. The building element window consists mainly of two building components: glazing and frames. We assume that the renovation time of a window is determined by the glazing lifetime. The building element roof consists of different layers, with and without load bearing properties. We assume that the renovation time of a roof is determined by the load bearing material, or thermal relevant (insulation). Therefore, roof layers as, for example, sealing or covering were not taken into account.

2. Diefenbach et al., 2010 defined "old buildings" as the buildings constructed until 1978.

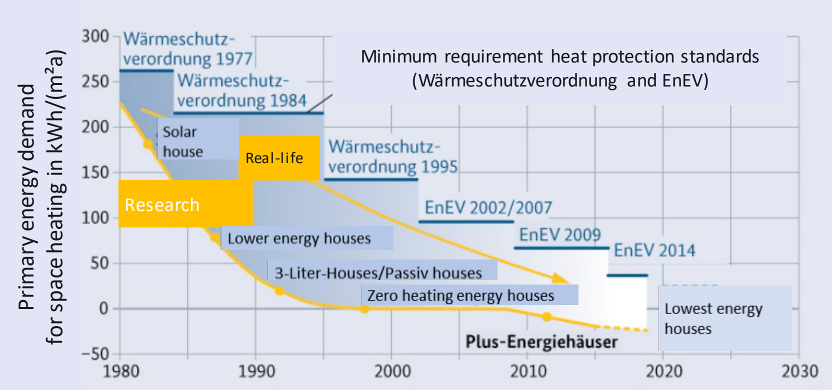

Figure 1. Development of German energy efficiency building codes. Source: adapted from Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit, 2016 (BMUB, 2016).

did not experience an improvement of the energy performance of their building envelope (Diefenbach et al., 2010). To some extent, this could be explained by the fact, that some building element's did not reach their end-of-life, therefore the first renovation cycles has been completed. On the other hand, as said above, the renovation measure can also only focus on maintenance or aesthetic reasons and thus not contribute to the energy performance of the building (e.g. plastering and painting of the façade).

MAIN ANALYSIS

The last step of this study aimed to analyse possible effects of the step-by-step renovation sequences on decarbonisation targets by upscaling the results from the step-by-step renovation sequences, for the reference buildings (single family houses in Germany) (Hartner et al., 2018) (Diefenbach et al., 2010). Following the same approach as for the step-by-step renovation sequences, the effects of a single stage renovation approach were also calculated. In the single stage approach, a time step of 80 years was considered, which corresponds to a completely building lifetime (Pfeiffer et al., 2010). Both approaches were then compared. To determine the energy efficiency of each renovation measure, we assumed that the renovation measures follow the requirements according to the German building codes[3] in force in the renovation year (BMUB, 2016), which become stricter over time.

We also analyzed the consistency of these step-by-step renovation sequences with long-term national decarbonisation scenarios until 2050 calculated with the Invert/EE-Lab. Invert/EE-Lab[4] is a dynamic bottom-up discrete choice building stock simulation tool. In particular, Invert/EE-Lab is designed to simulate the impact of policies and other side conditions in different techno-economic scenarios. The scenarios derived with this tool build on a highly disaggregated representation of the national building stock by a large number of reference buildings. Based on several parameters such as the age distribution of the building components; heat supply; distribution technologies in the building stock; and the ratio between the total costs of purchase of new components and the energy-consumption related annual costs using the installed component, the share of buildings and components is determined. In contrast to the approach and focus of this paper, Invert/EE-Lab assumes single stage renovation measures. By applying current policy settings in the model Invert/EE-Lab, results of a scenario study developed for the European Project SET-Nav ‚showed that 77 % CO2-Emission reduction can be achieved until 2050 (Hartner et al., 2018). This scenario was taken as a reference development for comparison with the concepts step-by-step and single stage.

Results

The discussion of the results is divided in two parts: first, the development of energy needs[5] for space heating for the concepts of step-by-step and single stage renovations are presented, including the description of the renovation cycles and the energy savings achieved. In the second part, the results were scaled up to a building stock level, and compared with the Invert/EE-Lab results.

