



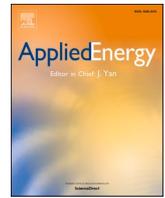
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Bio-based materials as a robust solution for building renovation: A case study

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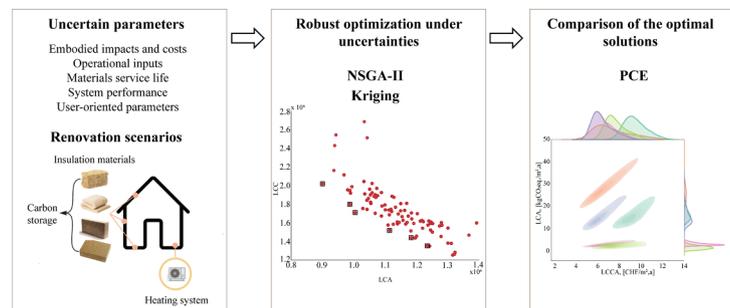
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HIGHLIGHTS

- The integrated analysis of LCA and LCCA of building renovation is performed considering future uncertainties.
- The robust optimal renovation solution is identified within conventional and bio-based materials.
- Bio-based materials are considered including dynamic carbon storage analysis.

GRAPHICAL ABSTRACT



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ABSTRACT

Boosting building renovation is urgently needed to achieve carbon neutrality by 2050. Building retrofit can be achieved by energy-efficient measures such as thermal insulation or replacement of a fossil heating system. Currently, conventional materials that are mostly used for envelope insulation raising the risk of a lock-in situation where measures to mitigate climate change are actually contributing to it. Bio-based materials are a promising alternative as they can be used to not only reduce the energy consumption of a building but also temporarily store carbon. To evaluate the potential benefits of such materials, life cycle assessment (LCA) and life cycle cost analysis (LCCA) are commonly used. Such assessment allows the analysis of a building over its whole life. However, considering that buildings are very long lasting systems, many associated uncertainties can affect the outcome of LCA and LCCA. To account for all the uncertainty sources and provide a robust solution for building renovation, uncertainty quantification can be applied. In this paper, we use robust optimization under uncertainties to define the most cost-effective and climate-friendly solution. We apply bio-based materials and include carbon storage calculation in the integrated LCA and LCCA. For the robust optimization, we use a novel methodology combining a well-known non-dominated sorting genetic algorithm II (NSGA-II) with surrogate modeling to lower computational cost. The methodology is applied for a case study located in Switzerland. The results show that bio-based materials provide a robust solution for building renovation but to achieve the highest

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reduction potential, bio-based envelope insulation should be combined with the replacement of the existing fossil heating system.

1. Introduction

Currently, around 75% of the building stock in the European Union (EU) is energy-inefficient [1]. Around 85% of these buildings will still stand by the year 2050, which is set as a target to achieve carbon neutrality in the EU [2]. Current weighted energy-related renovation rate in Europe is about 1% per year, which is not sufficient to meet this target. Therefore, it is clear that effective measures are needed to increase the renovation rate and decarbonize the building stock by 2050.

To evaluate the renovation scenarios in terms of emitted carbon and ensure the cost-effectiveness of these scenarios, the methods of environmental life cycle assessment (LCA) and life cycle cost analysis (LCCA) are commonly used. The main advantage of these analyses is the possibility to assess a building during its whole life cycle and include all stages from the materials' production to their end of life. However, the holistic aspect of the LCA and LCCA can also in turn results in a drawback due to the high numbers of parameters used in these methods such as the long service life of a building and the impact of the numerous uncertainties present in all stages of the analysis [3]. By uncertainties, we refer to the parameters that are inaccurately known, for example, either geometrical measurements of a building or the service life of the materials [4], or are uncertain by nature, such as future climate or users' behavior [5–7]. The combination of all the uncertainties in integrated LCA and LCCA can lead to large errors in estimation of the results [8]. Uncertainty quantification (UQ) aims at identifying such parameters and modelling their overall effect on the model output. It has been shown that UQ is an important step in LCA and LCCA to achieve reliable results [9–10].

Many UQ techniques have been recently used in the analyses of LCA [11–16] and LCCA [17–19] and reviews summarizing the possible techniques were published [20–22]. In these studies, the importance of probabilistic assessment was highlighted in order to achieve reliable results. Among various techniques, Monte Carlo simulation gained the highest popularity due to its easy applicability and clear procedure [21]. However, due to its low convergence rate, it might not be the most practical solution in case the associated simulations are time-consuming and, if a methodology would be further used for decision-making. In this case, surrogate models can be exploited as a replacement of a computationally demanding original model. In a recent paper, surrogate modeling was applied to the analyses of LCA and LCCA [23].

Besides using probabilistic modeling to assess a defined renovation scenario, sometimes the most robust solution within the provided ones needs to be obtained. For this purpose, optimization techniques are used. In the field of built environment, genetic algorithm is one of the most applied methodologies, the idea of which is based on the theory of natural evolution and the survival of the fittest. In case the model contains several objective functions, multi-objective genetic algorithm (MoGA) can be used. Several studies have recently shown the applicability of MoGA in the assessment of LCCA and LCA [24–27]. Within MoGA techniques, Non-dominated sorting genetic algorithm II (NSGA-II) is among the most widely used for multi-objective optimization [28–29]. Several researchers have applied NSGA-II for LCA or LCCA [30–32]. However, one drawback of NSGA-II is its computational cost, which might be substantial, especially if uncertainty quantification is coupled with a computationally demanding model [33]. Surrogate modeling is also useful in this case as it allows building an approximation of an original model and afterwards, using it within NSGA-II for optimization. This considerably reduces the overall computational time. In this paper, we use the methodology of coupling NSGA-II with Kriging as a Gaussian regression process for a surrogate modeling, proposed by Moustapha et al [34].

