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Article

A Longitudinal Study on the Carbon Emissions of a New Residential Development

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Abstract: Buildings account for nearly 50% of all greenhouse gases globally. While this has been widely recognized, the GHG mitigation strategies have traditionally concentrated on reducing the use phase emissions, as over 90% of the emissions are generated during the use phase according to several studies. However, two current developments increase the importance of the construction phase emissions and the embodied emissions of the building materials. Firstly, the improvements in the energy efficiency of buildings directly increase the relative share of the construction phase emissions. Secondly, the notification of the temporal allocation of the emissions increases the importance of the carbon spike from construction. While these perspectives have been noted, few studies exist that combine the two perspectives of the construction and the use phase. In this paper, we analyze the implications of low-carbon residential construction on the life cycle emissions of a residential area with a case study. Furthermore, we demonstrate that when the temporal allocation of the emissions is taken into account, the construction phase emissions can hinder or even reverse the carbon mitigation effect of low-carbon buildings for decades.

Keywords: life cycle assessment; carbon; climate change; buildings; construction

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1. Introduction

Climate change seems inevitable. According to the IPCC 2007 Synthesis Report, eleven of the twelve years before 2007 (1995-2006) ranked among the twelve warmest years in the instrumental record of global surface temperature (since 1850). Furthermore, to maintain the temperature rise at 2.0–2.4°C, a level to which in prevailing belief it is possible to adapt to, the annual greenhouse gas (GHG) emissions would need to be reduced by 50 to 85% by 2050, as the decay of the GHGs emitted to the atmosphere is slow [1].

Cities are estimated to produce up to 80% of all GHGs on a global scale [2]. In addition, buildings are estimated to offer the greatest economic climate change mitigation potential [1,3]. Urban development, and more specifically the development towards low-carbon living, will thus be one of the key aspects in fighting climate change.

The growing importance of the construction phase carbon emissions in the life-cycle emissions of a building was recently brought up by Dutil *et al.* (2011) in their article in Sustainability [4]. The growth is due to the improvements in the energy efficiency of buildings as well as the finding related to the importance of temporal allocation of the emissions. The issue is not new though, as numerous papers on carbon emissions from construction and construction materials have been published within the last couple of decades. However, the majority of the previous studies of buildings with life cycle perspective have concentrated on primary energy consumption or CO_2 emissions, and either on the greenhouse gas emissions from construction [5–7] or the construction materials [8] or emissions produced during the use phase of the buildings [9–11]. This previous research has proven operation phase to be the most significant life cycle phase in both impact categories [10,12,13] indicating also that the share of the construction phase is minor compared to the use phase. Embodied energy has also been an important target of study in previous life cycle assessments of buildings. Among these, several studies suggest that embodied energy of a building is equivalent to several decades of operational energy needed in the use phase of a building [14–16].

Although some earlier research has incorporated the perspectives of construction and use phase emissions in the same study [17], this paper will bring up issues often unrecognized. First, the research presented in this paper incorporates the GHG emissions from both construction and the use phase covering not just a single building, but a whole residential area. Second, the temporal perspective of the emissions, a theme of rapidly growing importance [18] but rarely addressed in building LCAs, probably due to uncertainties related to its perspective [19–21], is taken into account.

The inventory thus creates a comprehensive picture of housing-related carbon consumption, that is, the consumption-based carbon footprint, related to a new residential area. This enables an examination of the climate change effect of buildings in both short term, in the form of a carbon spike of construction, and in medium term, in the form of the energy consumption or carbon emissions creation of buildings.

The paper presents a case study of a new residential development in Pellaksenmäki, Finland. With the case study we analyze the implications of low-energy residential construction on the life cycle emissions of the residential area. In addition, we demonstrate the utilization of the carbon emissions assessment framework as a carbon management tool. Also, we raise into discussion the importance of construction phase emissions when the time perspective is considered. The case study would indicate

that, even though the share of the emissions from construction is relatively small compared to all building related emissions, the importance is high for two reasons. First, carbon effective buildings can potentially notably reduce the inhabitants' use phase emissions compared to the use phase emissions within the average housing stock. Second, the carbon spike from construction can hinder or even reverse this mitigation effect of low-energy buildings for decades. Thus, this kind of analysis should be an important factor in urban development policy making. Furthermore, while there might not be alternatives for new construction due to, *i.e.*, increasing population, the phenomenon of the construction phase carbon spike should be understood in policy making and city carbon management.

The results are presented in three phases. First, the construction phase emissions of the case area are assessed. Second, the use phase carbon consumption is presented taking into account the type of the case area. In the third phase, these two perspectives are put together and the effect of different GHG management strategies is assessed in this framework. Before the results section, the method and the research design are presented.

2. Method

The carbon emissions assessment framework consists of two different assessment models: one for the construction phase assessment and the other for the use phase assessment. Both are applications of the same hybrid life-cycle assessment (LCA) method, namely tiered hybrid LCA (for example, [22]). The method combines the strengths of the two traditional methods, process LCA and input-output LCA (IO LCA) in two significant ways (for example, [23]). First, the IO-LCA basis of the model ensures a comprehensive inventory without a need for a system boundary definition as is always needed in process LCA approaches. Second, the utilization of the process data increases the accuracy of the assessment compared to direct IO LCAs [17,22,24]. Hybrid LCA methods have also been found to offer high potential in search to increase the spatial and temporal detail of an LCA analysis [25].

The two assessment models are both based on the Carnegie-Mellon University's economic input-output LCA tool (EIO-LCA) [26], but with the most important processes producing carbon emissions replaced with local process data. The temporal asymmetry problem between the models and the Finnish economy is corrected with a purchasing power parity (PPP) multiplier, a correction utilized earlier by Weber and Matthews [27] as well as Heinonen and Junnila [10,28].

