SENSITIVITY ANALYSIS OF THE LIFE CYCLE EMISSIONS FROM AN NZEB CONCEPT

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ABSTRACT

The *net-zero emissions building* (nZEB) performance is investigated for building operation and embodied emissions in materials for Norway's cold climate. An nZEB concept for new residential buildings was developed in order to understand the balance and implications between operational and embodied emissions over the building's life. The main drivers for the CO_2 equivalent (CO_{2eq}) emissions were revealed for the building concept through a detailed emissions calculation.

Previous investigations showed that the criterion for zero emissions in operation is easily reached by the nZEB concept (independent of the CO_{2eq} factor considered). Nevertheless, embodied emissions from materials appeared significant compared to operational emissions. It was found that an overall emissions balance, including both operational and embodied energy, is difficult to reach and would be unobtainable in a scenario of low carbon electricity from the grid i.e. low CO_{2eq} factor for electricity.

In order to make these conclusions robust, a sensitivity analysis was performed on the dominant sources of CO_{2eq} emissions, as well as, on how it impacts the emission balance during the building lifetime. In the baseline work, *embodied emissions* were evaluated using the EcoInvent database in order to get a consistent life cycle assessment (LCA) method for all the building materials. The first step of this sensitivity analysis is therefore performed to compare embodied emissions when specific Norwegian *Environmental Product Declarations* (EPD) were used instead of generic data from EcoInvent thus making data more representative for the Norwegian context.

In addition, the photovoltaic (PV) system, which supplies renewable electricity to the building, also contributes significantly to the embodied emissions. The second step of the analysis evaluates different PV system design options in order to find the one with highest net emissions reduction. Finally, since the building concept was based on a highly-insulated building envelope, the dominant source of emissions during building operation turned out to be electric appliances. The third step of the analysis thus discusses the energy consumption of electric appliances and how it could be reduced through more efficient products, especially the so-called *hot-fed* machines (i.e. washing machines, tumble dryer and dishwasher).

Keywords: Generic and specific EPD data, embodied emissions materials, ZEB balance

INTRODUCTION

This sensitivity analysis represents further work based on the results of the original ZEB concept study published in 2013 [1], where the calculations of embodied emissions (EE) from the construction materials and components were based on generic material data from the Ecoinvent database. In the original ZEB report, the EE of the materials in the ZEB concept residential building were calculated to provide an overview of embodied emission using traditional materials in the envelope, ventilation & heating systems, as well as, those associated with the renewable energy system, such as the photovoltaic panels and solar thermal units. The objective was to identify the key materials and components l which contribute the most to EE. For instance, results show that the total EE from materials correspond to 7.2 $kgCO_{2eq}/m^2$ per year (59%) of the overall emissions, whilst the emissions from operation correspond to 5.0 $kgCO_{2eq}/m^2$ per year.

The main research question in this sensitivity analysis is to investigate if it is possible to achieve a ZEB OM ambition level if the EE for the construction materials used in the ZEB concept building is calculated using Norwegian EPD data rather than generic Ecoinvent data. A secondary question is to analyse the effect of using different CO_{2eq} factors for the electricity used in operation and see how this factor affects the ZEB ambition level for the residential concept building and the payback of CO_{2eq} emissions over the building's lifetime. The impact of reduced loads from electrical appliances is also included in this study. Full details of this sensitivity analysis can be found in Houlihan Wiberg et al., 2015. [2]

METHOD

Goal and Scope

The goal of this work is to investigate not only the effect on EE of materials and the overall performance of ZEB concept residential building, of using specific Norwegian EPD data instead of generic Ecoinvent data. The method includes the calculation of the CO_{2eq} emissions from both materials and operation. A functional unit of 1 m^2 of heated floor area in the residential building over the 60 year estimated lifetime of the building is used. The results are presented for emissions on an annual basis, where the functional unit of 1 m^2 is divided by the building lifetime. The estimated service lifetime of the different materials and components is mainly based on the guidelines from different product category rules. The analysis is limited to cradle-to-gate for the material emissions (product stage: A1-A3) and replacement (B4) has been included.