Previous research has shown that deep envelope renovation of residential buildings in Switzerland using conventional materials is neither robust nor effective due to the future uncertainties and climate change [35]. It was then shown that the most robust renovation strategy is the replacement of the heating system in current existing building mainly heated with fossil-based systems by a low carbon or renewable heating systems such as a wood boiler, a heat pump (air-to-water or using geothermal probes) or the connection to a renewable district heating coupled with a small amount of insulation on the facades (e.g. 4–10 cm for the facades) [35]. Choosing to replace only the fossil heating system by a wood boiler, heat pump or district heating would be more effective than opting for a deep renovation of the envelope. However, the available amount of wood in Switzerland (for both individual boilers and district heating) is not sufficient to supply the amount of energy needed in case no envelope renovation is performed. Furthermore, replacing only the heating system does not reduce the overall energy bill for the residents which leads to socially unfair environmental measures. Therefore, it is important to combine energy consumption reduction measures with energy carrier replacement towards low carbon energy sources.

In this work, we consider bio-based materials instead of conventional ones and identify if optimal solution still contains only heating system replacement. Bio-based materials are materials made of renewable energy sources, for example plant-based materials or agricultural by-products such as wood, hemp, flax, and straw or animal-based materials such as sheep wool or feathers. Such insulation materials are fully regenerative and besides having good thermal properties, they are capable of storing carbon. The topic of carbon being stored in building materials and its assessment has been recently discussed in several research [36–39]. A recent study has been performed on multi-objective optimization of bio-based materials [40]. It has been shown that fast-growing materials have a high potential to decarbonize the building stock [39].

Regarding the carbon storage assessment, several methodologies have been developed, namely 0/0, $-1/+1$ approach, and dynamic approach. The first one, 0/0 approach, which is also called “carbon neutral” approach, does not consider biogenic carbon stored and assumes 0 uptake of CO₂ and 0 release of CO₂ in the end of life. The second one, $-1/+1$ approach, in opposite to the first one, considers both the negative uptake of CO₂ in the module A of LCA and positive release of CO₂ in the module C. Such approach is recommended by most of the existing standards [41–43]. The main drawback of these analyses is that they do not consider the amount of time the carbon is stored in the building envelope and the amount of time needed for the material to regrow. To solve this issue, dynamic carbon storage methodology was proposed by Guest et al [44]. In this methodology, biogenic global warming potential (GWP) is proportional to the period of material to regrow and the amount of years the material is kept in a building component. In a recent paper, it has been shown that the dynamic approach is the most robust one within the existing methodologies [45].

In this paper, we use the integrated assessment of LCCA and LCA and include dynamic carbon storage to see the effect of the potential offset of emissions. The goal of this work is to identify whether bio-based materials can provide a robust, climate-friendly and cost-effective building renovation solution considering the future uncertainties. First, we define building renovation scenarios, which are comprised of the thermal insulation considering bio-based and conventional materials, and the fossil heating system replacement. Then, we identify the possible uncertainty sources related to all stages of analyses and describe them in terms of their range and distributions. Afterwards, we define the optimal renovation through the multi-objective robust optimization techniques,

coupling the NSGA-II methodology with surrogate modeling. The optimal solutions are then compared in a probabilistic context. The methodology is applied to a case study of a multi-family house located in Switzerland.

2. Methodology

The methodology of the paper is shown in Fig. 1. As a first step, integrated analyses of LCA and LCCA are performed and carbon storage assessment is added to the analysis. Then, possible renovation scenarios considering bio-based and conventional materials are defined as well as related uncertainty sources. A multi-objective optimization considering the determined uncertainties is then performed. Finally, the optimal solutions in a probabilistic context are compared to each other's.

2.1. Integrated assessment LCA & LCCA

First, the integrated assessment of LCA and LCCA is created. The stages of production, operation, replacement, end of life are included in the analysis. For LCCA, a stage of repair as a percentage of investment costs is also included as suggested by the Swiss Centre for buildings' rationalization (CRB) [46]. The functional unit of the analyses refers to