The model used for the construction phase assessment has been previously published by Säynäjoki *et al.* (2011) [29] with a more detailed description of the method and discussion about the qualities of the model. Similarly, the use phase part of the assessment framework consists of the directly building related emissions of the consumption-based carbon emissions assessment model published by Heinonen and Junnila (2011) [10,28]. The most comprehensive analysis of the strengths and deficiencies of the model is provided in a recent paper in Environmental Research Letters [10].

The case and the utilization of the assessment framework are presented in the next section. A discussion of the deficiencies of the assessment framework and the results is provided in Section 6.

3. Research Design

The study was conducted as a case study of a planned residential area in the Helsinki metropolitan area (HMA) in Finland. Almost 25% of the Finnish population already reside in the area and the

population is expected to grow by over 100,000 residents within the next 10 years [30], which is close to 50% of the expected overall population growth in Finland during the time [31]. Over 50% of the growth is due to migration from outside of the area. The area is thus very interesting for a carbon management study as the residential construction within the area occurs for two reasons having different carbon impacts:

1. Replacing existing buildings and infrastructure elsewhere.
2. Being forced by overall population growth.

Of these, the implications of the first option are primarily addressed by this study. While the second case has different carbon management implications, the phenomenon described in this study is the same, and therefore the results also offer important insights for policy making in that type of situation.

The size of the case area is a little over 500,000 m^2, and around 1100 inhabitants are expected to live in the finished area. The building permit is for roughly 70,000 m^2 of floor space consisting mainly of detached houses and low-rise apartment houses. The residential buildings will mainly be detached houses, but the master plan permits a maximum share of 30% of apartment buildings. The area also includes service buildings, e.g., nursery and retail buildings. The infrastructure consists of roads and paved spaces, water supply and green spaces. The construction costs of the area were estimated to be around 140 M€. The important characteristics of the case area are gathered in Table 1.

Table 1. The characteristics of the case area.

Characteristics	Description
Site	Residential development area in HMA
Size of the site	500,000 m^2
Building permit	70,000 m^2
Building types	70% detached houses, 30% low-rise apartment houses
Current situation of the area	Master plan accepted
Construction costs	140 M€ (estimated)
Residential buildings	91 M€
Service buildings	37 M€
Infrastructure	12 M€
Planned number of residents	1100

The case study consists of three parts, the construction phase LCA, the use phase LCA and the scenario analysis where three carbon management strategies are assessed for the area. The use phase LCA and the carbon management scenarios cover a 25 year life cycle. This timeframe was chosen for two reasons. First, in Finland 20–25 years is the life cycle after which some major renovations, for example renewal of building automation systems are needed [32]. The renovations cause a new, though less significant, carbon spike, but on the other hand they potentially mitigate the future use phase emissions. Second, 25 years is a long enough time span to demonstrate the effect of the construction phase carbon spike on the life cycle emissions of the building.

Concerning the construction phase assessment, the master plan data about the site and various construction phase emissions data sources were utilized as input data sources. Of the emissions data sources, an earlier case study by Säynäjoki *et al.* [29] was exploited as the primary data.

The construction phase carbon emissions assessment was conducted with a purchasing power parity corrected [33] application of a tiered hybrid LCA based on the Carnegie University's 2002 Economic Input-Output Life Cycle Assessment Model (EIO-LCA) [26]. The model has been created by Säynäjoki *et al.* [29]. The model utilizes construction cost data to assess the emissions. In the study, the costs are divided into 14 most important cost categories for the LCA assessment. These 14 categories cover 74% of the total costs of the buildings. The remaining 26% were added to the calculation as Others. The categories together with the IO model sectors and the boundaries of the process data are shown in Table 2.

Table 2. The utilized division of the input data together with the utilized emissions sources.

Part/sector	**IO model sector**	**Process data source and scope**
Buildings' construction		
Timber	Sawmills and Wood Preservation	
Concrete		Environmental reports of Rakennustietosäätiö RTS, full life cycle
Steel		Environmental reports of Rakennustietosäätiö RTS, full life cycle
HVAC-material	Air conditioning, refrigeration, and warm air heating equipment	
Brickwork (bricks + plaster)	Brick and Structural Clay Tile Manufacturing	
Electric material	Miscellaneous electrical equipment manufacturing	
Windows and doors	Wood Window and Door Manufacturing	
Energy	Upstream, Power generation and supply	Combustion, Plant specific
Furniture	Nonupholstered Wood Household Furniture Manufacturing	
Water insulation	Paint and Coating Manufacturing	
Domestic appliance	Household Refrigerator and Home Freezer Manufacturing	
Plastic pipes and basins	Plastics Pipe and Pipe Fitting Manufacturing	
Heat insulation	Industrial Process Furnace and Oven Manufacturing	
Subcontractors	Other nonresidential structures	
Others	Residential permanent site single- and multi-family structures	
Infrastructure		
Other construction components	Nonresidential maintenance and repair	
Mixed used streets' construction components	Museums, historical sites, zoos and parks	

Table 2. *Cont.*

Part/sector	IO model sector	Process data source and scope
Infrastructure		
Construction components of water supply and sewage	Water, sewage and other systems	
Contractor's costs	Residential permanent site single- and multi-family structures	
Designing	Architectural and engineering services	
Investor's and owner's tasks	Management of companies and enterprises	
Use and maintenance		
Housing management	Real estate	
Insurances, taxes and interests	Insurance carriers	
Building maintenance	Residential maintenance and repair construction	
Cabins and second houses	Residential permanent site single- and multi-family structures	
Waste	Waste management and remediation services	
Water and waste water	Water, sewage and other systems	
Other housing activities	Maintenance and repair of farm and nonfarm residential structures	
Home appliances	Household refrigerator and home freezer manufacturing	
Electricity	Upstream, Power generation and supply	Combustion, Plant specific
District heat	Upstream, Power generation and supply	Combustion, Plant specific

The hybrid LCA model consists of the EIO-LCA basis that ensures full coverage of the inventory with the most important carbon emissions sources, according to Säynäjoki *et al.* (2011) [29], covered with local or national process data. These categories are Concrete, Steel, and Energy, of which Concrete and Steel output matrices were fully replaced with Finnish data [34], whereas in Energy only the production phase emissions were replaced by local process data following the tiered hybrid LCA method. We assumed the construction site energy to be produced by the local power plant, and therefore utilized the emissions of the Espoo Suomenoja power plant. The plant is a combined heat and power plant with natural gas and coal as the primary fuels [35]. The combustion phase carbon emission intensities of the plant are 339 g/kWh for heat and 305 g/kWh for electricity according to the energy method.

