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A scenario analysis of the life cycle greenhouse gas emissions of a new residential area

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Abstract

While buildings are often credited as accounting for some 40% of the global greenhouse gas (GHG) emissions, the construction phase is typically assumed to account for only around one tenth of the overall emissions. However, the relative importance of construction phase emissions is quickly increasing as the energy efficiency of buildings increases. In addition, the significance of construction may actually be much higher when the temporal perspective of the emissions is taken into account. The construction phase carbon spike, i.e. high GHG emissions in a short time associated with the beginning of the building's life cycle, may be high enough to question whether new construction, no matter how energy efficient the buildings are, can contribute to reaching the greenhouse gas mitigation goals of the near future. Furthermore, the construction of energy efficient buildings causes more GHG emissions than the construction of conventional buildings. On the other hand, renovating the current building stock together with making energy efficiency improvements might lead to a smaller construction phase carbon spike and still to the same reduced energy consumption in the use phase as the new energy efficient buildings. The study uses a new residential development project in Northern Europe to assess the overall life cycle GHG emissions of a new residential area and to evaluate the influence of including the temporal allocation of the life cycle GHG emissions in the assessment. In the study, buildings with different energy efficiency levels are compared with a similar hypothetical area of buildings of the average existing building stock, as well as with a renovation of an area with average buildings from the 1960s. The GHG emissions are modeled with a hybrid life cycle assessment. The study suggests that the carbon payback time of constructing new residential areas is several decades long even when using very energy efficient buildings compared to utilizing the current building stock. Thus, while increasing the overall energy efficiency is important in the long term, the construction of new energy efficient buildings cannot be used as a means to achieve the short term and medium term climate change mitigation goals as cities and governments often suggest. Furthermore, given the magnitude of the carbon spike from construction and its implications, the climate change mitigation strategies should set reduction targets for the construction phase emissions alongside the ones for the use phase, which currently receives almost all of the attention from policy-makers.

Keywords: carbon spike, greenhouse gas, GHG, residential development, construction, life cycle assessment

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1. Introduction

Greenhouse gas (GHG) emissions drive global climate change, which is considered one of the most important global challenges of the near future [1]. The Intergovernmental Panel

on Climate Change (IPCC) announced in 2007 that climate change is due to GHGs released by human activities with the probability of 90% and that carbon dioxide (CO₂) is considered the most important GHG [1]. IPCC presents future scenarios that estimate the increase in the global average temperature and the rise of the average sea level with different changes in global carbon emissions compared to the year 2000 level [1]. If the change of global carbon emissions in the year 2050 is -30% to +5% compared to the year 2000 level, the global average temperature increases 2.8–3.2 °C and the average sea level rises 0.6–1.9 m. In the most optimistic scenario the carbon emissions decrease by -85% to -50% by the year 2050. The result is an increase of 2.0–2.4 °C in the global average temperature and a global sea level rise of 0.4–1.4 m. The pessimistic scenario is an increase of +90% to +140% in carbon emissions. The result would be an increase of 4.9–6.1 °C in the global average temperature and a rise of 1.0–3.7 m in the global average sea level. Thus, rapid action is needed to achieve even the less optimistic scenario.

According to recent studies, the building sector is considered to have the most feasible potential worldwide for reducing the GHG emissions in the short term i.e. the time frame of the near future climate mitigation goals [1, 2]. Buildings' share of the total worldwide energy consumption is approximately one third [3]. In Nordic countries, the heating of buildings alone accounts for as much as two thirds of buildings' GHG emissions [4, 5]. While the annual renewal of the Finnish building stock is approximately 1%, the densification of urban structure has been stated as one of the key means to capitalizing the mitigation potential related to buildings [6, 7], infill construction of new energy efficient residential areas being one of the key strategies [8]. This will mean that a lot of new construction will take place during the next couple of decades. In addition, the construction of new energy efficient buildings is seen as a mitigation action itself: for example, Finland's environmental agency and several major cities, in their strategies, consider the construction of new energy efficient buildings as one means to reach the future carbon mitigation goals [9–11].