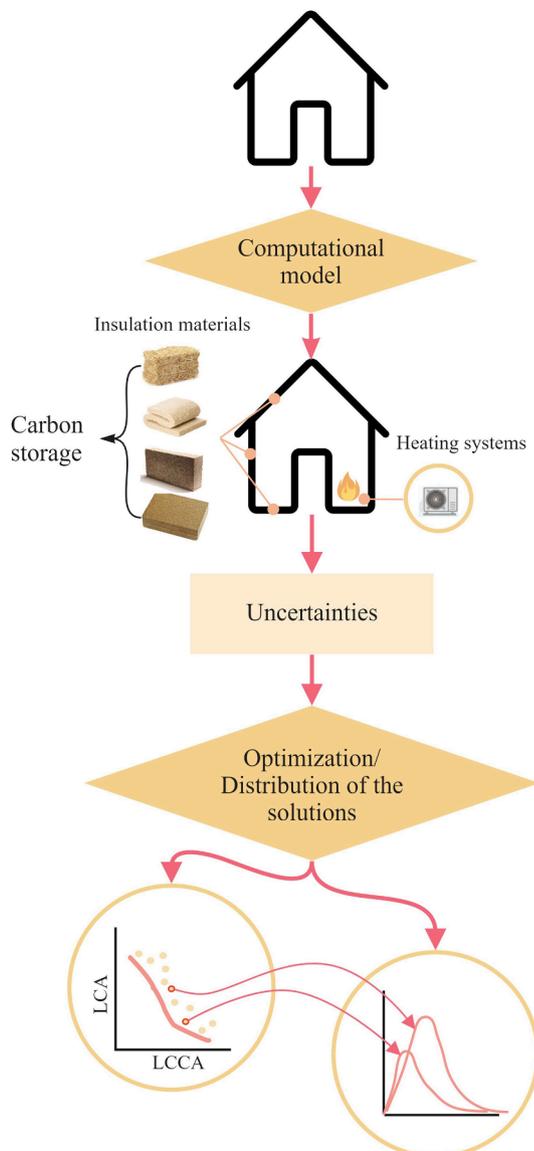


Fig. 1. Methodology of the paper.

the building operation over its lifetime. The lifetime of a building is considered to be 60 years as suggested by the local standard [47]. The contribution to climate change (GWP) is the only environmental impact category assessed and is expressed in $\text{kgCO}_2\text{eq.}$. Swiss francs are used as an indicator for the economic cost calculation. During the assessment of the operational stage, quasi-static heating demand calculation is used according to the local Swiss regulation SIA 380/1 [48]. In this assessment, monthly energy balance equation is applied, which includes the losses associated with building envelope and ventilation losses as well as solar and occupants related heat gains. The overall detailed procedure can be found in Galimshina et al [49].

2.1.1. Carbon storage

Carbon storage can be defined as the sequestration of carbon in products for a certain period of time, resulting in a (temporary) reduction of the CO_2 concentration in the atmosphere [50]. In order to account for the positive effect of carbon storage, some LCA methods, namely the British Publicly Available Specification (PAS) 2050 [51] and the European Commission's International Reference Life Cycle Data System Handbook [52] allow the use of a credit for temporary carbon storage. The way to calculate this temporary carbon storage is currently a highly discussed issue [45,53,54]. However, it seems accepted that Bio-based products, provide an opportunity to store carbon in buildings constructed with these materials [55,56]. In order to capture the effect of time, dynamic approaches have been developed. Levasseur et al [53] proposed an approach based on time-dependent characterization factors. Cherubini et al. [57] developed specific characterization factors for biogenic CO_2 considering the rotation period of biomass. The longer the rotation period, the longer the mean stay of CO_2 in the atmosphere and therefore the higher the contribution to climate change is. Guest et al. [58] extended the method proposed by Cherubini et al. [57].

In this work, the benefit of using bio-based material is based on the GWP_{bio} index calculation proposed by Guest et al [44]. To account for the timing of emissions, the GWP_{bio} index is based on the period of material's regrow (rotation period) and the amount of years the material is stored in the building envelope. The most often used bio-based materials in construction field with the consequent GWP_{bio} index depending on the storage according to the Swiss standard [47] is shown in Fig. 2. In Switzerland, structural materials have 60 years amortization period life expectancy while insulation materials have 30 years and heat generation systems have 20 years. In reality, this period can be longer or shorter depending on many factors [59]. For example, in case straw material is used as an insulation material, the GWP_{bio} index would be -0.23 .

Once the GWP_{bio} index is determined, it is multiplied by potential carbon storage, the calculation of which is based on CEN/TC 175 standard [60].

2.2. Renovation scenarios

In this work, the renovation scenarios are defined based on the thermal insulation of the envelope and the replacement of a fossil heating system by the same one with higher efficiency or low carbon ones such as wood pellets boiler or air-to-water heat pump. District heating was not taken into account in this paper considering that carbon intensity values provided by wood or gas for district heating would be similar to the one of individual boilers. Regarding the envelope insulation, bio-based solutions and conventional ones are identified. Bio-based solutions include hemp mat, straw bale, wood fiber and hempcrete. One conventional solution such as EPS is added in the analysis in view of comparison. The properties of the materials and selected thicknesses can be seen in the Table 1. The applied thicknesses are selected according to the possible market ranges. The embodied emissions for hempcrete, straw and EPS are taken from KBOB database [61], the data for wood fibre and hemp mat are taken from EPDs [62,63]. The modules A1-A3 are included in embodied emissions to stick with the

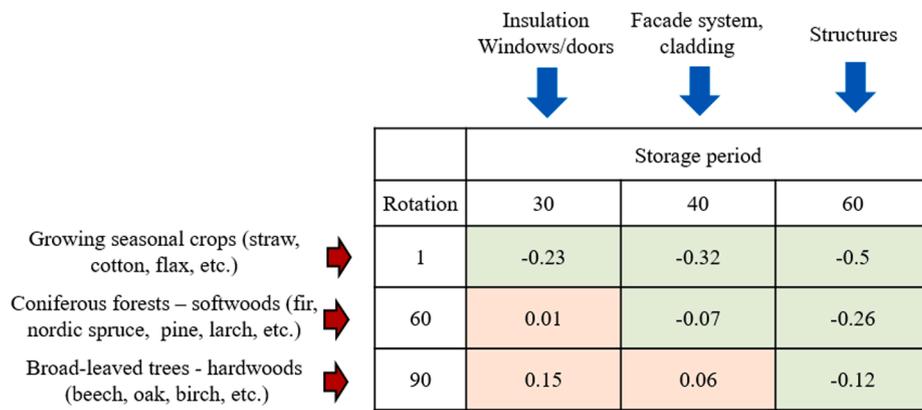


Fig. 2. GWP-index for construction sector. GWP_{bio} values taken from Guest et al [44]. Storage period taken from the amortization period of SIA 2032 [47].