Concerning the infrastructure part, the utilized model is a direct input-output model with a purchasing power parity correction including six categories. The categories and the selected output sectors are presented in Table 2 below.

The use phase assessment covers the directly housing-related processes, namely energy consumption and building operation and maintenance, which include water, waste, maintenance and repair construction and home appliances. The assessment was conducted based on annual per capita monetary consumption according to the Consumer Survey of Statistics Finland [36]. The model utilized for the assessment is the same carbon consumption assessment model as in Heinonen and

Junnila (2011) [10], but covers only the above-mentioned directly housing-related consumption categories of energy consumption and building operation and maintenance.

For assessment purposes, two typical residents were defined, a detached house resident and an apartment house resident. The typical residents are based on average consumers of similar housing types (apartment house and detached house) in the city of Espoo in the Helsinki metropolitan area, where the Pellaksenmäki area is located, but assuming that the built houses follow the 2010 National Building Code of Finland in energy efficiency, which requires little more than 50% lower heating energy consumption compared to the average residential buildings in Espoo. The two resident types differ quite heavily from each other in their earnings and consumption volume as the detached houses near the metropolitan area center attract wealthier people. Of the two selected resident types, the consumption volume of the detached house resident is 21,000 € and their annual net income is 35,000 €, whereas the apartment house resident only consumes 17,000 € annually, the same as his/her annual net earnings [36].

In the use phase hybrid LCA model, the production phase emissions of heat and electricity, comprising both domestic and communal building energy consumption, have been covered with the same local power plant process data as in the construction hybrid. The rest of the EIO-LCA output matrix was left untouched according to the tiered hybrid LCA method. Table 2 presents the utilized input sectors together with the source of the output, that is, the carbon emissions.

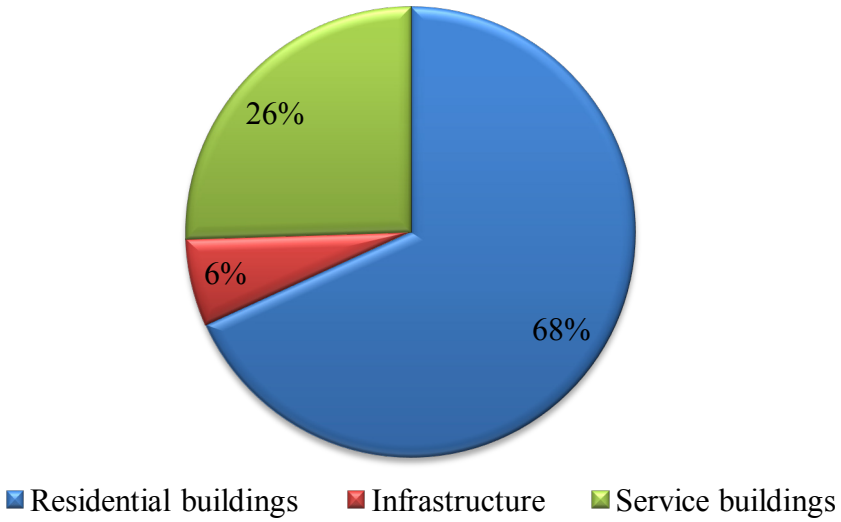
The next section presents the results of the GHG assessment of the residential area and the carbon management scenarios. All the assessments are conducted assuming that the 30% share of apartment buildings allowed by the master plan is realized. In addition to the assessment results, the figures present a line showing the emissions that a residential area of similar size consisting of average housing stock of Espoo in energy efficiency would cause during the same 25 years. This scenario, called "No new construction" in the figures, demonstrates the short term effect of the carbon spike from construction. Even though it is obvious that new construction cannot be totally avoided, it is important to understand the magnitude of the construction phase emissions in short and medium term.

4. Results

4.1. Construction Phase Carbon Emissions

The life cycle carbon emissions of the construction phase of the case residential area in the Helsinki metropolitan area are 140,000 tons of CO_2-equivalents (tons CO_2-eqv.). The share of the building construction is 94% (131,500 tons) and the share of the infrastructure construction is 6% (8500 tons). Interestingly, as all the buildings of the residential area were included in the assessment, we noticed that as much as 36,000 tons of the building construction emissions are related to the service buildings and storehouses. Thus, only 96,000 tons CO_2-eqv. (68%) relate directly to the construction of the residential buildings. Figure 1 shows the division of the construction phase emissions.

Figure 1. The division of the construction phase carbon emissions.



The largest single source of emissions from the buildings construction is concrete with a share of 16,000 tons CO_2-eqv. (12%). The next most significant sources are masonry (incl. materials) and construction site energy, both 10,500 tons (8%), and steel with 9,250 tons (7%). The sub-contraction category accounts for as much as 28% of the emissions of the buildings construction, but the category comprises all sub-contraction work and materials, and thus cannot be analyzed in detail. The HVAC materials, Electrical appliances, Windows and doors, Furniture, Water insulation, Home appliances, Plastic pipes and wells and Heat insulation categories together account only for 11% of the buildings' related emissions. The high level of disaggregation of the construction site emissions becomes clear from the fact that after the 13 most important categories, 21% is still left for all the small categories presented by the sector others in the model.