DEVELOPMENT OF ENERGY NEEDS FOR SPACE HEATING (CONCEPTS STEP-BY-STEP AND SINGLE STAGE)

Figures 2–10 show the specific energy needs for space heating in kWh/(m^{2}a) development, from the assumed construction year (as the mean value within a certain vintage class) until 2050 for a reference building of each building vintage (before 1918 until 2009). The development of the specific energy needs for space heating is defined by two thermal retrofit concepts: step-by-step and single stage renovation. In both retrofit concepts, it is assumed that the building's energy efficiency improves according to the building code inforce. As the German heat protection legislation started in 1977 (Figure *1*), the renovation cycles, which happened before this year, were not considered to generate an energy performance improvement. In the step-by-step concept, the renovation sequence is deter-

3. For the present study, we consider the German building codes for new buildings. To further explanations to this topic, see limitations and next steps.

4. For more information about the Invert/EE-Lab model, see www.invert.at (Müller, 2015), (Kranzl et al., 2013) and (Steinbach, 2016).

5.Energy needs for heating and cooling: heat to be delivered to, or extracted from, a thermally conditioned space to maintain the intended space temperature conditions during a given period of time (ISO 52016-1, 2017). It can also be interpreted as useful energy demand.

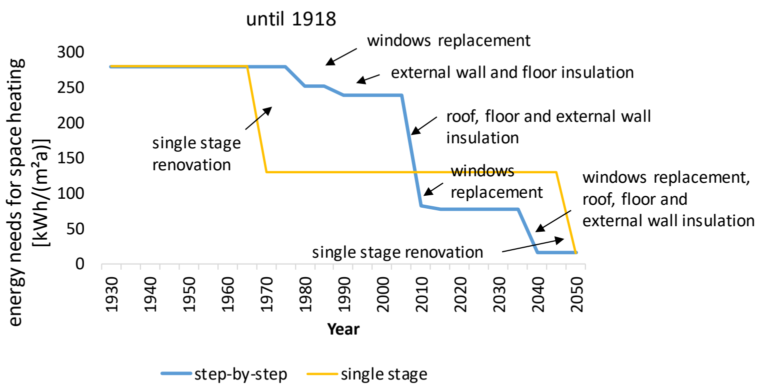

Figure 2. Renovation sequences and development of energy needs for space heating, according to step-by-step versus single stage concept – reference buildings for construction vintage "until 1918".

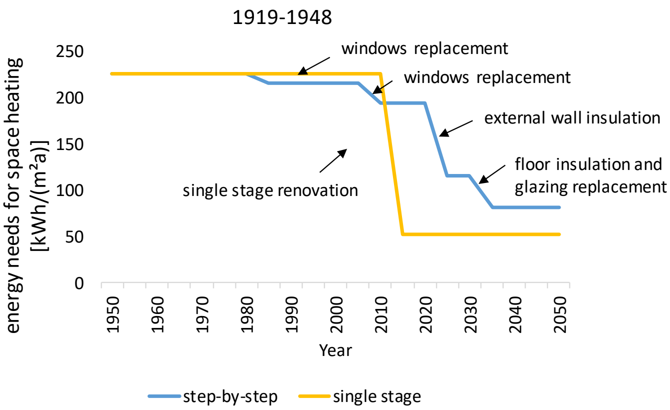

Figure 3. Renovation sequences and development of energy needs for space heating, according to step-by-step versus single stage concept – reference buildings for construction vintage "1919–1948".

mined according to the construction material's life time (see Table 2). In the single stage concept, the renovation occurs in a constant time step frequency of 80 years, which corresponds to the building's lifetime (Pfeiffer et al, 2010).

Step-by-step concept: Roof (wood chairs): two thermal relevant roof renovation cycles would happen. The first in 2010, and the second in 2040. External wall (brick): three thermal relevant external wall renovation cycles would happen. The first in 1980, the second in 2010 and the last one, in 2040. Windows (multi-glazing): three thermal relevant glazing renovation cycles would happen. The first in 1990, the second in 2015, and, the third in 2040. Floor (wood): three thermal relevant floor renovation cycles would happen. The first in 1980, the second in 2010 and, the third in 2040. **Single stage concept:** renovation cycles would happen two times: in 1970 and 2050.

Step-by-step concept: Roof (wood chairs): no roof renovation cycles would happen. External wall (brick): one thermal relevant external wall renovation cycles would happen in 2025. Windows (multi-glazing): three thermal relevant glazing renovation cycles would happen. The first in 1985, the second in 2010, and, the third in 2035. Floor (natural stone): one thermal relevant floor renovation cycles would happen in 2035. **Single stage concept:** renovation cycles would happen one time in 2015.