Table 1

Properties of the selected insulation materials.

Material	Thickness (mm)	Thermal conductivity (W/m*K)	Density (kg/m ³)	Fiber content (%)	Carbon content* (%)	Embodied emissions (kgCO ₂ eq./m ²)	Investment cost (CHF/m ²)
Wood fibre	60	0.038	50	100	50	1.38	55
	100					2.30	65
	120					2.76	109
	200					4.60	130
Hempcrete	80	0.07	600	64	45	13.82	53
	200					34.56	93
	300					51.84	124
	380					65.66	141
Hemp mat	30	0.04	37	100	45.7	0.69	34
	60					1.38	43
	120					2.76	62
	180					4.14	76
	220					5.06	87
Straw	480	0.066	105	100	44.3	4.54	104
	200					1.89	86
	700					6.62	115
EPS	50	0.033	30	0	0	11.46	36
	100					22.92	56
	150					34.38	71
	200					45.84	87
	300					68.76	111

*carbon content of a dried mass product.

boundaries of the KBOB data.

Besides the building envelope, the replacement of the heating system is also considered. Within the possible heating types, a wood pellets boiler, an air-to-water heat pump with the coefficient of performance (COP) of 3.5 and a conventional gas boiler are examined. In case of the heat pump, the lower flow temperature differences are considered and the replacement of the heat distribution system (steel radiators) is performed if the heating load is not lowered sufficiently.

2.3. Uncertain parameters and multi-objective robust optimization under uncertainties

The next step in this work is to identify uncertain parameters and describe them in a probabilistic context. Several groups of uncertain parameters are defined - climate change, operational costs and environmental impacts, service lives of building materials, embodied environmental impacts and investment cost, system performance and user-oriented parameters. A detailed parameters' description can be seen in Galimshina et al [35] and ranges with distributions for each parameter can be found in Supporting information of this paper.

Once the parameters are defined and described, the multi-objective optimization is performed. First, to limit the amount of the parameters to the most influential ones and decrease the computational time, sensitivity analysis using Sobol' indices is performed [64]. The

optimization is performed for two quantities of interest (QoI) – LCCA and LCA. Some of the parameters are considered exogenous, or random, and modelled according to the defined distributions presented in Table S1 of the Supporting information. Other parameters are considered deterministic, for example the renovation choices presented in Table 1. These parameters are treated as categorical in this assessment. In this work, the multi-objective robust optimization consists in minimizing the 90th percentile of LCCA and LCA, given the uncertainties in the input with respect to the multiple options in renovation scenarios. For optimization, we use NSGA-II, one of the most popular and efficient algorithms for multi-objective optimization, which is especially suitable for the solution of problems involving mixed categorical-continuous parameters. [65]. However, one of the drawbacks of NSGA-II is its heavy computational burden considering here the cost of probabilistic assessment within the objective functions' evaluations. To reduce this computational cost, we use surrogate modelling, in particular Gaussian process modelling also known as Kriging [66]. The surrogate model is built over a number of original model evaluations, called experimental design, which is normally a matter of a few hundred of evaluations. Once it is built, the original model is replaced by metamodel and further evaluations take considerably low amount of time, the order of a second. This allows us then to use a built metamodel for NSGA-II and significantly lower the amount of time for evaluation. It must be noted that the precision of the results depends on the accuracy of the built model. To

ensure the validity of the obtained Pareto front, the error is estimated locally after each surrogate model evaluation during the optimization process. The surrogate is then locally enriched when needed in order to sequentially improve the quality of the estimated Pareto front. The details of the optimization process can be found in Moustapha et al [67].

2.4. Probabilistic comparison of the optimal solutions

Once the optimization process is finished, the Pareto front of the most cost-effective and climate-friendly solutions is obtained. Within the obtained Pareto solutions, median, the most environmentally-friendly and the most cost-effective solutions are afterwards analyzed. The median solutions for different heating systems are compared in a probabilistic context. The solutions are also compared to the conventional renovation scenario and non-renovated building to see the magnitude of the impacts of the optimal renovation scenarios.

3. Case study

During this work, the applicability of the methodology is tested on a case study. The case study building is located in Western Switzerland. The building is taken from the eRen project, where building representatives for different construction periods were described [68]. The eRen project defined 15 building models to represent the residential building stock for multi-family houses in Western Switzerland. The building-representatives are based on the analysis of 193 buildings based on professional building owners stock, technical guidelines and the inventory of dwellings in the canton of Genève. These buildings represent from 72 to 89% of the overall dwellings number in Switzerland [68]. The building-representatives have different energy reference areas as well as different structural materials, e.g. reinforced concrete, hollow bricks, or stone. They also range in energy performance and amount of insulation. However, in general, most of the buildings were not insulated unless building renovation had been performed previously. The multi-family house used in this case study represents the buildings constructed in the 70's. This building has the average energy performance for the buildings constructed between 1919 and 1980. These buildings represent the key target for renovation strategies in Switzerland as they are abundant [69], usually with low energy performance and are not submitted to historic conservation laws which can hinder renovation strategies for older buildings. The basic building characteristics are presented in Table 2. The sketch of the building with components applied for renovation can be seen in Fig. 3. The case study is located in the temperate climate zone with four seasons each year. The average yearly temperature is 9.4 °C. The coldest month is January where the average temperature is 0.3 °C and warmest month is July with an average temperature of 18.7 °C. The heating design temperature is -7 °C and the altitude is 490 m. In general, surface temperatures increased in Switzerland in all the cantons since 1864. Nine out of the ten warmest years have been recorded in 21st century and will further increase in all the regions with stronger warming over summer months.