Of the 8,500 tons CO_2-eqv. from the infrastructure construction, over 80% are attributable to two categories: Construction components of water supply and sewage and Other construction components, with shares of 3500 tons and 3800 tons respectively. The rest of the categories together account for 17% of the total carbon emissions.

The construction phase emissions of 140,000 tons CO_2-eqv. amount to 125 tons per capita if divided among the planned 1130 future residents. Moreover, even if only the residential buildings, residential service buildings and infrastructure are considered (105,000 tons), emissions are still as much as 93 tons/resident. While construction causes a rather small share of the overall building life cycle emissions, the carbon spike is quite high when the per capita emissions are compared to the annual carbon consumption of the residents, as shown below.

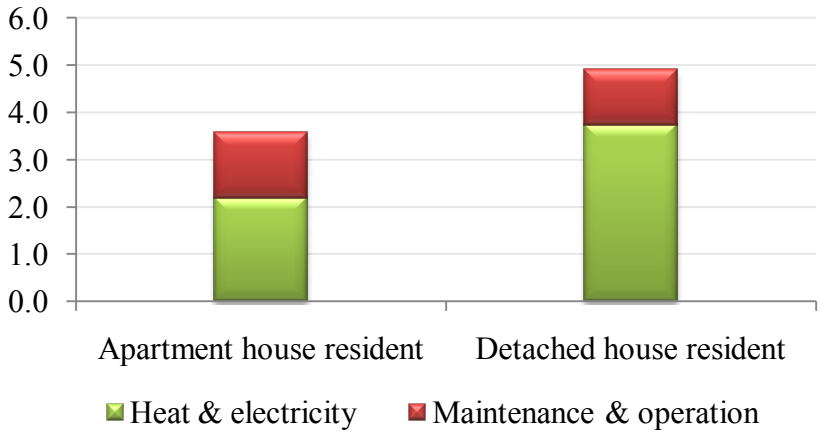
4.2. Use Phase Carbon Consumption

Of the two typical residents, the annual directly housing-related carbon emissions of the detached house resident are 4.9 tons of CO_2-equivalents per capita, whereas the apartment house resident only causes emissions of 3.6 tons CO_2-eqv. annually. The annual housing activity related carbon footprint of an average Finnish consumer is 4.3 tons CO_2-eqv. [10].

The dominant source of carbon emissions is housing energy consumption. Of the carbon emissions, the detached house resident's share is 3.7 tons and the apartment house resident's share is 2.2 tons. The figure includes both heat and electricity. For the apartment house resident, the share of the communal building energy paid within rents or housing management charges is also included. Of the energy related emissions, the share of district heating is around 40%.

The share of the maintenance and operation of the building is thus 1.2 tons CO_2-eqv. for the detached house resident and 1.4 tons CO_2-eqv. for the apartment house resident. The Figure 2 shows the outcome of the assessment.

Figure 2. The annual use phase carbon emissions (tons CO_2-eqv.) of the apartment house and detached house residents.

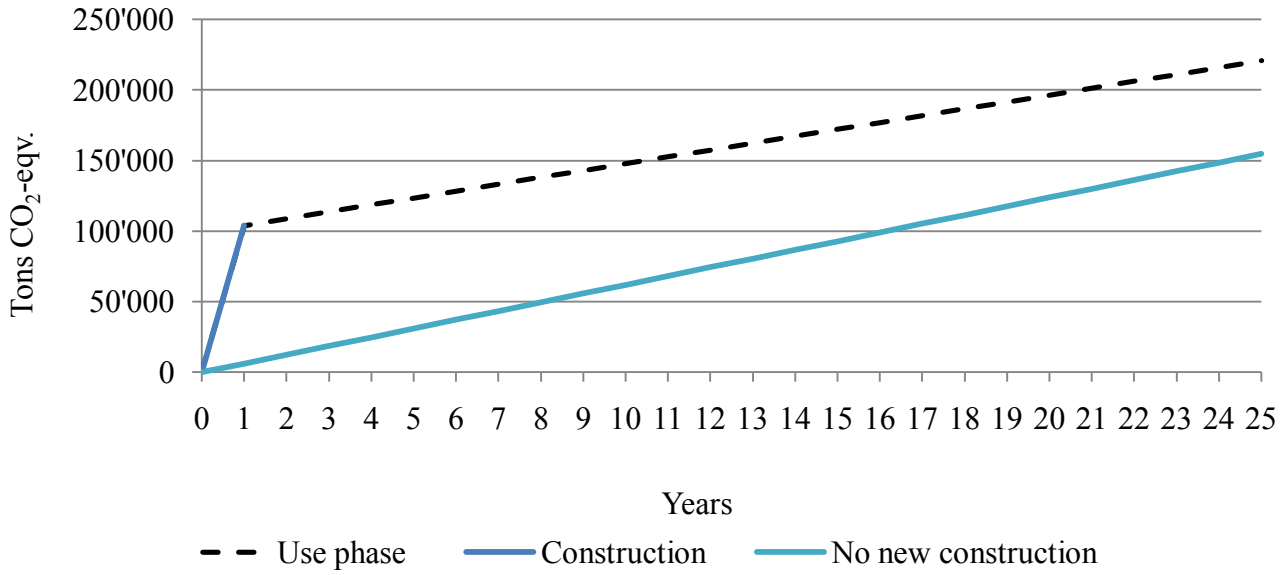


4.3. Life Cycle Emissions of the Pellaksenmäki Residential Area

The third phase of the study was to combine the emissions of the construction phase and the use phase. The construction phase emissions are generated within a short time frame, whereas the use phase emissions accumulate during a very long time, which makes it interesting to analyze the climate change implications of both in the same framework. The life cycle chosen for the assessment is 25 years, as this allows analysis on the level of the current climate change mitigation targets. The service buildings are left out of the assessment at this point, as it might lead to biased conclusions if the emissions related to them are allocated to the residents of the area.