While life cycle emissions of construction projects have been comprehensively studied [4, 12, 13], the whole building life cycle has often been inadequately taken into account. According to previous studies, the life cycle emissions of the construction (including the embodied carbon of building materials) only cause one tenth of the building's total life cycle emissions and the energy consumption of the use phase has been stated as the most significant single source of emissions [4, 14]. Accordingly, the relevance of the construction phase is often considered minor. However, some recent studies indicate that the production phase of an energy efficient passive house may account for more than a half of the building's total life cycle primary energy use [15]. This is due to the increase in building energy efficiency, increasing the relative importance of the construction phase, including the emissions embodied in the materials. The energy efficient building types have higher primary energy use in the production phase and lower heating requirements in the use phase, so the relation of the production and the use phase

emissions is evening up [15]. Thus, increases in the amount of embodied energy in the construction phase of an energy efficient building result in fewer GHG emissions in the use phase [16].

However, the emissions of the construction phase occur at the beginning of the building's life cycle and in a very short time horizon. Thus, the importance of the construction phase might be even higher when the temporal allocation of the emissions, that is, the actual time of occurrence of the emissions, is taken into account [14, 17]. According to recent studies, releasing GHGs today may be more harmful than releasing them in the future [18]. The reason is that the real problem of carbon emissions is the increasing concentration of GHGs in the atmosphere, which increases the importance of emissions taking place early in the life cycle compared to those occurring in the distant future. Although the construction of new energy efficient buildings might lead to low carbon emissions in the future, the construction phase causes a high amount of GHGs in a short time period. From the climate change point of view, these emissions may cause climate change to advance in the undesired direction severely enough that long-term advances in better energy efficiency occur too late.

Notwithstanding, previous research indicates that studies with life cycle assessment usually do not take the temporal and spatial profiles of the emissions into consideration [14]. Truncations and assumptions of spatial and temporal profiles usually lead to uncertainties in the impact assessments of these studies [19, 20]. In particular, irregularly occurring emissions are often left outside the analysis [21]. Owens further discusses the spatial and temporal limitations of life cycle assessment (LCA) results [21].

Recent studies have focused on the significance of the temporal allocation of the emissions. For example, Levasseur *et al* argue for the importance of the temporal aspect in life cycle assessments [22]. They developed a dynamic LCA model to include the temporal profile of emissions into the assessments [22]. Schwietzke *et al* in their recent study on the implications of a temporal allocation of the GHG emissions in the field of corn ethanol farming, demonstrated how the time perspective affects the assessment results when a long time span is concerned [18]. Their results indicated that releasing GHGs early in the product life cycle is more harmful than causing them in the later stage because of the cumulative climate impacts of GHGs in the atmosphere [18]. Their application concentrated on analyzing and comparing biofuels and fossil fuels, but a similar idea can be applied to buildings as well, as some early attempts by Junnila, Dutil *et al* and Heinonen *et al* show [14, 17, 23].

As these studies have already suggested, while being accountable for only a minor share of the overall life cycle emissions, the construction of new residential areas still generates a significant amount of GHG emissions, called here a 'carbon spike'. The carbon spike is caused in a very short time horizon from less than a year to a maximum of a few years. The legislation and regulations concerning the eco-efficiency of buildings are predominantly focused on the use phase because of its large overall share of the

life cycle GHG emissions, whereas the construction phase emissions remain merely unregulated [17, 24]. The question of whether the construction of new residential areas can contribute to achieving the current climate change mitigation goals or whether construction just raises the level of carbon concentration in the atmosphere, while being highly relevant due to the high carbon spike of construction, remains mostly unanswered.

The purpose of this study is to evaluate the relevance of the construction phase carbon spike when the temporal allocation of the residential development related emissions is taken into account. By concentrating on the carbon spike and analyzing through different building scenarios, the study advances the discussion on the significance of the spike, which, according to our knowledge, was initiated by Heinonen *et al* [14]. Also, the study analyzes whether similar carbon spikes exist in renovation projects of the old buildings including energy efficiency improvements. This is a topic that is much less studied than the emissions of new construction projects, but still of very high current importance; there is a huge ageing inefficient building stock existing in all developed countries.

The study employs a life cycle assessment method on a case residential development area in Southern Finland to demonstrate that the importance of the construction phase emissions might be significantly higher than what is often anticipated when the time perspective is taken into account in the assessment. Furthermore, using a scenario analysis, the study stresses that new residential construction, no matter how energy efficient the new buildings are, cannot be used as a means to achieve short and middle term climate change mitigation goals.

The paper is structured as follows. Section 2 will present the LCA method utilized, specifically the employed hybrid LCA method, and introduces the case area of the study as well as the research design. The results of the study are presented in section 3. Finally, section 4 discusses the implications of the results and the uncertainties related to the assessment.