The current building is applied for integrated LCA and LCCA assessment. The renovation solutions shown in Table 1 are considered as

Table 2
Basic description of a studied building.

Location and context of the building	Western Switzerland, detached multifamily building in a rural area [78]
Year of construction	1972
Energy performance (heating) [kWh/m ² ,a]	90
Energy reference area [m ²]	1446
Walls construction	Double brick wall
Slabs construction	Reinforced concrete
Windows construction	Double glazing with low-E layer, PVC frame
Heating system	Gas boiler

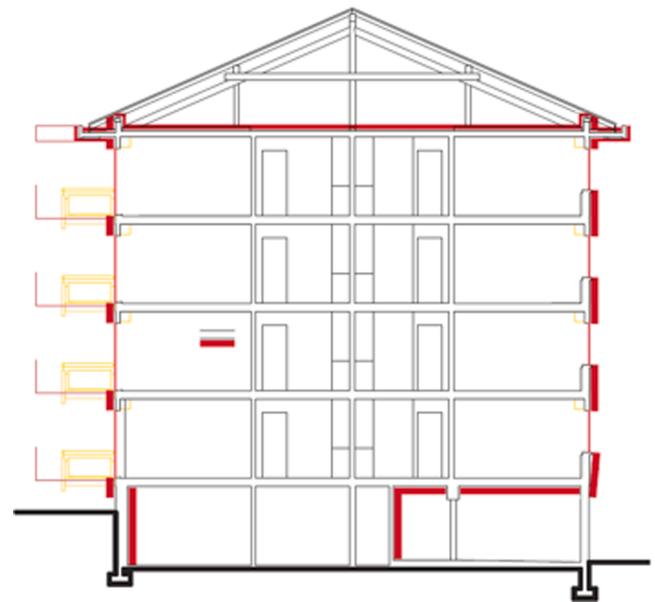


Fig. 3. Building sketch with renovated components marked in red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

design parameters in optimization. The latter is performed for each heating system separately. Due to the possible moisture issues and risk of mold growth, it is assumed that only EPS and hempcrete with variable thicknesses are added to the underground components.

The proposed renovation solutions examined for this case study are also compared to the conventional renovation scenario, which can be seen in the Table 3.

4. Results

First, global sensitivity analysis was performed to limit the number of parameters and the results for each heating system taken separately can be seen in the Table S2 in Supporting information. The results of optimization for three examined types of heating systems, can be seen in Fig. 4. It can be noticed that three types of heating systems are clearly separated on a figure in terms of LCA and are considerably close in terms of LCCA. The figure also shows the median and extreme solutions for each heating type and the type and amount of the material needed for each solution and component in the building.

Considering the amount of needed material for renovation, a clear trend can be seen where the more climate-friendly solutions require more bio-based materials while the most cost-effective solutions contain less material and more conventional EPS. The median solutions are also shown in Table 4, the extreme solutions for each heating type can be found in Supporting Information.

The median solutions were afterwards compared in a probabilistic context and kernel density estimation plots were built (see Fig. 5). In this comparison, it is clear that all solutions lie in the same area in terms of economic performance, while they are quite separated considering greenhouse gas emissions performance. Solutions of non-renovated

Table 3
Conventional renovation scenario.

Heating system	Exterior wall	Int. walls ag. cellar	Ceiling	Floor (against cellars)	Windows
Gas	18 cm rock wool	16 cm XPS	20 cm mineral wool	–	Triple glazing, PVC frame

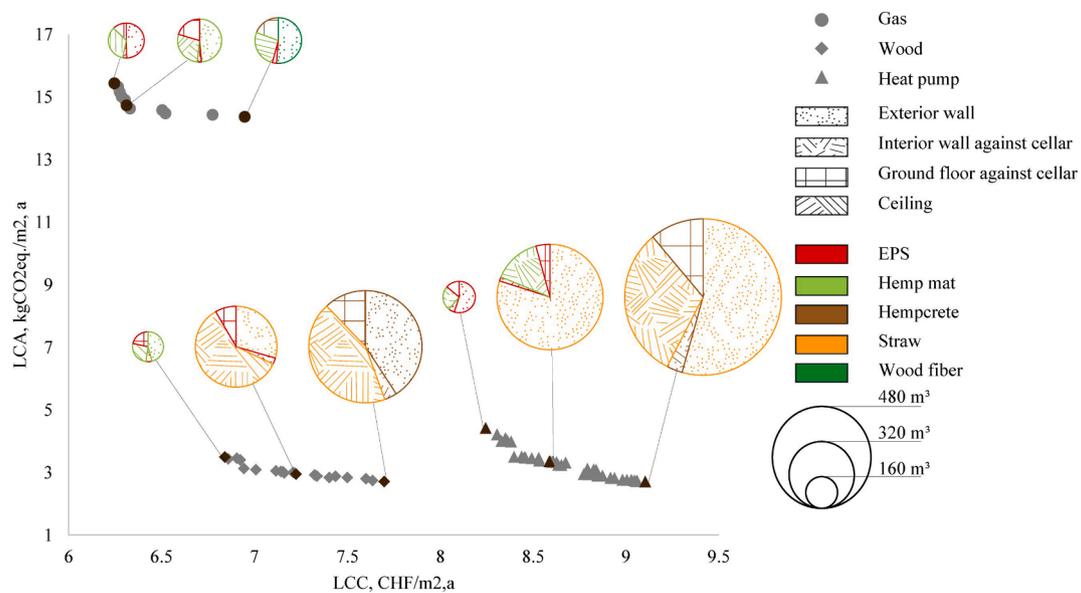


Fig. 4. Optimization results for the three examined heating types. The pattern represents the type of a component, color shows the type of a material and the size represents the amount of material needed for a renovation scenario.