Step-by-step concept: Roof (wood chairs) and floor (natural stone): no roof renovation cycles would happen. External wall (brick): one thermal relevant external wall renovation cycles would happen in 2045. Windows (multi-glazing): three thermal relevant glazing renovation cycles would happen. The first in 1980, the second in 2005, and, the third in 2030. **Single stage concept:** renovation cycles would happen one time in 2035.

Step-by-step concept: Roof (with insulation) and floor (with insulation): two thermal relevant roof renovation cycles would happen. The first in 1995, and the second in 2025. External wall (brick): no external wall renovation cycles would happen. Windows (multi-glazing): three thermal relevant glazing renovation cycles would happen. The first in 1990, the second in 2015, and, the third in 2040. **Single stage concept:** renovation cycles would happen one time in 2045.

Step-by-step concept: Roof (with insulation): two thermal relevant roof renovation cycles would happen. The first in 2005, the second in 2035. External wall (with insulation): two thermal relevant roof renovation cycles would happen. The first in 2005, the second in 2035. Windows (multi-glazing): three thermal relevant glazing renovation cycles would happen. The first in 2000, the second in 2025, and, the third in 2050. Floor (with insulation): two thermal relevant roof renovation cycles would happen.

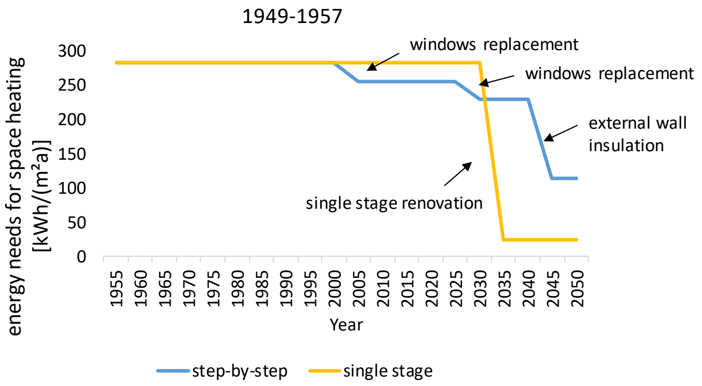

Figure 4. Renovation sequences and development of energy needs for space heating, according to step-by-step versus single stage concept – reference buildings for construction vintage "1949–1957".

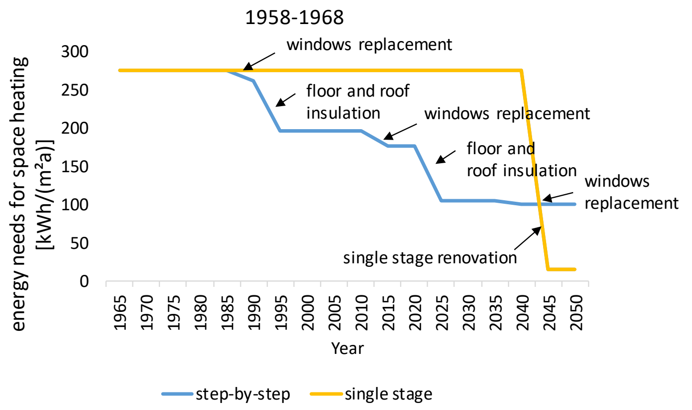

Figure 5. Renovation sequences and development of energy needs for space heating, according to step-by-step versus single stage concept – reference buildings for construction vintage "1958–1968".

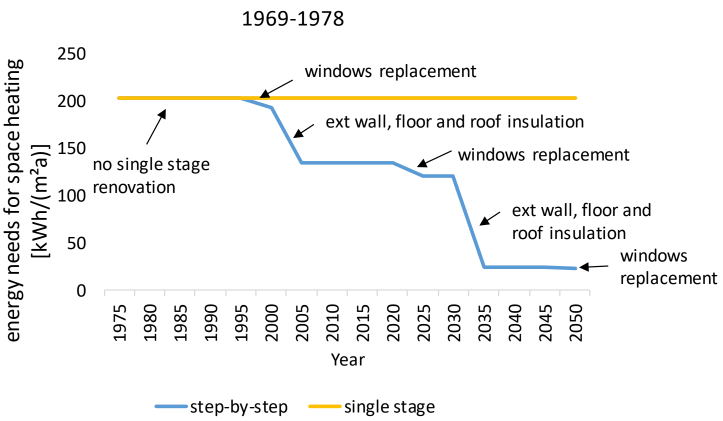

Figure 6. Renovation sequences and development of energy needs for space heating, according to step-by-step versus single stage concept – reference buildings for construction vintage "1969–1978".