2. Method and research process

2.1. The hybrid LCA method of the study

The method used in the study is an application of a hybrid life cycle assessment [25]. The hybrid LCA method is considered as the best method within LCA methods in complex system modeling contexts [26]. The hybrid approach combines features of two popular LCA methods: a process LCA and an input–output (IO) LCA. The result is a LCA model that builds on the advantages and reduces the disadvantages of the two traditional LCA methods [27].

Of the two, process LCA is the most traditional way of conducting a LCA. The method is based on local and current process data that is used to convert amounts of materials and energy into carbon emissions. The carbon emissions of each process in the product life cycle are analyzed separately according to the boundary definition of the modeling. The emissions are then added together to reveal the total life cycle

emissions. The advantages of process LCA lie in the accuracy of the model [28]. Since every process is analyzed separately using proper process data, the process LCA method is also suitable in comparing similar products within one product category [28].

The perspective of process LCA is bottom up, making it vulnerable to truncation errors from the boundary definition problem [25, 28]. As the amount of processes in the product life cycle is almost indefinite, the chain of processes for the analysis has to be cut at some point. Thus, processes that also affect the results may be left out of the analysis with the irrelevant ones. Other disadvantages of the assessment method are the high amount of process data and the heavy workload related to the modeling.

The second method, IO LCA, is based on converting monetary costs into carbon emissions based on matrices that use industry average data. IO LCA is a top down method, which does not suffer from truncation errors [25, 28]. Thus, the whole production chain of a product is taken into account in the analysis without the problem of cutting the modeling chain. Performing IO LCAs is also time-effective and assessment models are often available free of charge [27].

However, IO LCAs suffer from aggregation error. The method is usually based on national average sectors and is therefore unable to distinguish different manufacturing processes of similar products from each other [4, 25, 27]. Thus, IO LCA is not a suitable method for comparing different products within one industry. Furthermore, within each national economy, the IO LCA models normally assume domestic production of imports. This means that each national economy based IO LCA model the boundary, while infinite in the included transactions, is still national in the sense that all imports are assumed as domestic production with domestic emissions' intensities. The emissions in the higher order tiers that are actually generated abroad are still assessed with domestic intensities. This is a potential source of bias if the GHG intensities between the countries would differ significantly.

Hybrid LCA methods combine the strengths of the two methods and reduce the inherent weaknesses related to them. The IO basis of a hybrid model allows to avoid the truncation error, whereas the process data reduces the aggregation error as well as the disparity error between the model and the case object [25]. In addition, the accuracy of the model may be greatly improved by using the process LCA data for the most significant processes and also to maintain the completeness of the model with an IO LCA basis.

The hybrid LCA model has been widely used in assessment of building construction GHGs. Treloar *et al* proposed a hybrid LCA method that integrates traditional process LCA and IO LCA data within the IO model. The proposed model enables reliable comparisons of construction products with less work and costs compared to the process LCA [29]. Bilec *et al* used an application of hybrid LCA to reveal the life cycle emissions of a parking garage construction project. Another aim of their research was to issue a foundation for the development of the hybrid LCA model for construction projects [28]. Sharrard *et al* enhanced

Table 1. Characteristics of the area.

Residential area characteristics	
Number of houses	220
Number of residents	550
Total permitted building volume	35 270 m ²
Construction costs	76.3 million euro, buildings 91%, infrastructure 9%

the hybrid LCA method by updating and reformulating the environmental effect vectors of 13 construction sectors of the economic input–output life cycle assessment (EIO-LCA) model of Carnegie Mellon University [30]. The researchers improved the accuracy and comparability of the EIO-LCA method by enabling the modifiability of the construction sectors inside EIO-LCA matrices [12].

In this study, the EIO-LCA model forms the basis of the hybrid model. Local and current process data are employed to enhance the accuracy of the model regarding the most important emissions sources. The assessment model is described in more detail in sections 2.3 and 2.4. Before this, the case being analyzed in the paper is presented.

2.2. The case

The case area of the study is located in Southern Finland. With a temperate coniferous-mixed forest zone with cold, wet winters, the area belongs to the hemiboreal climate in the Köppen climate classification [31]. The planned area will consist of 220 detached or semi-detached houses. The total permitted building area for the project is 35 270 square meters (m²). The number of residents will be approximately 550 when the area is in use. The developing company of the area is a major Finnish construction company. According to the developing company, the overall construction costs of the area are 76.3 million euros (M€), of which buildings account for approximately 70 M€. The power generation emissions of the local power plant are 301 g per produced kilowatt-hour (g kWh⁻¹) according to the local energy provider's report [32]. In addition, the renovation and improvement costs per square meter were retrieved from existing literature [33]. The characteristics of the case area are presented in more detail in table 1.