Table 4
Median solution for three selected heating types.

Heating type	Exterior wall	Int. walls ag. cellar	Ceiling	Floor (against cellars)	LCCA (CHF/m ² .a)	LCA (kgCO _{2eq.} /m ² .a)	Biogenic GWP (kgCO _{2eq.} /m ² .a)
Gas	Hemp mat, 180 mm	EPS, 100 mm	Hemp mat, 180 mm	EPS, 200 mm	6.3	14.7	-0.04
Wood	Straw bale, 200 mm	EPS, 150 mm	Straw bale, 700 mm	EPS, 150 mm	7.2	3.0	-0.19
Heat pump	Straw bale, 700 mm	EPS, 100 mm	Hemp mat, 220 mm	EPS, 100 mm	8.6	3.2	-0.28

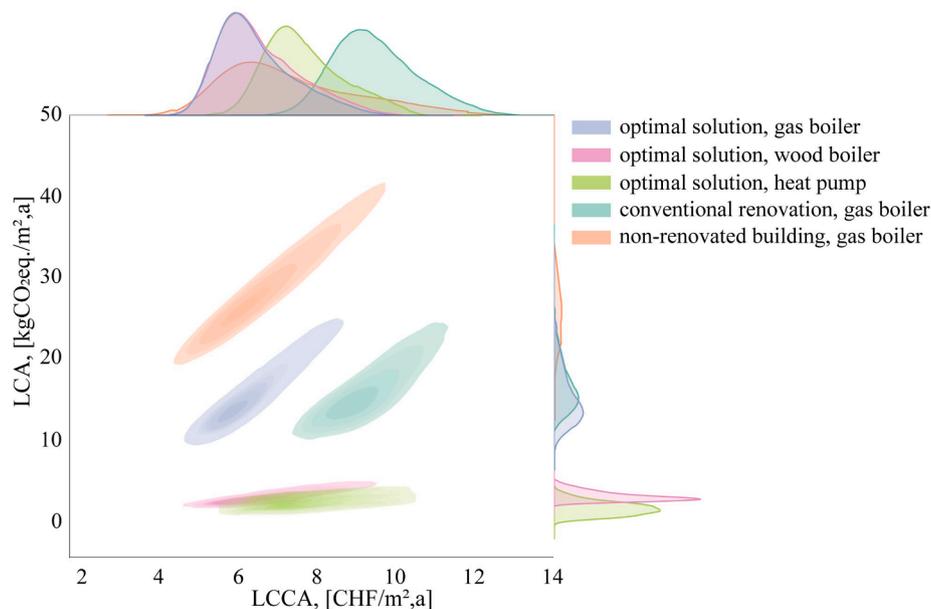


Fig. 5. Probabilistic comparison of the median solutions.

building, gas and wood pellets have almost the same costs while wood pellets solution has by far lower LCA results.

It can also be seen that the conventional solution has the highest cost but a lower GWP than non-renovated building. The non-renovated building solution shares the lowest cost with the gas boiler solution considering median solutions, while it has the highest amount of kgCO_{2eq.} for the building life cycle. The heat pump shows the lowest LCA

results but higher cost than wood pellets boiler solution, which has similar LCA outcome.

Regarding robustness, no matter the underlying uncertainties, wood pellets solution and heat pump show the highest robustness in LCA while non-renovated solution is the least robust one. So a robust solution can be made in terms of GHG emissions. The same cannot be applied to LCCA as none of the solutions shows high robustness and the non-

renovated solution has again the lowest robustness.

In order to understand the most influential stage in LCA and LCCA, we have compared the median solutions to see the shares of embodied-operational impact and the share of potential carbon storage. The results can be seen in Fig. 6a and b.

Embodied GHG emissions (A1-A3) have a small share in the overall impact, while insulation material type as emissions are fully dominated by the operational GWP. It can also be clearly seen that carbon storage does not contribute significantly to lowering the emissions. Results are different for LCCA as investment cost has either almost the same cost as operational ones, for example gas and wood, or is even dominating to total life cycle cost, for example heat pump or conventional renovation. Avoiding renovation does not drastically change overall costs over the life cycle of the building, however, the burden of this total costs is clearly shifted from the user to the owner, regardless of the selected renovation strategy.

5. Discussion

In a previous study, it was identified that robust renovation scenario comprised fossil heating system replacement and a small amount of insulation on the facades considering conventional insulation materials and keeping the same windows [35]. It was noticed that the replacement of only the heating system is more effective than deep energy renovation including the envelope. The current study unveils that the use of bio-based materials provides opposite results where the thick amount of insulation, e.g. 60 cm of straw bale, provides the most environmentally – friendly and cost-effective solution. This can be explained by the low embodied carbon of bio-based insulation and potential carbon storage. However, it can be clearly seen that the heating system is still the most sensitive parameter in an existing building (where most of the construction materials especially the structural ones are already there and do not lead to additional substantial investment and additional GHG emissions unlike for a new construction). The influence of the heating system was also confirmed by previous studies [49,70]. The identified optimal solution of wood boiler or heat pump does not only provide a robust and climate-friendly solution but also contributes to energy savings and consequently, reduces the energy bill of its residents.

