LCA of the Zero Emission Neighbourhood Ydalir

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Abstract. Buildings represent a critical piece of a low-carbon future and their long lifetime necessitates urgent adoption of state-of-the-art performance standards. So far, LCA studies have assessed buildings, mobility and energy systems mainly individually. Zero Emission Neighbourhoods (ZEN) give a unique chance to combine these elements. In Norway, the Research Centre on ZEN has as a goal to enable the transition to a low carbon society by developing sustainable ZENs.

In this study, a LCA model for neighbourhood based on a modular structure with five physical elements; buildings, mobility, infrastructure, networks and on-site energy was applied on Ydalir, a pilot project of the ZEN Centre. Revealing that regardless of which scenario considered, the ZEN Ydalir does not achieve their ambitious goal of zero emissions. Further, the results show that the operation of mobility is a major source of the total greenhouse gas (GHG) emissions, accounting for 21-46%. Considering the life cycle stage materials, buildings are the largest contributor representing 24% of all GHG emissions. Thus, these two areas have been highlighted as the best options for improvement. Parameters related to uncertainties or are large contributors to the environmental impact are included in a sensitivity analysis.

1. Introduction

In Paris in December 2015, the United Nations Climate Change conference was held. Here the main goal of limiting the global warming to a maximum of 2 degrees compared to pre-industrial time, was defined. This has led to a growth of climate awareness and as the building sector is responsible for 40% of the total energy consumption and 30% of all energy-related greenhouse gas (GHG) emissions in the European Union (EU) [1], decreasing the emissions from this sector is critical. To improve the environmental aspect of the building sector, several leading international organizations have taken measures. In Norway, the Research Centre on Zero Emission Neighbourhoods (ZEN) has been founded with a goal of reducing the emissions on neighbourhoods to a minimum level through combining local production of local renewable energy, storage and interacting systems. The ZEN Centre will run over the period 2017-24 with the vision “Sustainable neighbourhoods with zero greenhouse emissions” [2]. By using life cycle analysis (LCA) as a helping tool, researchers have consequently had to acknowledge the new challenges that arise regarding functional unit, system boundaries and sensitivity parameters.

To map and assess the source of the emissions from buildings the well-established tool LCA is commonly used, as it looks at the entire life span of the building [3]. LCA systematically goes through each life cycle from raw materials acquisition, production of energy and materials, usage and end-of-life processing [4]. LCA is commonly used in assessing both buildings and neighbourhoods. However, when performing LCAs on an urban scale, the focus becomes quite different from when assessing individual buildings. Other aspects as density, transportation, infrastructure and consumption have to be
included and different system boundaries and framework are needed to be able to assess critical environmental impacts of neighbourhoods [5].

Defining the system boundaries is crucial for the LCA’s results and their reliability. The system boundaries define which life cycle stages and physical elements (i.e., buildings, open spaces and mobility) that are to be included in the analysis. Some LCA studies only include the buildings [6], while others also consider the mobility of the inhabitants [7, 8]. The most comprehensive and complex LCA studies are the ones that include several elements such as building, mobility and other elements as networks and infrastructure [9, 10]. There are also variations in what life cycle stages are considered, from studies that only look at the usage to the opposite side of the scale where construction and deconstruction are included [11, 12]. These differences create challenges in comparing results from LCA studies. However, some key points are worth noting.

Studies have shown that transportation of the inhabitants has significant impact on the total emissions. Nichols and Kockelman [9] found that 44-47% of the total emissions from the use stage came from transportation. Similarly, when including materials in construction, usage stage and transportation, Bastos, Batterman [8] found that transportation contributed with 51-57% of the total emissions. These findings indicate that further research on the field of emissions related to mobility in neighbourhoods is necessary.

The predictions and assumptions of the future scenarios are crucial when performing LCA. The service lifetime of each element in a neighbourhood makes the forecasting challenging and a source of uncertainties. Several studies highlight this challenge, and emphasize evolving technology, time distribution of environmental impact and emission intensity of electricity as key factors [8, 10, 12]. These factors can have great impact on the predictions of future scenarios and long-term decisions.

Further research on the field on ZENs is obviously required, on both critical factors for the results and what life cycle stages and physical elements contribute considerably to the environmental impact categories. This insight should build the foundation in future ZEN projects.