2.3. The construction phase assessment model

The construction phase assessment model follows the hybrid LCA method described above. For the input–output part, the Carnegie Mellon EIO-LCA output matrices are utilized, since it is the most disaggregated model available and therefore offers the best sectoral choices. In addition, the plausibility of utilizing a US based model in a Finnish context has been argued earlier by Junnila and Heinonen *et al* [34, 35]. According to the studies, the model can be utilized in an open economy context like Finland. Process LCA was employed for the most important emissions categories where the production is predominantly Finnish based.

The developing company provided the input data for the assessments. In the received data, the costs of the buildings' construction were divided into 15 aggregated sectors and the infrastructure's costs into six sectors. These sectors were first matched with the industry sectors of the EIO-LCA. This initial screening LCA showed the most important materials and functions in the means of GHG emissions. The utilized sectors and the sector-by-sector results of the construction phase GHG assessment are presented in the supplementary information (S1 available at stacks.iop.org/ERL/7/034037/mmedia).

In the second phase, the most significant sectors, i.e. concrete and steel products and energy, were analyzed in more detail by enhancing the model with process data. For this, the developing company provided volume data on the most important materials and an estimation of energy consumption in the construction process. Concerning energy, the life cycle emissions were modeled by replacing the first-tier, the combustion phase, emissions of the EIO-LCA output matrix with the process emissions of the local power plant, but leaving the higher order life cycle phases of the matrix untouched. For concrete and steel, as presumably products of Finnish origin, local GHG emissions data provided by The Finnish Building Information Foundation RTS were utilized for the full life cycle [36].

In the end the share of the process data in the construction phase assessment model is approximately one fourth. The share of energy is 7%, the share of concrete is 10% and the share of steel is 6% of the total GHG emissions. Thus, the EIO-LCA part of the model covers approximately three fourths of the construction project's GHG emissions. By implementing the hybrid LCA model, the total GHG emissions of the construction project decreased by 16%. The GHG emissions of the case project were modeled with SimaPro software as well in order to validate the results of the hybrid LCA method. The SimaPro modeling with the same cost data and same amounts of energy, concrete and steel products reported similar results.

2.4. The use phase assessment

The use phase emissions of the residential area within the scope of the study include energy, maintenance, repair and replacement but not refurbishment. The assessed energy consumption includes the heating and cooling of the buildings as well as communal building electricity, whereas household electricity was left outside the scope of the study since it is only loosely connected to the building type [37]. The energy consumption levels were taken from the energy efficiency guidelines published by RIL—Finnish Association of Civil Engineers [33]. As the guidelines include only heating and cooling energy, the share of communal building electricity was included using data from Statistics Finland as the reference. According to the data, the share of communal building electricity for the type of detached and row houses of the case area is approximately 9.5 kWh m⁻² [38].

The buildings of the area require maintenance activities to maintain their functionality through the life cycle. The

maintenance emissions of the case area were taken into consideration according to the literature guidelines [39]. The reference includes costs for approximately 20 different maintenance operations for terraced houses. The operations are divided into building and premise related tasks and each task has an individual maintenance period. The maintenance costs are defined in the Finnish mark currency and converted into the current value according to the mark–euro exchange rate and the building cost index 1992–2012. The costs of maintenance activities are converted into GHGs using the EIO-LCA sector ‘residential maintenance and repair’. The required maintenance operations, the costs of the operations and the carbon emissions caused by the operations are presented in the supplementary information (S2 available at stacks.iop.org/ERL/7/034037/mmedia).

Predicting the future is complicated and inaccurate. Nevertheless, the carbon intensity of energy production is going to improve in the future with high probability, and thus the model was enhanced to incorporate this development. For example, Finnish Energy Industries has estimated an 85–90% reduction in the carbon intensity of energy production by year 2050 [40]. This energy production scenario was implemented into the model so that the energy intensity of the energy production is assumed to linearly decrease each year, reaching carbon emissions of 45 g kWh⁻¹ in the year 2060. The energy scenario has a significant impact on the results of the assessment and the uncertainties related to it are discussed in section 4.

The overall life cycle emissions of the case area were estimated by adding the use phase emissions of energy consumption, maintenance, repair and replacement activities into the emissions of the construction phase. A time span of 50 yr was selected for the analysis since it positions a part of the building life cycle with the carbon mitigation goals of the following decades and is long enough to reveal the magnitude of the carbon spike of the construction phase. The energy consumption of the base case buildings is based on the 2008 Finnish National Building Code (NBC), which limits the energy consumption at a level of 100 kWh m⁻² [33].