It is interesting to note that only in one solution wood fiber insulation is considered as an optimal one. In all other scenarios, hemp or straw insulation are chosen. This can be attributed to the fast period of regrow of straw and hemp (1 year) in comparison to wood (20–60 years) which induces a negative GWP_{bio} -index even for relatively short storage periods in buildings (30 years). This is an important outcome in favor of the fast-growing bio-based materials, which is also in line with previous studies [39,71].

The current study also shows a small impact of embodied GWP in the overall share of the GHG emissions. This can be partially explained by the low embodied GWP of bio-based materials. However, even looking

at the conventional scenario where EPS is used as insulation, we can see a clear dominance of the operational energy. This is in line with a previous study [72] showing that insulation materials have a very small share of embodied emissions. The results also indicate a very small impact of carbon storage in the assessment. However, the impact on a bigger scale needs to be considered. In the previous research, it has been shown that the amount of land in Europe for growing straw is sufficient to supply the building stock [73] and, in case straw is used as an insulation material, up to 3% of the overall GHG emissions from all sectors can be offset by storing carbon in building envelope [39]. This is indeed a small contribution but as every small steps counts, this should be considered in future renovation policy recommendations.

Another important note is the methodology used for the carbon storage calculations. Within the three currently available methodologies, the dynamic approach was selected for this study following previous critical review [45]. However, we have analyzed the possibility of using other methodologies. The results are shown in Fig. 7.

From the Fig. 7 we can see that the most optimistic methodology, the so called $-1/+1$ approach, has the smallest LCA result showing a very small part of results being even climate positive. On the opposite, the classic method accounting only for fossil-based emissions (0/0 approach) has higher impact than the dynamic approach. The dynamic method gives a small incentive for the use of bio-based, but stay within the same range of results as conventional method. As such, it seems to be the most reasonable method to account for carbon storage. Indeed, it includes the potential storage and avoids the risk of accounting only for the positive effect of bio-based materials without considering the release of emissions in the end of life.

Finally, an important question is the wood availability in case building renovation is performed using bio-based materials. In a previous paper, we have identified that optimal renovation scenario consists of the replacement of the fossil heating system and a little amount of insulation and showed that only heating system replacement is more efficient than sole deep envelope renovation [35]. One would then need 43,640 GWh/year in order to fulfill the energy demand of the Swiss building stock. This is far beyond what the Swiss forest can provide as energy source. A recent report [74] estimates the wood energy potential in Switzerland to range from 2,500 and 25,100 GWh/year depending on the extraction intensity (from sustainable to maximum theoretical). The theoretical potential is the amount of wood as energy source that is available and sustainable potential is the theoretical potential after excluding ecological, economic, legal and political constraints. In this paper, we have identified that the optimal renovation consists of the replacement of the heating system but also a thick amount of insulation once considering bio-based materials. According to this optimal solution with wood boiler (or by extension with district heating using wood as energy carrier, a more and more popular solutions favor by Swiss municipalities), the mean potential energy saving is around 44%, which represents a need for 24,000 GWh/year once upscaled to the building

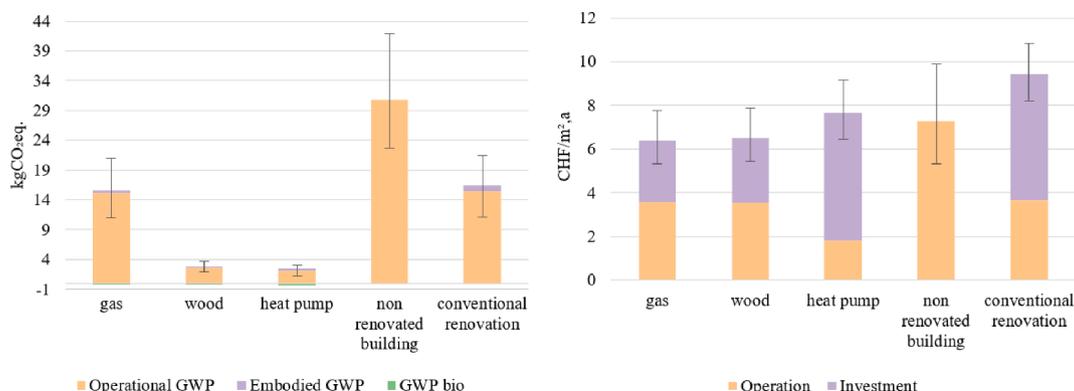


Fig. 6. a and b. Median solutions divided by stages of the analysis.

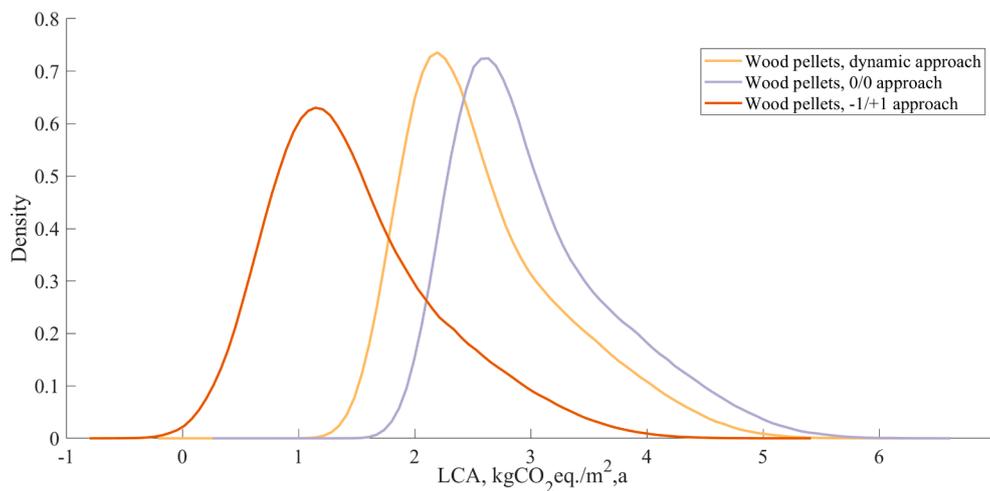


Fig. 7. Comparison of the methodologies for carbon storage calculation.