Figure 3 presents the carbon spike from construction together with the annual building-related carbon emissions on the Pellaksenmäki residential area level. The use phase emissions are calculated assuming that the 30% share of apartment buildings allowed by the master plan is built. The construction phase emissions were assumed constant regardless of the building types in any case. This assumption is discussed further in Section 6. The "No new construction" line shows the emissions of an area of similar size consisting of average Espoo housing stock during the same life cycle. The line demonstrates the magnitude of the carbon spike of construction. Also, it shows the long carbon payback time of new construction in the case when new buildings replace old ones, and, even when new buildings are needed, the short and middle term negative effect of construction on the building related carbon emissions despite the higher energy efficiency of the buildings.

Figure 3. Total emissions of the residential area during the 25 year life cycle.



The construction phase carbon emissions from residential buildings and infrastructure are 105,000 tons of CO_2-equivalents. The annual use phase emissions of the future residents of the area are approximately 5000 tons with the assumed division of the building types and thus the type residents. With these assumptions, the total carbon emissions of the area are 224,000 tons CO_2-eqv. during the selected 25 year life cycle. This result suggests that the share of the construction phase emissions is close to 50% during the selected time frame.

5. Carbon Management Scenarios for the Pellaksenmäki Residential Area

The construction phase carbon emissions are often reported to be around 10% of the total emissions of a building (for example, [17]). However, as was indicated above, the share might be substantially higher depending on the selected life span of the building. Either way, the construction phase causes a significant carbon spike to the per capita carbon consumption, with a potentially very long carbon payback time in the case where existing buildings, though with weaker energy efficiency, would have been available. Even when new construction is necessary, as it often is, the break-even point, the time in which the use phase emissions are equal to the emissions from construction, might be quite far in the future. This substantially increases the importance of the construction phase emissions when compared to the time span of both national and global climate change mitigation targets.

In this study, three alternative scenarios were built to analyze the effect of different construction phase carbon management strategies.

1. Reduction of the construction phase carbon emissions.
2. Construction of low-energy buildings.
3. Local low-carbon energy production possibilities.

5.1. Reduction of the Construction Phase Carbon Emissions

Earlier in the paper, the total construction phase emissions of the Pellaksenmäki residential area were assessed to be 93 tons of CO_2-eqv. per resident. This is almost 26 times the annual use phase carbon emissions of the typical apartment house resident of the Pellaksenmäki area, and almost 19 times those of the detached house resident.

The construction phase emissions can be cut by two alternative means. First, the amount of the materials and energy used can be reduced, and thus the carbon emissions lowered ceteris paribus. Second, high-carbon intensity materials can be replaced with substitute materials with lower carbon intensity. In addition, the energy used can be replaced with a low carbon alternative. While the first topic, lowering the material and energy intensity of construction, is very relevant, the analysis was outside of the scope of this study.

From the perspective of the carbon intensity of materials, an analysis of a hypothetical replacement of a share of both concrete and steel with wood was conducted. Concrete and steel combined have been previously estimated to account for 19% of the construction phase carbon emissions. If a rather large share, 50% of these, is replaced with wood, the total construction phase emissions fall less than 10%. The 50% share is high and hypothetically chosen for the analysis, but still aims to roughly present the situation where the applicable parts, such as wall elements, are replaced with another material. The result thus shows that no single action is effective enough to substantially decrease the construction phase emissions. When solutions to this are sought, a combination of multiple low-carbon material replacements is needed.

The share of electricity consumption during the construction phase accounted for 8% of the total emissions in the earlier assessment. In the base model, we assumed that the energy is produced by the local power plant near the construction site. The power plant is a combined heat and power unit using primarily non-renewable fuels. The carbon emissions of the plant are 305 g/kWh for electricity. If we assume that the electricity of the construction site is from the Nordic energy pool, called the Nordic mix, the carbon intensity would drop down to 40 g/kWh (for example [37]). This would cut an additional 6% off from the total emissions. However, even this added to the scenario of replacing materials, the total effect would be only a little over 15% of the construction phase carbon emissions.

5.2. Low-Energy Construction

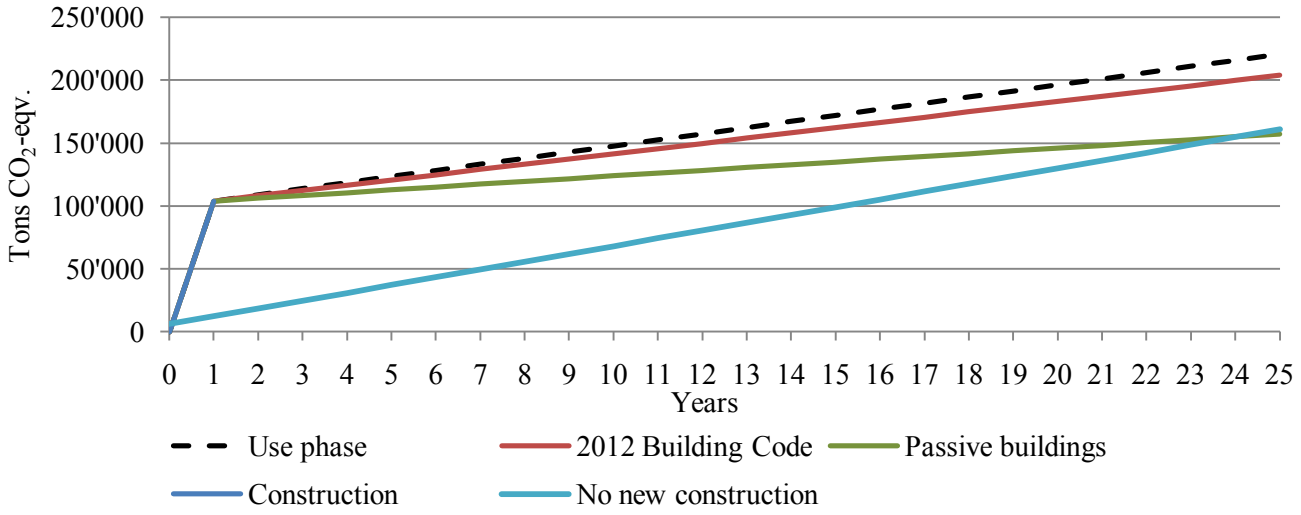
The requirements for the energy efficiency of new residential buildings have grown substantially in the past 20–30 years in Finland. Whereas an average residential building consumed energy almost 200 kWh/m^2 of energy in the 1980s, the requirement of the Finnish 2010 National Building Code is 100 kWh/m^2. A further 20% will be cut from the total energy consumption by the 2012 Building Code [38], meaning that all new residential buildings after 2012 can be categorized as low-energy buildings. Passive buildings have even lower consumption at 40 kWh/m^2, as do of course zero energy buildings (0 kWh/m^2).