2.5. Scenario analysis

The second part of the study consists of a scenario analysis, in which various house types with different energy efficiencies were considered for comparison: the low energy building 50 (LE-50), the passive house 15 (PH-15) and the renovated 1960s reference building (R-60s) in addition to the base case, the 2008 NBC building. Of these, the renovation of the R-60s was presumed to occur at the same time as the residential area construction project. The energy consumption of the LE-50, i.e. the required annual heating and cooling energy, is 50 kWh m⁻². Correspondingly, the energy consumption of the PH-15 is 15 kWh m⁻². The renovations of the R-60s were assumed to decrease the energy consumption of the buildings to a low energy level, i.e. 50 kWh m⁻². In addition, an existing building type, a 1985 reference building (R-80s), was included in the study to depict the impact of the carbon spike from construction activities. The R-80s demonstrates a scenario

Table 2. The construction costs and annual heating and cooling energy consumptions in the different housing scenarios.

Residential building type	Construction costs of the area (M€)	Heating energy consumption (kWh m ⁻²)
Base case	76.3	100
LE-50	77.7	50
PH-15	81.1	15
Renovated R-60s	50.6	50
R-80s	—	195

of an existing residential area with low energy efficiency but with no imperative major renovation needs during the assessed 50 yr time span. The energy consumption of the R-80s is 195 kWh m⁻². The energy consumption and changes in the construction costs related to the energy efficiency of the buildings are based on the data published by the Finnish Association of Civil Engineers (RIL) [33]. The renovation costs were retrieved from the data provided by the Housing Finance and Development Centre of Finland (ARA) [41]. The communal building electricity consumption of 9.5 kWh m⁻² was assumed to stay constant in the different scenarios.

For the emissions of different new construction scenarios, the assessment model presented earlier was utilized. The additional costs of the energy efficient building types compared to the base case are due to more sophisticated HVAC and heat recovery systems, improved walls, windows, roofs and base floors and more airtight envelope [33]. These additional costs were converted into carbon emissions with the EIO-LCA sector ‘other major household appliance manufacturing’. The carbon emissions of renovations and energy efficiency improvements of the R-60s buildings were modeled using the average carbon per euro intensity of the case project. The construction costs of the area’s infrastructure were assumed to stay constant in the different scenarios that included new construction. Naturally, the renovation of the R-60s area was assumed to not include infrastructure construction. Table 2 shows the construction costs and energy consumption levels of the buildings in the different scenarios.

3. Results

3.1. Base case

According to the assessment, the life cycle GHG emissions of the construction and use phases of the case area are altogether approximately 104 700 tons on a 50 yr time horizon. The GHG emissions of the construction of the case area are approximately 60 500 tons. The share of the buildings is 91% and the share of infrastructure is 9%. The remaining 44 200 tons are generated during the 50 yr use phase and they originate from heating, cooling and use of communal building electricity.

A notable aspect of the result is that the share of the construction phase emissions of residential development is nearly 60% of the overall emissions within the selected 50 yr time horizon. The share of construction phase emissions was found to be slightly higher in the scenarios with higher energy

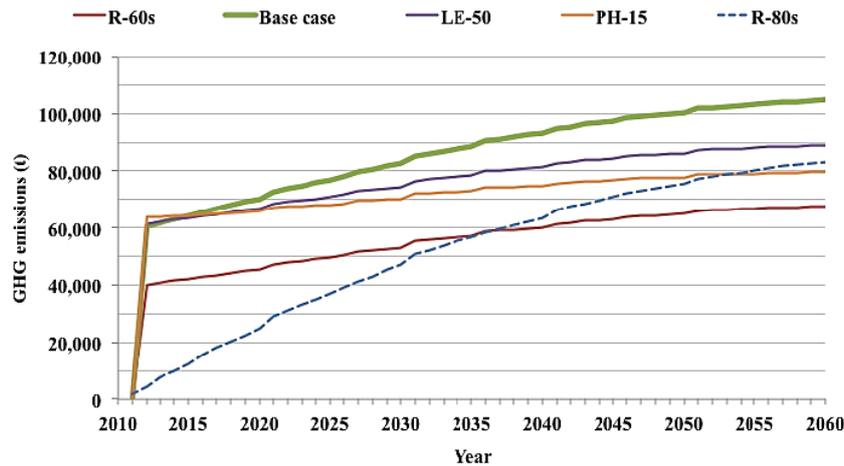


Figure 1. The cumulative GHG emissions over a 50 yr time horizon for the different housing scenarios.

efficiency level buildings. The results are depicted in detail in section 3.2.