2. Method

This study is based on the LCA model developed by Lausselet, Borgnes [13] with some minor modifications, and further adapted and applied to the case study at hand, the ZEN Ydalir. Ydalir is a pilot project for the ZEN Centre, located in Elverum.

2.1. Model

The LCA study is designed as a modular structure defined by three dimensions; the physical elements (buildings, mobility, infrastructure, networks and on-site energy), the life cycle stages and time. To match the neighbourhood at interest, the elements and life cycle stages can be adjusted for each assessment.

The total emissions from the neighbourhood is calculated by Equation 1.

\[ E_{tot} = E_{b,mat} + E_{b,oper} + E_{m,mat} + E_{m,oper} + E_{o,mat} + E_{o,oper} \]  \hspace{1cm} (1)

Where \( E_{b,mat}, E_{m,mat} \) and \( E_{o,mat} \) are the emissions from the materials from buildings, mobility and infrastructure, respectively, and \( E_{b,oper}, E_{m,oper} \) and \( E_{o,oper} \) are the emissions from the energy use in operation respectively from buildings mobility and infrastructure.

The Norwegian standard on method for greenhouse gas calculations in buildings suggests that two different energy intensity scenarios are to be assessed, namely scenario 1 (NO) and scenario 2
(EU28+NO). These are based on the assumed evolution of the Norwegian and European electricity mix, respectively.

2.2. Case Study, Ydalir
The LCA model has been applied on the ZEN Ydalir, including the elements building, mobility, infrastructure, networks and on-site energy. For each element the life cycle stages production stage (A1-A3), replacement (B4) and energy use in operation (B6) are included. In addition, construction (A5) is included for infrastructure, while for networks energy use in operation (B6) is excluded. The analysis period is 60 years, and this study focuses on the GHG emissions associated to each element over this period. At Ydalir three different sources of energy have been chosen; district heating, combined heat and power (CHP) machines and photovoltaic (PV) panels. Both electric and heat excess energy not used by the neighbourhood is exported to the external grid and credited with negative emissions.

2.2.1. Buildings
The building stock at Ydalir consists of 1000 residential buildings and two non-residential buildings; a school and a kindergarten. Resulting in a total area of 108 614 m². The residential buildings are still under planning and the ZEB 1 from a concept analysis by Kristjansdottir, Houlihan-Wiberg [14] has been chosen for its resemblance with the present design of the residential. It is also assumed that the residential buildings will have the same amount of emissions per area as for the ZEB 1, while the materials for the school and the kindergarten are collected from EDPs. Further, the annual energy use in operation are 78 kWh/m² for the residentials and 109 kWh/m² for the non-residential buildings. These numbers are based on the passive house standard NS 3700 [15] and NS 3701 [16] for the residential and non-residential buildings respectively. The total thermal load for the buildings at Ydalir is 4.81 GWh/year and the electrical load is 3.93 GWh/year. The loads are assumed to stay constant over the building’s lifetime.

2.2.2. Mobility
At Ydalir three means of transportation have been assessed; personal vehicle, bus and light rail. The travel habits of the inhabitants is based on the National travel survey [17] and further adapted to specific measures taken at Ydalir regarding parking space availability. Car-sharing has also been included as a scenario where the total travel distance has been halved.

The evolution of the vehicle stocks is adapted to two different scenarios; a trend path and a ultra-low emissions path [18]. Both scenarios assess the evolutions of the personal vehicle and bus stock, looking at several fuel/energy carriers. The forecast lasts over the period from 2010 to 2050 and is then expected to stay constant until 2080.

Considering the embodied emissions from each mean of transportation and the emissions intensity of the fuel/energy carrier, the initial emissions have been collected from Vestlandsforskning [19] after suggestions from the Norwegian standard NS 3720 [20]. Future evolution has then been adopted from a scenario analysis by Lausselet, Ellingsen [21].

2.2.3. Infrastructure
The infrastructure includes embodied emissions from roads and sidewalks, energy use in operation from public lighting and the diesel consumption from construction. The embodied emissions are collected from Arda, while the operation of the public lighting has been calculated from an average of dark hours per day.