As described above, we assumed the Pellaksenmäki residential area to be built according to the prevailing regulatory level of 100 kWh/m^2. The 2012 low-energy buildings and passive buildings were chosen as the alternatives, since their energy levels are reachable with existing residential construction

technology. One critical assumption we made was that the energy consumption level of the buildings would not affect the construction phase emissions. This assumption is discussed further in the next section.

Figure 4 shows that, as the energy efficiency level of the base scenario is already quite high, the effect of low-energy buildings on the life cycle carbon emissions of the area is rather weak. During the 25 year life cycle, the decrease in the emissions is only less than 10%, cutting the total load from 224,000 tons to 207,000 tons. In the case of passive buildings, which consume 75% less energy than the 2010 norm buildings, the emissions would drop by 70,000 tons, that is, by almost 30%. Also, for passive buildings, the construction phase emissions would be as much as nearly two thirds of the 25 year life cycle of the area.

Figure 4. The life cycle emissions of the residential area with the different building energy efficiencies.



5.3. Local Low-Carbon Energy Production Possibilities

The use phase carbon emissions assessments were conducted assuming that the housing energy, both electricity and heat, are produced by the local Suomenoja power plant. The Suomenoja power plant is a combined heat and power producer using almost entirely fossil fuels. The carbon intensity of the production in 2007 was 339 g/kWh for heat and 305 g/kWh for electricity, according to the statistics of Finnish energy industries (ET) [35] (energy method).

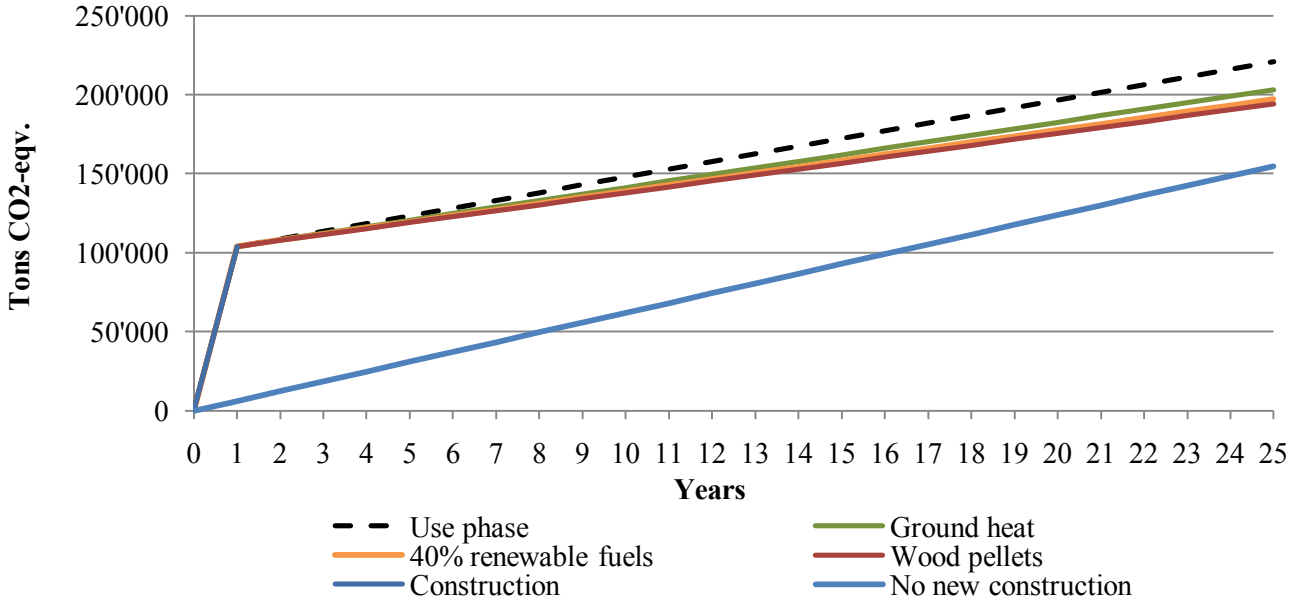
Especially for the heat production, some local production alternatives would be suitable for a residential area. This study chose two alternatives for the district heat, namely ground heat and wood pellets. For ground heat, a three times higher efficiency compared to district heat was assumed. According to Kuronen *et al.*, a four-fold increase in efficiency could even be achieved under right circumstances [37]. For the wood pellets, zero combustion phase emissions were assumed. For both alternatives, the same production and delivery chain emissions were used as for the district heat in the base scenario.