3.2. Scenarios

The life cycle carbon emissions of different scenarios during the 50 yr time horizon are 89 100 tons for the LE-50, 79 600 tons for the PH-15, 67 700 tons for the R-60s and 83 000 tons for the R-80s buildings. Following the assumed energy efficiency levels in the different scenarios, the use phase causes 27 600 tons for the LE-50, 16 000 tons for the PH-15s, 27 600 tons for the R-60s and 83 000 tons for the R-80s buildings. When compared to the base case, the R-60s causes approximately 35% and PH-15 25% fewer emissions during the 50 yr time horizon. The scenario with LE-50 buildings causes approximately 15% fewer emissions compared to the base case. Finally, the scenario with R-80s buildings causes approximately 20% fewer emissions than the base case on the 50 yr time horizon.

When only the construction phase emissions are concerned, the differences are rather small except for the renovation scenario, which would seem to cause significantly fewer emissions than the new construction scenarios. The LE-50 scenario causes 61 500 tons of construction phase emissions, which is approximately 1.5% higher than in the base case. PH-15 buildings would cause emissions of 63 700 tons, approximately 5% more than in the base case. Finally, the renovations in the R-60s scenario in which the existing buildings of the residential area are renovated cause 40 200 tons of carbon emissions, that is over 30% less than in the base case.

The most interesting finding of the study is that the construction phase emissions seem to dominate the life cycle emissions beyond the currently set mitigation goals. As figure 1 shows, the construction phase emissions dominate in the time horizon of the near future climate mitigation goals for the years 2020 and 2050 [42]. Figure 1 also shows how the importance of the energy efficiency decreases in time as the GHG intensity of energy production decreases, which significantly increases the relative importance of the

short-term emissions, i.e. the carbon spike of construction. The improved energy efficiency of the new residential area produces benefits only after several decades. The time horizon of the carbon payback time of a new residential area compared to an existing one with R-80s buildings is several decades long in all the assessed new construction scenarios. An approximate carbon payback time of an area with P-15 buildings is 40 yr and over 50 yr for all other new construction scenarios.

Furthermore, the carbon payback time of renovating an area with the R-60s buildings is approximately 25 yr, substantially less than in the new development scenarios. Because of the improved energy efficiency of the renovated residential area and the future energy scenario, none of the new construction scenarios with energy efficient building types even up the cumulative GHG emissions with the R-60s buildings on the 50 yr time horizon. The R-80s scenario shows interestingly that even with very energy efficient buildings, the carbon payback time is over 40 yr despite the fact that the energy consumption of a passive house is only 8% compared to the R-80s. The cumulative emissions of the different housing scenarios on the 50 yr time horizon are presented in the figure 1.

According to figure 1, if new residential developments are initiated, the PH-15 scenario seems the best option despite the increased construction phase emissions. Compared to the base case, the carbon payback time of the increase in the construction phase emissions of the PH-15 scenario is under 5 yr and even less for the LE-50 scenario. Thus, the benefits of the low energy consumption of the PH-15s start realizing already after only a couple of years compared to the other scenarios. In total, the cumulative carbon emissions during the 50 yr' lifespan are approximately 25% lower than those of the base case and 10% lower than those of the LE-50 scenario.

When further analyzing the results, the shares of construction and use phase emissions vary significantly between the different scenarios. The emissions of the base case are quite evenly distributed between the construction and use phases. The use phase emissions dominate in the R-80s scenario. The construction phase represents the major