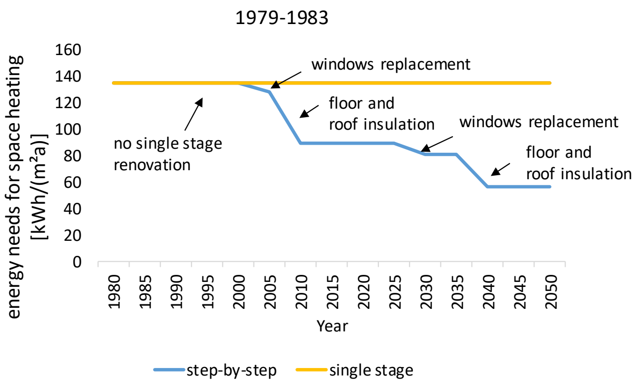

Figure 7. Renovation sequences and development of energy needs for space heating, according to step-by-step versus single stage concept – reference buildings for construction vintage "1979–1983".

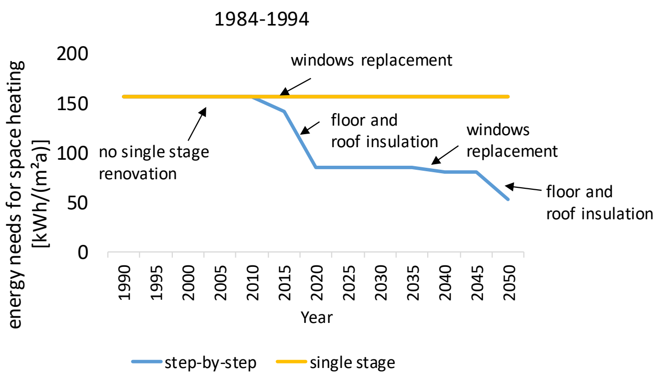

Figure 8. Renovation sequences and development of energy needs for space heating, according to step-by-step versus single stage concept – reference buildings for construction vintage "1984–1994".

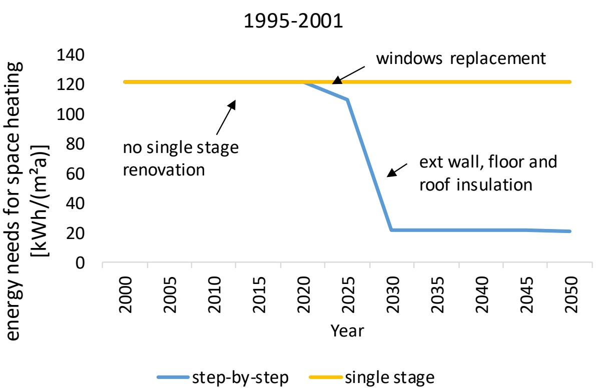

Figure 9. Renovation sequences and development of energy needs for space heating, according to step-by-step versus single stage concept – reference buildings for construction vintage "1995–2001".

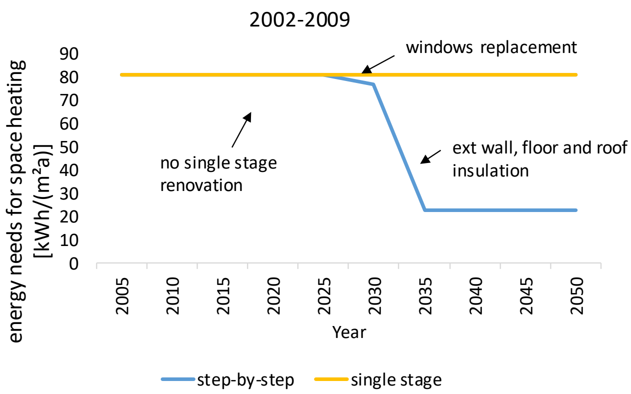

Figure 10. Renovation sequences and development of energy needs for space heating, according to step-by-step versus single stage concept – reference buildings for construction vintage "2002–2009".