Compared to the local heat production possibilities, a wider effect on the consumer carbon footprint would be achieved with an increase in the share of renewable fuels in the fuel mix of the local power

plant. The change would affect the emissions from housing energy use related to both heat and electricity use. Also, the emissions related to all goods produced with the same energy would decrease. Thus, an increase in the share of renewable fuels from 0 to 40% was chosen as the third alternative carbon management option. For this share, zero combustion phase emissions were assumed.

Compared to the base scenario, the most significant change would be achieved with wood pellets, with which the emissions of the Pellaksenmäki residential area would be 197,000 tons of CO_2-eqv. during the 25 year life cycle, compared to 224,000 tons in the base scenario. The differences are again rather small, as the increase in the share of renewable fuels would lead to total emissions of 200,000 tons, and to 206,000 tons with a ground heat system. Figure 5 depicts the options.

Figure 5. The life cycle emissions of the residential area with the different heating options.



6. Uncertainty Analysis

A study like this always includes possible sources of bias that, if not assessed and understood properly, raise the level of uncertainty regarding the robustness of the results. The identified origins of bias fall into four categories in this study. First, the consequences of the utilization of the selected US economy based model in the context of the Finnish economy should be assessed. Second, the two hybrid LCA models utilized in the study are subject to the inherent problems of the method. Third, the utilization of two different data sets and combining them to describe the same phenomena might lead to false conclusions. Finally, the assumptions made about the future residents affect the results and the overall conclusions.

The consistency of the EIO-LCA model with the Finnish economy based model has been assessed by Junnila (2006) [39], concluding that the results are parallel. Also, Heinonen and Junnila (2011) have recently utilized a similar EIO-LCA based hybrid LCA model to analyze consumption based carbon emissions in metropolitan areas, discussing extensively the consistency of the model and the data based on the Finnish economy [10].

Regardless of the context, the LCA models are subject to the typical problems of the method. To address the temporal asymmetry problem between the model and the input data, a purchasing power parity correction was utilized. The aggregation problem inherent in the IO-LCA method was estimated to be low after the incorporation of process data into the hybrid models. In addition, a sensitivity analysis concerning the EIO-LCA sector choices was conducted with only a minor effect seen in the results. However, the uncertainties related to the temporal perspective of the study cannot be addressed by the above mentioned purchasing parity correction. These uncertainties relate at least to the selected time horizon, the possible changes in the inputs and outputs over time [19,40] and the discount factors in long time horizons [41,42]. The 25 year time frame was argued in the section 3, but an even longer time frame would probably decrease the share of the construction of the total emissions, even if the repair construction emissions were allocated as construction. On the other hand, 25 years is a short time for profound changes in the inputs and outputs to take place, reducing the uncertainty. The use phase emissions are dominated by energy use, which is tied to the local district heating infrastructure, and major changes are thus unlikely to occur during the selected life cycle. Due to many questions related to the use of discounting factors [42], they were not utilized in this study. In the future, one solution for the problems of the temporal perspective could be the concept of dynamic LCA that improves the life cycle assessment methodology, especially concerning temporal issues [43].

The next point to consider is the uncertainty arising from the input datasets. The datasets utilized in the study include two different kinds of data. The construction phase cost data are producer price data that should fit the utilized producer price EIO-LCA model well. Here, however, the quality of the data presents a possible source of bias. The level of aggregation of the data is quite high. Two sectors that are subject to high uncertainty about the content, sub-contraction and others, cover 49% of the total costs of the building's construction. However, the robustness of the results was found to be good when tested with an assessment of one construction sector in the whole construction phase. The difference between the hybrid model results and the one-sector EIO-LCA assessment was roughly 20%. One weakness of the model is that no differences in the construction phase carbon emissions are assumed, regardless of the distribution of the building types. Whereas this weakness could be addressed in the future, the difference has been assessed as relatively small.

The use phase input data is purchaser price data from The Finnish Consumer survey [36]. The data is highly disaggregated and the reliability is high. However, the purchaser price perspective constitutes an asymmetry between the data and the producer price model. In the study, the covered use phase emissions are dominated by energy use, where process data covers the vast majority of the emissions. Furthermore, Heinonen and Junnila (2011), with a similar model, assessed the same carbon footprint for an average Finn as that previously estimated by a Finnish economy based ENVIMAT model [10,44], which strongly supports the accuracy of the model.

Finally, it was assumed that the future residents of the Pellaksenmäki residential area fitted the average emission profiles of apartment house and detached house residents in Espoo, but their housing energy consumption was assumed to be in accordance with the present efficiency levels. In Espoo, the difference between the two profiles is significant due to a large income difference. However, the actual profile of the future residents depends heavily on the choices about the qualities of the buildings, the building types and the planning of the whole area. While this might weaken the credibility of the

results, the selection of the two profiles of future residents demonstrates the difference achieved by these decisions.

7. Discussion

The purpose of this paper was to present a life cycle assessment framework for carbon management and climate change policy making in urban areas, and to bring into discussion the implications of the carbon spike of construction compared the higher, but annually relatively low use phase emissions. The new contribution is a comprehensive framework, where both the construction phase and the use phase are analyzed together, taking into account the time perspective of the emissions.

The utilization of the framework was demonstrated by an analysis of carbon emissions of a new Pellaksenmäki residential development in Espoo in Southern Finland. This kind of integrated analysis gives a new perspective to the relative significance of the emissions resulting from the actions in the two phases. Whereas the overall share of the construction phase emissions is around 10% of the building's life cycle emissions according to several studies, in this paper we have demonstrated that the carbon spike from construction can be so high that the overall emissions of a residential area can be dominated by the construction phase for decades.

In addition, we showed that the presented framework can be utilized effectively in scenario building by constructing a set of low-carbon scenarios for the case area. The scenarios, while not offering a comprehensive review, also indicated that when the construction phase emissions are included in the analysis, significant improvements in the buildings' use phase emissions are needed to radically change the overall life cycle emissions of the whole residential area.