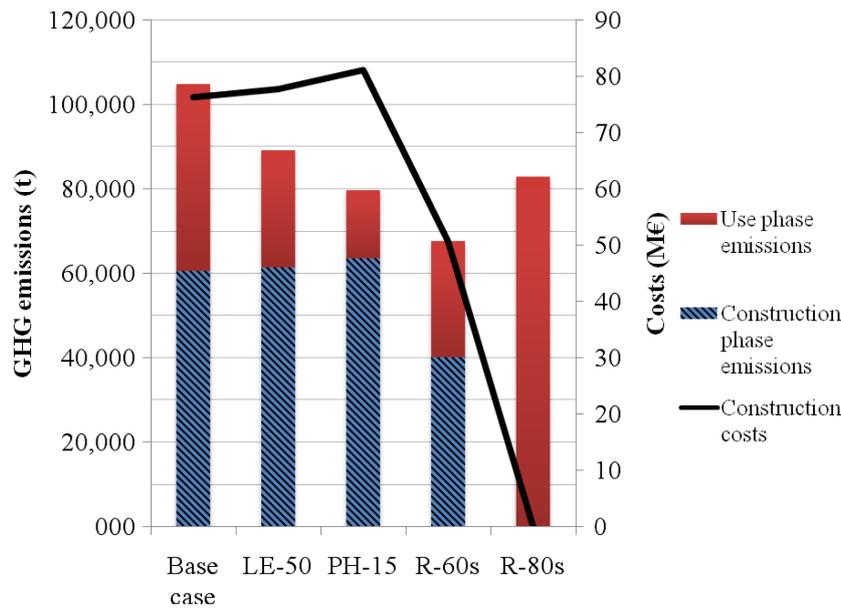


Figure 2. The Life cycle emissions and construction costs of the different scenarios on a 50 yr time horizon.

role in all scenarios that include construction of low energy buildings. The construction costs differ only slightly between the new construction scenarios but are significantly lower in the R-60s scenario. The R-80s scenario does not include any construction activity, so there are no costs related to it. The life cycle emissions of the different scenarios with a 50 yr time horizon as well as their construction costs are presented in figure 2.

Based on the study, a typical new residential area (the base case) construction process causes 60 500 tons of carbon emissions. The construction of LE-50 buildings causes an additional 1300 tons of carbon emissions for the whole area. Thus, the relative increase of carbon emissions is approximately 1.5% for the LE-50 building. The construction phase of PH-15 buildings in the area causes 3100 tons extra carbon emissions, equaling a 5% increase compared to the base case buildings.

The combined costs for renovations and energy efficiency improvements are 1435€ m⁻². The average carbon intensity of the construction phase is approximately 790 g/€ and the total permitted building area is 35 270 m². Thus, the renovations and energy efficiency improvements cause carbon emissions of approximately 40 000 tons for the whole residential area.

It is noteworthy that the future energy scenario has a significant impact on the results of the life cycle analysis. In the case of energy scenario removal from the modeling, the absolute use phase emissions would differ more between the different building scenarios. However, the mutual order between the different building types would stay the same. The cumulative GHG emissions of the R-60s and PH-15 scenarios would be approximately the same on the 50 yr time period. The cumulative GHG emissions of the R-80s scenario would reach the emissions of the base case in approximately 45 yr. The carbon payback times of the low energy scenarios compared to the R-80s scenario would be reduced due to the

noteworthy differences in the annual use phase emissions, especially in the later phases of the analysis period.

4. Discussion and conclusions

The motivation of this study was to test whether it is plausible to utilize the construction of new residential areas as a climate change mitigation strategy. The study was conducted utilizing an application of the hybrid LCA method. The novelty of the study lies in including the temporal perspective of the approach on the allocation of the emissions when analyzing the life cycle GHG impacts of buildings of different energy efficiency levels. In addition, the study brings into comparison both new residential developments and renovation of the existing building stock. The inclusion of the temporal perspective is of high importance, since emissions occurring now and in the short term are claimed to be more harmful to the climate than those taking place very late in the buildings' life cycle [18]. The research indicates that new construction projects cause such a significant spike of carbon emissions in a short time that the benefits of improved energy efficiency only occur after several decades when compared to either renovating the old building stock or using existing residential areas built in the past. The high relative share of the construction phase is due to mainly three things: the extensive inclusion of up-stream production stages in evaluations, the relatively strict building energy codes in Finland and the inclusion of infrastructure development. The high energy performance of the buildings raises the relative significance of the construction phase emissions, as the construction of energy efficient buildings causes more GHG emission than conventional buildings. Another factor for the high share of the construction phase in the total GHG emissions is the chosen time period of the analysis. Although the time period of 100 years is often chosen for the use phase analysis, the 50 yr time horizon was used here as it is a highly relevant

period considering the current climate change mitigation goals that aim for high GHG reductions during the next few decades.

Regarding only the scenarios where new construction occurs, the most energy efficient building types are recommended. The increased carbon emissions from construction are rapidly compensated by the improved energy efficiencies, especially in the case of passive houses. The carbon payback time of energy efficient buildings is only a few years. The carbon emissions of residential areas consisting of low energy buildings or passive houses meet the cumulative carbon emissions of the base case area in approximately 5 yr. After that, especially the area consisting of passive houses benefits of significant annual carbon savings for the rest of the life cycle as compared to the base case.