The first in 2005, the second in 2035. **Single stage concept:** no single stage renovation cycles would happen until 2050.

Step-by-step concept: Roof (with insulation) and floor (with insulation): two thermal relevant roof renovation cycles would happen. The first in 2010, the second in 2040. External wall (brick):no external wall renovation cycles would happen. Windows (multi-glazing): two thermal relevant glazing renovation cycles would happen. The first in 2005, the second in 2030. The first in 2010, the second in 2040. **Single stage concept:** no single stage renovation cycles would happen until 2050.

Step-by-step concept: Roof (with insulation) and floor (with insulation): two thermal relevant roof renovation cycles would happen. The first in 2020, the second in 2050. External wall (cement): no external wall renovation cycles would happen. Windows (multi-glazing): two thermal relevant roof renovation cycles would happen. The first in 2015, the second in 2040. **Single stage concept:** no single stage renovation cycles would happen until 2050.

Step-by-step concept: Roof (with insulation) and external wall (with insulation): one thermal relevant renovation cycles would happen in 2030. Windows (multi-glazing): two thermal relevant roof renovation cycles would happen. The first in 2025, the second in 2050. Floor (with insulation): one thermal relevant roof renovation cycles would happen, in 2030. **Single stage concept:** no single stage renovation cycles would happen until 2050.

Step-by-step concept: Roof (with insulation), external wall (with insulation) and floor (with insulation): one thermal relevant roof renovation cycles would happen in 2035. Windows (multi-glazing): one thermal relevant roof renovation cycles would happen, in 2035. **Single stage concept:** no single stage renovation cycles would happen until 2050.

Table 3 shows a summary of the last renovation (step-by-step and single stage concept).

Figure 11 shows the specific energy needs in kWh/(m²a) of the construction year and after renovation according to both step-by-step and single stage concepts (for each building vintage). Also, the energy savings [%] achieved by both concepts are showed above each column.

COMPARISON OF ENERGY NEEDS FOR SPACE HEATING ACCORDING TO THE CONCEPTS STEP-BY-STEP, SINGLE STAGE AND THE MODEL INVERT/EE-LAB

Figure 12 shows the comparison of specific energy needs for space heating in kWh/(m²a) between the step-by-step concept, single stage concept and the model Invert/EE-Lab, for a refer-

Table 3. Last renovation year.

Building vintage		until 1918	1919 - 1948	1949 - 1957	1958 - 1968	1969 - 1978	1979 - 1983	1984 - 1994	1995 - 2001	2002 - 2009
Construction year of reference building		1890	1935	1955	1965	1975	1980	1990	2000	2005
Step-by-step	Roof	2040	no renovation	no renovation	2025	2035	2040	2050	2030	2035
	Floor	2040	2035	no renovation	2025	2035	2040	2050	2030	2035
	External Wall	2040	2025	2045	no renovation	2035	2050	no renovation	2030	2035
	Window	2040	2035	2030	2040	2050	2030	2040	2050	2035
Single stage	all building elements	2050	2015	2035	2045	no renovation	no renovation	no renovation	no renovation	no renovation

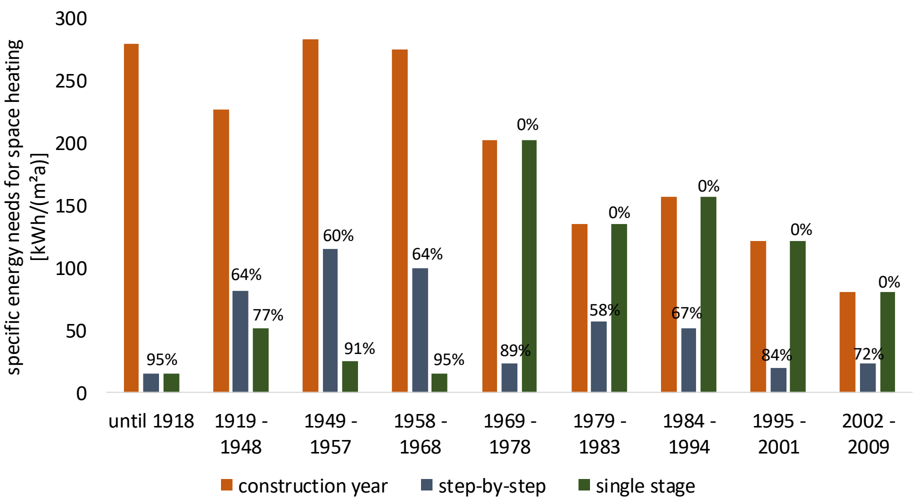

Figure 11. Energy needs (before and after renovation) and energy savings according to both step-by-step and single stage concept, for each building vintage.