2.2.4. On-site Energy Production District Heating
The district heating system will cover the total heating demand for the buildings at Ydalir. The heat production is off-site, but still within the system boundaries. The embodied emissions related to the pipes are included, but not the emissions of the heat production plant. There will be some excess heat that will be exported from the neighbourhood to the external grid and contribute as negative emissions.

### 2.2.5. On-site Energy Production Photovoltaic

The PV-panels will be mounted to roofs, facades and in the surrounding area. There will be 18m² of PV-per residential building. The embodied emissions have been collected from Ecoinvent 3.2. The panels produce an average of 130 kWh/m², which result in an annual total of 2.34 GWh. The emissions associated to the operation are assumed to have a symmetric weighting to the emission intensity of electricity respectively for each scenario. However, as the electricity produced from the PV-panels are assumed to replace the electricity from the scenarios, emissions are seen as negative contributors (i.e avoided emissions). The electricity is either consumed by the neighbourhood itself or exported to the external grid.

### 2.3. Scenarios

Four scenarios on mobility have been created in order to analyse the impact mobility have on the total emissions from the neighbourhood. Scenario A represents the base case where the travel distance is for Ydalir and the technology development path for mobility follows the trend path. Scenario B is also for travel distance Ydalir, but the technology follows the ultra-low emission path. Scenario C and D illustrate the results for Ydalir and car-sharing for the trend path and ultra-low emission path respectively.

### 2.4. Sensitivity analysis

A sensitivity analysis was carried out with the goal of revealing the critical parameters in the LCA model. The factors expected to have significant impact to the results or associated with large uncertainties were chosen and increased with 25%. The parameters analysed were mobility energy use in operation, area of PV panels, energy load (thermal and electric), emissions embodied in building materials, emissions associated with vehicle production, travel distance/inhabitant/year, emission intensity district heat and emission intensity electricity. Further, the sensitivity ratio was calculated using Equation 2.

\[
SR = \frac{\Delta R/R_0}{\Delta P/P_0}
\]

\(\Delta R/R_0\) represent the relative change in the results while \(\Delta P/P_0\) is the relative change in the input parameters.

### 3. Results

#### 3.1. General Results

The results from using the described methodology with the emissions associated to the included physical elements (buildings, mobility, infrastructure, networks and on-site energy) and the life cycle stages (A1-3, B4 and B6) were 162 ktone CO₂eq over the lifetime of 60 years (scenario A). Equivalent to 1.1 tonne CO₂eq/capita/year or 24.8 kg CO₂eq/m²/year. Figure 1 illustrates the different results depending on the different mobility scenarios. As shown in Figure 3.1, scenario D is the most optimistic scenario regarding mobility.
Figure 3.1 Results of total emissions over lifetime, A-Ydalir & trend path, B-Ydalir & ultra-low emission path, C-Ydalir + car-sharing & trend path D-Ydalir + car-sharing & ultra-low emission path.

The results for the scenario A (base case), show that when all emissions considered, the energy use in operation stage contribute with 54% of the total emissions, and 46% of these are from the element mobility, making energy use in operation of mobility the greatest source of emissions. However, when looking at scenario D, it is the product stage of buildings that becomes the greatest source of emissions, representing 22% of the total emissions. By comparing scenario B and C, it can be concluded that it is the daily travels of the residents that have the greatest impact on the total emissions.

3.2. Sensitivity Analysis.
Figure 3.2 shows the results from the sensitivity analysis and the impact from four fundamental assumptions. It is revealed that the two most critical parameters are connected to mobility, namely the mobility energy use in operation and travel distance/habitant/year. The assumptions related to mobility, the technology development path and travel distances, are also shown to have major impact on the results, by both increasing and decreasing the total emissions from the neighbourhood. The assumption regarding the emission intensity for scenario 2 is also worth noticing as this increase the total emissions from the neighbourhood by 19.4%.
4. Discussion

4.1. LCA Modelling on Neighbourhood Scale
The placement of the system boundaries to decide which life cycle stages and physical elements to include in an LCA, appears to have significant impacts on the results. The model revealed that mobility contributes with 38-64% of the emissions depending on the scenario and its preconditions. This states the major impact mobility have on the resulting emissions. Similarly to results of Nichols and Kockelman [9] and Bastos, Batterman [8]. The variations are the results of optimistic or pessimistic assumptions of the future evolutions of mobility. In the most optimistic assumptions (scenario D), the buildings become the largest contributor with 43% of the total emissions.