The renovations of the reference house of the 1960s were taken into account in the study to give a wider perspective for the results and also to include the concept of retrofitting into the study. Interestingly, it would seem that the carbon emissions would be lower than in any other scenario. The energy improvements implemented in the renovation process decrease the energy consumption of the area to the level of low energy buildings, and thus of all building types only the area with passive houses has lower energy consumption than the renovated area. However, even though the renovation of an existing area seems as a better alternative when compared to the new constructions, the carbon payback time of a renovation project is significant. Thus, the energy and material efficiency of renovation processes should be improved in the future to decrease the carbon spike.

The assessment method utilized as well as the input data include uncertainties that may affect the results. A more detailed discussion on these is provided in Säynäjoki *et al* and Heinonen *et al* [14, 43], but some of the most important uncertainties are brought up here. The construction emissions of the case project were modeled with a hybrid LCA model that uses the US economy based EIO-LCA modeling tool as the basis. Although previous research suggests that the model is adequately suitable in modeling the Finnish economy [14, 34], some general uncertainties remain in the method. The sectors of the modeling tool are aggregated and therefore they are not capable of distinguishing different characteristics of the materials or projects in the same sector of economy [28]. Therefore, uncertainties in the initial construction phase carbon emission modeling lead to uncertainties in the theoretical carbon payback times in the different scenarios of the study, as they are based on the results of the case study. Regarding the utilized data, all of the primary data, i.e. construction, renovation and maintenance costs, amounts of materials needed in the construction process and energy consumption figures used in the modeling was extracted from Finnish sources. Approximately one fourth of the hybrid LCA model of the construction phase was modeled using local secondary data. The secondary data used in converting the masses of construction materials into carbon emissions is based on the reporting of Finnish material manufacturers. The carbon intensity of the energy production is also based on the local data. After the construction of the hybrid LCA model,

the remaining monetary costs of construction and renovation processes were converted into carbon emissions using the US based EIO-LCA model. Ultimately, this rather high share of the local data reduces the uncertainties related to the analysis.

The prediction of the carbon intensity of energy production in the future also generates uncertainties in the modeling. The scenario that was implemented in the study seems as a quite optimistic one. Modifying the energy scenario into a more pessimistic direction would decrease the carbon payback times of the most energy efficient building types compared to the more energy consuming ones. However, the conclusions of the study would stay the same even if the future energy scenario was completely removed from the model. The carbon payback time of the PH-15 scenario compared to other new construction scenarios would be just a few years and no other building type than PH-15 would cause as little carbon emissions as a renovated R-60 building type on a 50 yr time horizon.

When positioning the study among the existing research within the field, a few studies were found. This result is in line with the review article of Sartori *et al* [44]. As Gustavsson *et al* suggested, in the case of new energy efficient housing types, the construction phase accounts for the majority of the life cycle GHG emissions [15]. Notwithstanding, some recent studies give a perspective into the findings. Dutil *et al* suggest renovations with energy efficiency improvements as a suitable way to reduce carbon emissions with little additional emissions caused by new construction [17]. Renovations of the current building stock a few decades old are taking place in any case in the near future, as certain elements of old buildings are reaching the end of their operating time. Thus, energy efficiency improvements of old buildings are practical to implement in the renovation process [17]. The results of the study also further validate the conclusions of Heinonen *et al* while taking the discussion on the carbon spike phenomenon to a new level [14]. The carbon payback time of new construction is indeed several decades long and therefore building new residential areas is not a suitable action in short-term carbon mitigation strategies regardless of the energy efficiency level of the buildings. The possibility of renovating the existing areas instead of building new ones seems to be a significantly better option. The construction phase emissions of current developments are always actual emissions but operation phase emissions will be caused during the future operation. At the same time the carbon mitigation targets are set for specific period of time.

To conclude, based on the results of the study, we argue that without substantially reducing the construction phase emissions, new residential construction cannot be used as a means to achieve the climate change goals of the near future. For example, the European 2020 targets are set to reduce the emissions by 20% by 2020. If we now start substantial amount of low energy constructions, the emissions from real estate and construction sector would increase instead of decrease by 2020. This timing aspect is not yet well understood. Notwithstanding, the results of the study indicate that if new residential construction projects are initiated, passive houses should be favored from the point of view of climate change

mitigation even when the construction phase carbon spike is included in the life cycle emissions.

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