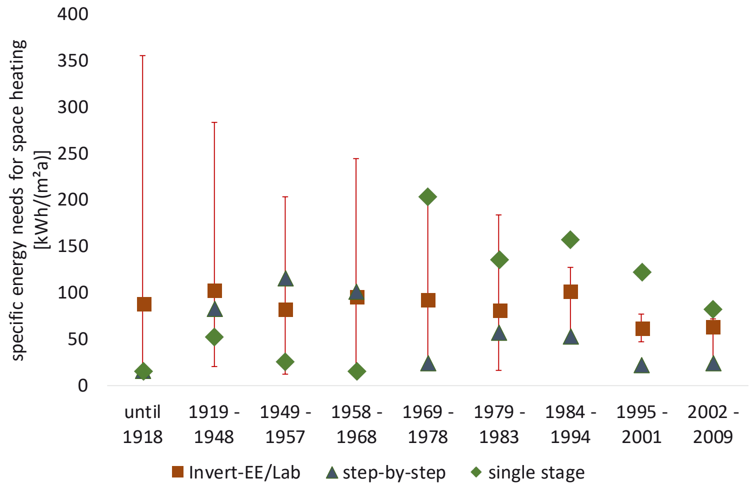

Figure 12. Comparison of specific energy needs for space heating in kWh/(m²a) between step-by-step concept, single stage concept and Invert/EE-Lab model, for a reference building of each building vintage (before 1918 until 2009).

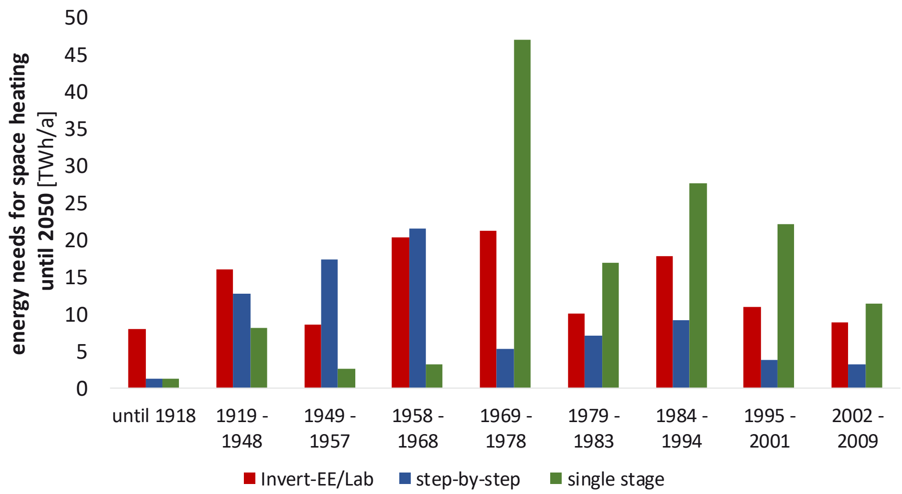

Figure 13. Comparison of total energy needs for space heating TWh/a between step-by-step concept, single stage concept and Invert/EE-Lab model, for each building vintage.

ence building of each building vintage (before 1918 until 2009). Regarding the Invert/EE-Lab results, the figure shows the average weighted energy needs for space heating and its ranges.

According to the building vintage, the energy needs from both step-by-step and single stage concept differ from each other. For building construction years until 1968, the single stage concept allows lower energy needs than the step-by-step. This trend changes up 1969, when the step-by-step concept allows lower energy needs. Both concepts present results between Invert-EE/Lab model's ranges, what confirms the plausibility of both approaches.