Simulation Tools

The 3D architectural drawings and 3D BIM modeling have been done using Revit version 2012 Embodied emission. The material quantities have been imported from the Revit BIM-model, via Excel. The embodied emissions calculations have been done using the LCA Software tool SimaPro version 7.3.3 [3] which uses emissions data from the Ecoinvent v.2.2 database [4]. Simulation of annual heating and cooling demand, peak heating and cooling load, net energy budget, heat loss calculation, thermal comfort simulation and CO2-level simulation have been done in SIMIEN version 5.011 [5]. Thermal bridge calculations have been done in the numerical software tool Therm [6]. Performance calculations of the air source heat pump combined with solar thermal collectors have been done using PolySun [7]. Performance of the PV-systems has been calculated with simplified spreadsheet models (Excel), but is verified by the PV-tool PV-syst [8].

Concrete, insulation, plasterboard materials EPD data have been selected for this first step of the sensitivity study since these are responsible for the highest emissions, apart from PV. Even though the EE from PV contribute the most emissions, they are not included in this analysis since there are no available Norwegian EPDs for this product. Instead, the influence of different PV technologies and different module orientations on the embodied and avoided emissions is incorporated from the work presented by Good et el.(2014) at the Eurosun conference [9]. Wood was also selected in this sensitivity study to study the benefits of using locally resourced materials using Norwegian EPD data.

For both the generic data and EPD material data, tables containing detailed information on the process, place of production, density, grid electricity mix ($kgCO_{2eq}/kWh$) and EE ($kgCO_{2eq}/m^3$) together with references can be found in the full sensitivity report [2]. An example of the table used for the analysis can be shown with concrete which exists in the foundation and ground works, and apart from PV, was one of the materials driving the highest emissions in the original study of the residential concept building. The Norwegian EPD data for Betong Øst [10] produced in Norway based on 1 m^3 of product, according to precast concrete PCR [11], is used for the sensitivity analysis (Table 1).

Table 1. Concrete materials used for the sensitivity analysis.

Concrete	Process	Place of Production	Density (kg)	Electricity mix	Embodied emissions (kg CO_2eq/m^3)
ZEB original data	Concrete, normal, at plant/CH U ZEB	Switzerland	2380	CH U	261,2
Norwegian EPD	Ferdigbetong B25M60	Norway	2358	Nordpool	189, 9

It should be noted that when conducting EPDs for building materials, the choice of emission factor used for the electricity mix varies between different consultants and researchers. Some researchers and consultants use the production/consumption electricity mix for Norway based on an average for the last three years while others use the Nordic electricity mix with a higher emission factor. Currently there is no consensus on which electricity mix should be used for Norwegian EPDs other than that the emission factor used for electricity in the production of the material should be stated on the EPD.

The emissions from the building needs to be balanced (offset) by renewable electricity production (e.g. PV), which is either used for self-consumption (reducing delivered electricity) or exported electricity to the grid. The design of the onsite electricity production and the total life cycle CO_{2eq} balance is calculated to see if the PV-production meets the (different) ZEB-definition levels. At a given location, the electricity yield of a PV system is highly dependent on the design of the installation. Four different design options were evaluated in order to find the most favourable in terms of EE versus electricity yield. The amount of emissions that are replaced by the electricity from the PV system also depends on the grid factor of the electricity it replaces. Four alternative design options suitable for flat roofs, each with three different PV technologies (mono-Si, poly-Si and CIS), were simulated in PVsyst [1]. The design alternatives were A) optimal orientation (south facing at 40° tilt), B) south facing at 15° tilt, C) south/north facing at 15° tilt, and D) east/west facing at 40° tilt. The total EE for the systems were calculated as well as the net emissions reduction, i.e. difference between *avoided* emissions from the renewable electricity and the *EE* of the modules.