The Pellaksenmäki residential area is planned to accommodate 1100 residents. According to the study, the construction phase emissions of the area are 140,000 tons of CO_2-equivalents. Of these, 96,000 tons are related to residential buildings, 8500 tons to the infrastructure and the remaining 36,500 tons come from service buildings planned for the area. Allocated for the future residents, this amounts to 125 tons per capita when all emissions are considered. If the service buildings are left out, the figure is 93 tons per capita. A comparison of these figures to the use phase emissions indicates that a higher importance should be given to the construction phase emissions than the share of all life cycle emissions would suggest.

For the two resident types, the detached house resident and the apartment house resident defined for the study, the annual direct building-related use phase emissions are 4.9 tons of CO_2-eqv. and 3.6 tons of CO_2-eqv. respectively. Thus, the construction phase emissions create a carbon spike equivalent to emissions from decades of use of the buildings. Also, Heinonen and Junnila have calculated an annual carbon footprint of 12.5 tons of CO_2-eqv. for an average Helsinki metropolitan area resident when all the life cycle emissions of consumption are included. Compared to this, the per capita figure of the construction phase is still equal to 7-10 years of carbon emissions.

Next we assessed the overall emissions of the new Pellaksenmäki residential development during a 25 year life cycle. The 25 year span was selected, as during this time no major re-developments are probable, but 25 years is long enough to demonstrate the development of the total emissions. Also, the selected time frame allows for conclusions in comparison to the national carbon emissions cutoff targets.

The assessment of the overall emissions of the area during 25 year life cycle, taking into account only residential buildings (construction and use) and infrastructure, resulted in carbon emissions of 224,000 tons assuming that the master plan maximum of 30% of are built. Thus, the share of construction, 105,000 tons, is only little less than 50%.

After the overall emissions assessment, we demonstrated the utilization of the assessment framework in the creation of an urban development policy by an analysis of three different carbon management strategies. First we assessed the effect on the overall carbon emissions of some construction phase carbon emissions mitigation possibilities. Here, due to the high level of divergence among the construction phase emissions sources, no significant reductions seem possible with any single action. Even a radical material switch, 50% of concrete and steel replaced by wood, resulted in less than a 10% reduction in the construction phase emissions, which is around 5% of the overall life cycle emissions. A second carbon management strategy, energy efficient buildings, led to somewhat larger changes in the life cycle emissions. With passive buildings, the overall emissions would fall by 16% compared to the master plan model. Finally, the three different low-carbon energy production strategies analyzed all produced less than 10% reductions to the overall carbon emissions.

Thus, quite interestingly, none of the assessed carbon management strategies resulted in very significant reductions. The basic reason for this is the assumed 2010 construction regulation for the energy efficiency level of the buildings. The assumed level is almost 60% more efficient than the average of the existing building stock in Espoo, substantially reducing the effect of further improvements in the energy efficiency, as well as the effect of cleaner energy production. In addition, because close to 50% of the total carbon emissions during the 25 year life cycle are generated during the construction phase, the effect of mitigation strategies aimed to reduce the use phase emissions are diminished.

In addition to the somewhat unexpectedly large share of the construction phase emissions, these seem to have an even higher importance. When the time perspective of the carbon emissions is taken into account, it would seem that the sudden carbon spike from construction could reverse the carbon mitigation effect of the higher energy efficiency of new buildings on the inhabitants' carbon emissions for decades compared to the residents of the average housing stock. In this study, the carbon payback time, the period within which the net effect of construction is zero compared to a situation where all the buildings are average buildings and no new construction occurs, is over 30 years with the assumed 2010 National Building Code energy efficiency. If all the buildings were passive buildings, the payback time would drop to 20 years, but still the effect would be negative for a long time. And, while a majority of new residential construction is necessary, these figures show the magnitude of the carbon spike of construction and raise the importance of taking this into account when carbon management policies are considered and mitigation targets set in short and middle term. As the scenarios showed, within the 25 year time frame, only the passive buildings scenario led to lower total emissions than in the "No new construction" scenario.

One final finding brings a new perspective into analyzing the life cycle emissions of a residential area. When the energy efficiency increases, the relative importance of the emissions related to the use of materials increases rapidly. This emphasizes further the significance of a comprehensive life cycle assessment of the emissions regardless of the place where the emissions are generated. In the case of a residential area, the dominant materials are the construction materials, which naturally are brought to the construction site from elsewhere. However, the global perspective seems highly relevant on, for

example, city scale as well. While it has often been estimated that cities would produce less carbon emissions than the surrounding areas on a per capita basis (for example, [45,46]), it seems that the situation might even be reversed when all consumption is included in the assessments [10,47]. In addition, Schulz (2007) demonstrated how over 90% of the materials used in Singapore are imported [48]. While he did not have a climate change perspective, it would seem clear that a majority of the emissions is generated outside of the city itself.

8. Conclusions

This study brought into further discussion the true importance of the construction phase emissions, as well as the efficiency of new residential construction as a means to achieve the national and global climate change mitigation targets. The results would suggest that the construction phase emissions should be taken into more careful consideration if higher energy efficiency of the new residential buildings is expected to contribute to achieving climate change mitigation targets in even the middle term analyzed in this paper.

In addition to the policy implications, we presented an assessment framework that can be efficiently utilized in urban development policy making. While the framework includes some uncertainties and assumptions, the robustness of the results seems good in the context of urban development policy making. The framework incorporates the life cycle emissions of both the construction phase and the use phase and contains the important, but rarely noted temporal perspective of carbon emissions. Future development of the assessment framework is needed, as well as a more comprehensive analysis of the consequences of the carbon spike from construction.

Conflict of Interest

The authors declare no conflict of interest.

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