After the specific energy needs for space heating for the reference buildings have been calculated, they were up-scaled to a building stock level. The total energy needs for space heating in TWh/a in 2050 according to each concept is: 122 TWh/a (Invert-EE/Lab), 81 TWh/a (step-by-step) and 140 TWh/a (single stage). Figure 13 shows the comparison of total energy needs for space heating TWh/a between the step-by-step concept, single stage concept and Invert/EE-Lab model, for each building vintage (before 1918 until 2009). Further conclusions are discussed in the next chapter.

Conclusions

The first conclusions refer to the step-by-step sequence of renovation measures for each building vintage according to the approach applied in this paper. Buildings constructed until 1957 present a wide range of material's lifetimes (25 to 120 years), which means that it takes longer until all building elements have been completed at least one renovation cycle. In the building vintage 1958–1968 and 1979–1983 this range is smaller (25 to 90 years). The building vintage up to 1995 presents a shorter interval until at least one renovation cycle has been completed (25–30 years), because in these buildings external walls, roof and floor were constructed from the beginning with insulation layers, which – according to Pfeiffer et al, 2010 – show lower lifetimes compared to construction materials without insulation. This implies that in non-insulated building elements (external walls, roof and floor), after the first renovation cycle was completed, the subsequent renovation cycles happen more frequently, because of the addition of an insulation layer. In terms of renovation sequences for a reference building, the building construction year was an important parameter to define the time analysis of future measures, and therefore, the projection of the energy needs for space heating.

The comparison between both concepts showed that buildings constructed before 1969 presented higher energy savings with the single stage concept than with the step-by-step. Buildings constructed after 1969 would not go through any single stage renovation until 2050, so up 1969 the step-by-step concept presented higher energy savings. These results are highly connected with the assumption of the building lifetime of 80–years for the single stage concept. Therefore, we believe that a plausibility analysis taking into account other time steps (i.e. 60 years) should also be done.

In general, the concepts applied and analysed in the paper delivered different results: due to the fact that insulated building elements have shorter renovation cycles than non-insulated ones after the first thermal renovation cycle, the step-by-step concept leads to a faster adaptation of the building elements to the building code in force. On the other hand, in the single stage concept, building's energy performance remains the same over a longer period of time. Also, in the single stage concept the renovation time step is determined by building's lifetime, which means that by the time of the renovation a building element might not have reached its end-of-life.

Overall, for the year 2050 the results show that the analysis of both thermal renovation concepts, step-by-step and single-stage present plausible results when compared to the Invert-EE/Lab Model. When upscaling the specific energy needs for space heating from a single reference building to the national building stock level, the distribution of buildings, in terms of number of buildings and their different energy needs, becomes a relevant parameter. The Invert-EE/Lab Model calculates a wide range of energy needs for space heating, where older building vintages present a wider range than newer ones. In terms of total energy needs for space heating (TWh/a) in 2050, the step-by-step approach resulted in lower energy demand than the single stage approach. Especially, because the step-by-step concept leads to deep renovation of some building elements in buildings constructed after 1969 (middle aged and younger buildings). Contrary to the single stage concept, where buildings constructed after 1969 would not perform any deep renovation, although some of them present higher energy needs (for example, building vintage 1969–1978, 203 kWh/m²a).

Limitations and next steps

Limitations of this study are related to the reference buildings (described according to the chosen database), and other assumptions regarding building elements and components. Further sensitivity analysis including important input parameters should be done, as for example, reduced or increased time intervals between renovation in the single-stage concept, which is highly relevant for the overall results. Another point is the consideration of the building code for existing buildings. We assume that in the future, benchmarks for existing buildings will follow the same threshold as for new buildings. This assumption, however, influences the achieved energy needs, therefore further sensitivity analysis will include other retrofitting targets. Also, economic consequences of not reaching materials end-of-life should be taken into account, by defining the time step of the single stage concept. By choosing the step-by-step renovation sequence, other common retrofitting measures, as for example, ceiling renovation (stead of roof) will also be included.

Furthermore, we foresee following next steps: 1) integration of replacement of heating systems with hot water preparation; 2) considering a more realistic distribution of the building elements' lifetimes, e.g. by using a Weibull distribution (as also done in the model Invert/EE-Lab); 3) consideration of actual building codes and for existing buildings; 4) combination of step-by-step renovation measures, as in reality, building owners may decide to perform more than one measure at once; 5) empirical evaluation of the historical renovation cycles; and 6) adding other analyses, as for example, investment costs and overall economic assessment.

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