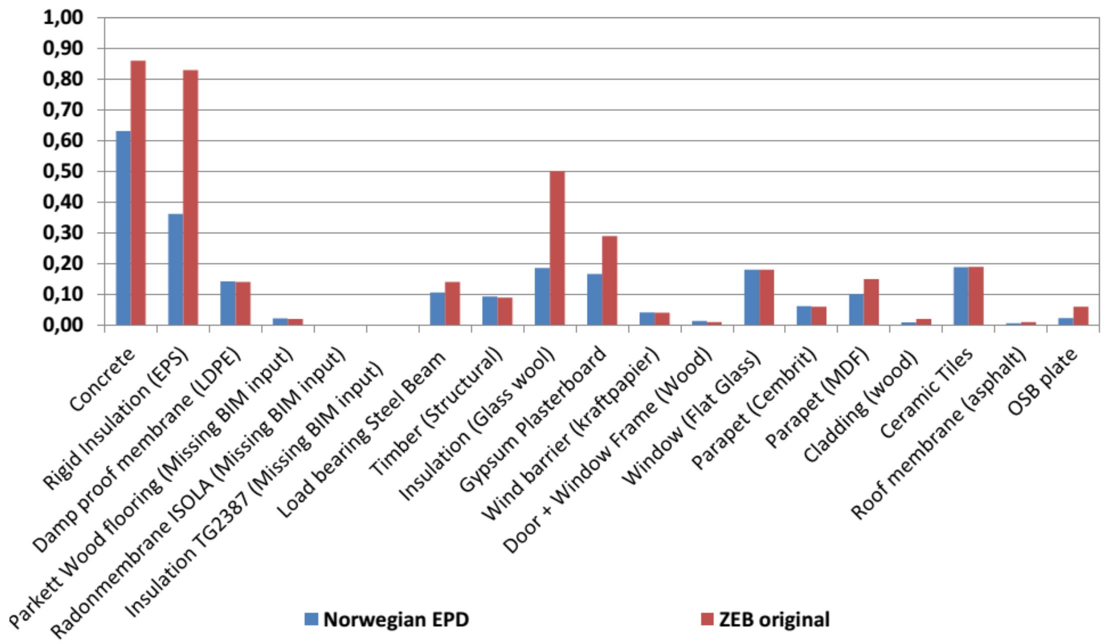

Figure 1. CO_{2eq} emission comparisons between ZEB original study and Norwegian EPD switch for main materials inputs.

RESULTS

The reduction in emissions resulting from the switch to specific Norwegian EPD data compared to those used in the original ZEB residential building using generic Ecoinvent data, is shown in Figure 1.

The overall results show that by identifying the materials responsible for the highest emissions such as concrete, mineral wool and EPS insulation, plasterboard (and wood even though this is not a high emitter) in all the building components, the total EE for these materials can be reduced from the baseline of 7,2 to 5,8 $kgCO_{2eq}/m^2$/year when the Norwegian EPD data was substituted for the generic data. Although, this reduction is largely as a result of the Norwegian EPD using a much lower emission factor for the Nordel electricity mix and that the material efficiency, process technique used, heat energy and other factors can also play a crucial role.

PV System

The analysis of the three module types showed that CIS modules had the lowest amount of EE per generated kilowatt hour, i.e. the "greenest" electricity, but that the mono-Si modules had the highest net emissions reduction due to their high efficiency. The PV system simulations showed that amount of net avoided emissions was largest for system C, with low-tilt modules facing north and south, even though the EE of this system was largest. System A performed better in terms of kilowatt hours per module, and the north facing modules in system C gave only 70% of the electricity compared to the modules in system A. The avoided emissions (negative) are larger with the EU grid factor (0.45 kg CO_{2eq}/kWh) is used, than when the ZEB grid factor (0.132 kg CO_{2eq}/kWh) whereas the EE (positive) are the same.

Emissions from operation of electric appliances and hot-fed machines

Finally, since the building concept is based on a highly-insulated building envelope, the dominant source of emissions during building operation turned out to be electric appliances. In the baseline work, the estimated yearly electricity consumption was taken as 2388 kWh/year. A literature survey [2] proved that this value is well representative for the average yearly electricity consumption of existing households in Norway. Therefore, this value does not account for best equipments with the highest efficiency, or neither accounts for user behaviors that promote energy saving. This average electricity consumption of 2388 kWh/year can thus be reduced but it is difficult to quantify this potential of reduction.