stock. This demand could theoretically be fulfilled by wood considering a very intense harvesting activity. However, considering the economic, ecologic and social restrictions, only 11% could be covered. This means that only a combination of wood boilers (and/or district heating with wood as energy carrier) and heat pumps can be applied for upscaling the solution provided by this study to the building stock. Both systems will put additional stress to respectively the wood forestry and industry sectors and to the electricity supply. Furthermore, these results represent the deterministic and rough estimation and further detailed studies would be needed to apply the uncertainty sources.

Limitations

This study is limited to the application of the methodology for one building-representative from one construction period. The current case study represents the target for renovation in Switzerland as a construction period of 1970th have the biggest amount of residential buildings that are currently in need of renovation. However, to check the applicability of the methodology, a bigger number of buildings should be considered.

Another aspect that was not considered in this work is the potential future prices and circumstances on the increasing use of wood pellets. In this work, the applied uncertainty range explains the potential variation of the seasonal costs however, it has been shown that the future development of the wood pellet prices is highly uncertain due to the policies that will influence the market [75]. Furthermore, the increasing demand for forest products driven by the green economy is creating new challenges for forest management and the further increase in the use of wood pellets for heating might have detrimental consequences [76]. Further studies should be carried out on the future uncertainty of the market price trends and evolutions of the wood pellets heating.

Another important aspect that was not considered in this work is the thermal comfort. In previous research it was identified that thick insulation (e.g. triple glazing and 20 cm insulation) leads to a large amount of overheating hours [35]. This risk of lowering indoor comfort by reducing energy consumption is exacerbated by climate change. There is therefore a limitation to push for envelope renovation [35]. However, it is known that when considering the hygrothermal properties of bio-based materials, we can achieve stable indoor temperature and level of comfort despite outside temperature fluctuations [77]. As a consequence, using bio-based materials as insulation could allow to accommodate the two antagonist objectives of good indoor comfort, which requires low insulation (when conventional materials are used) and small energy consumption in order to reduce energy bill and CO₂ emissions. Unfortunately, our current model using only semi-static

energy simulation was unable to grasp this aspect. This would certainly requires further studies as our current study demonstrates that bio-based materials can't be fundamentally justified through a drastic reduction of CO₂ emissions.

Another limitation is the extreme range values of some of the input parameters. The reason behind this was to avoid underestimation of the parameters that were not properly covered. However, the uncertainty range for some parameters could be narrowed down with more research performed. This would secure the result but won't change it as the results also show that the major variation comes from climate change for all heating system types (See [Supporting information](#)), which variation was carefully addressed in a previous study [35].

Another limitation of this study is that only the replacement of a heating system and envelope insulation were considered without taking into account possible local renewable energy production. The inclusion of the renewable energy installations such as photovoltaic panels or solar thermal collectors could provide more insights towards climate-friendly and cost-effective renovation solutions. However, conventional solar photovoltaics and solar collectors are also carbon intensive technologies, the payback of which needs to be further explored, especially in Switzerland where the electricity CO₂ content is already low due to a high share of hydropower and due to the current high cost per kWh for individual solar collectors compared to PV and other energy solutions. There is also potential uncertainty sources such as efficiency rates or degradation of the panels that would need to be included.

Recommendations

Our results show clearly that the heating system is the most crucial parameter for renovation. Choosing wood pellet or heat pump significantly improve the environment and economic costs. It also provides a more robust solution considering future uncertainty than fossil-based heating systems.

Once the heating system is chosen, the insulation type acts on a second level and allow distinguishing between the most climate-friendly and the most cost-effective solutions. Actually, reaching the most climate-friendly solution involves a high amount of insulation on the facades and using only bio-based materials. Concerning the cost-effective solution, optimal renovation implies considerably lower amount of insulation and EPS as a material. The most robust solution in terms of LCA is the wood boiler or the heat pump with the big amount of bio-based insulation on the facades. The least robust solution is the non-renovated building.

To summarize, the use of bio-based materials combined with low carbon energy system provides an optimal solution where the large

amount of insulation material reduces considerably the heating demand. This is beneficial for the environment as well as for the users' operational costs for heating. Furthermore, the use of bio-based materials compared to EPS allow maintaining a good indoor comfort thanks to hygrometric buffering capacity and insulate without being in a lock-in situation where the embodied emissions of insulation materials counteract the savings from energy demand reduction.

CRedit authorship contribution statement

Alina Galimshina: Conceptualization, Methodology, Software, Writing – original draft. **Maliki Moustapha:** Methodology, Software, Writing – review & editing. **Alexander Hollberg:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Pierryyves Padey:** Conceptualization, Methodology. **Sébastien Lasvaux:** Methodology, Resources, Writing – review & editing. **Bruno Sudret:** Conceptualization, Software, Supervision. **Guillaume Habert:** Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of Competing Interest

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

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.apenergy.2022.119102>.

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