4.2. Uncertainties and Limitations
In association with the emissions from Ydalir, several assumptions on the emission intensities have been made in order to calculate the total emissions over the lifetime. When expanding LCA models from individual building to complex neighbourhoods, the impacts of the assumptions, and which life cycle stages and physical elements to include, become more uncertain.

Regarding buildings, it is assumed that the buildings in the neighbourhood will be built over a period of 15-20 years. However, in this model it is assumed that all the buildings will be built immediately with no considerations towards evolution of technology, change in the Norwegian building regulations (TEK) or an establishment of a ZEN definition. The emissions associated to the materials used in the residential buildings are also related to some uncertainties as these are not based on the actual buildings that will be built at Ydalir, but on ZEB 1.

The results clearly state that mobility has the most significant impact on the total emissions, and it is the energy use in operation and the daily travels of the inhabitants that affects the results. There are high uncertainties connected to predicting the evolution of the vehicle stocks. The model only assumes changes until 2050 and then constant values. This is an unrealistic prediction, but as further assumptions are associated to high uncertainties, it is chosen not to be included. Another important notion is that mobility connected to the users of the school and the kindergarten that do not live at Ydalir, is not considered.
The use of PV to locally produce electricity can be questioned for the particular case of Norway. Yet, while the efficiency is lower than in Southern European countries, the use of PV at those latitude is a proven concept [22]. Also, as long as the carbon intensity of the European electricity mix is higher than electricity produced by PV placed in Norway, to produce electricity from PV in Norway will help decarbonize the European grid. It will as well liberate and redirect low carbon hydropower to other purposes such as for example as to help electrifying the mobility sector.

There are also some uncertainties related to the included infrastructure. The embodied emissions from the materials have been highly simplified and higher emissions from this element is therefore expected. Regarding the operation of the infrastructure, only public lighting has been included. Road maintenance, snow clearance and other operational elements have been excluded, which is a limitation to the model.

4.3. Further Work

The modular structure of this model has the advantages to highlight the source of emissions related to both life cycle stages and physical elements. However, there are still limitations that weaken the model and some parameters that need further attention.

Regarding the materials replacement in buildings, infrastructure and networks, the model does not consider any improvements in the technology development. As the emissions from materials replacement represent 22-27% of the total emissions, when all elements are included, this should be looked closer at. Another area that needs further research is the behaviour of the inhabitants. The travel habits and energy use of the inhabitants are based on national numbers and is a source of uncertainties.

An LCA often include several impact categories to show a comprehensive picture of the product or process at hand. In this study, only greenhouse gas equivalents related to climate change has been analysed and discussed. In order to avoid problem shifting phenomena, other impact categories as land use change, acidification and human toxicity should also be included into the model. However, the lack of data on other impact categories bring challenges and further work on this field is therefore suggested.

5. Conclusion

In order to research the dominant drivers both related to the physical elements and the life cycle stages in the ZEN Ydalir, a modular structure was chosen for the LCA. The modular structure consists of five physical elements; buildings, mobility, infrastructure, networks and on-site energy, as well as three life cycle stages; product stage, replacement stage and the energy use in operation stage.

The results revealed that regardless of which scenario considered, the ZEN Ydalir does not manage to achieve their ambitious goal of zero emissions with the present plan. Nevertheless, the results highlight some important take-away messages on areas for further improvement on the field of ZEN. The results show the major impact the energy use in operation of mobility has on the total emissions from the neighbourhood, contributing with 21-46% of the total emissions, depending on the scenario. Looking at scenario A, the scenario assumed to be the most realistic regarding the evolution of the vehicle stock, 24% of the emissions comes from the product stage, and 22% from the replacements. On the other hand, for scenario D, the most optimistic scenario regarding the vehicle stock, the product stage and replacement stage contribute with 39% and 27% of the emissions. As the operation of mobility and materials from buildings are the two major contributors, these two areas are highlighted as options for improvement on the way to the goal of zero emission societies.
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