Among electric appliances, the dishwasher, the clothes dryer and the washing machine account for 765 kWh. Being a large contributor to the total electricity load, alternative strategies to reduce their consumption are here investigated. Basically, these equipments use electricity to directly warm up the water during a cycle. This way of converting electricity is known to be ineffective. On the contrary, *heat-fed* machines are equipped with a built-in heat exchanger that enables the centralized heating system of the building to provide for the heat to warm the water as well as the content of the machine (e.g. structure, the crockery). A recent experimental study [3-5] as shown that, using an inlet hot water at 80°C, 81% of the electricity for the washing machine can be substituted by hot water, 80% for the dishwasher and 87% for the clothes dryer. Unfortunately, this quantity drops drastically if an inlet temperature of 55°C is used: the substitution is then reduced to 55%, 50% and 78%, respectively. This temperature limit of 55°C does well correspond to the heat pump technology used in the ZEB residential concept. Assuming yearly average COP of 2.5 for produced water at 55°C, calculations show a reduction of ~300 kWh. It thus corresponds to a ~40% reduction compared to the initial 765 kWh. It clearly proves that this kind of improvement should be considered in a sound ZEB concept.

CO_{2eq} factors for grid electricity during operation

The baseline factor of 132gCO_{2eq}/kWh is based on a specific scenario termed UltraGreen. It assumes that the Nordic and European grids will be strongly interconnected and that a massive de-carbonization of the European electricity grid will take place in the next 40 years is in good agreement with the objective of the European Union. In practice, the 132 gCO_{2eq}/kWh is taken as the 60-year average of this evolution, explaining its relatively low value. Even though realistic, the performance of the ZEB concept with regards to alternative scenarios for the CO_{2eq} factor is investigated and is detailed in Georges et al. [17]. Only the main results will be reported here.

Modified Model

In the modified model, the generic data has been replaced with the EPDs resulting in the EE from materials being reduced from 7.2 to 5.8 kgCO_{2eq}/m²year. In addition, the electricity load can be reduced from the 14.9 to 11.6 kWh/m² per year essentially using more consolidated data for household appliances and hot-fed machines. This corresponds to an annual CO_{2eq} reduction of 0.24 kg/m^2.The balance of CO_{2eq} emissions is changed when both the emissions from materials and operation are included together depending on the choice of the grid mix as shown Figure 3

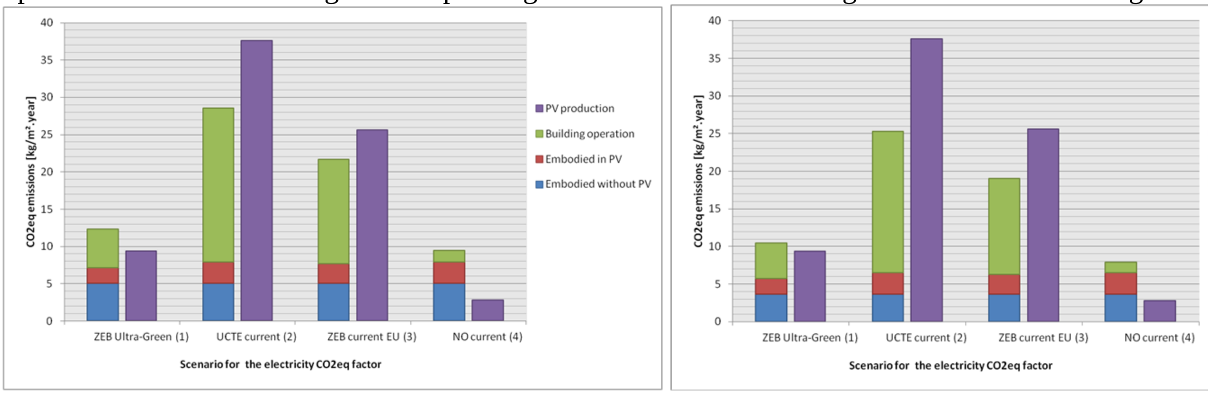

Figure 3. Annual CO_{2eq} emissions and offset from PV for the original (left) and modified (right) ZEB concept, for the different CO_{2eq} factors for the electricity [2].

The improvement in the modified model is clearly noticeable but does not alter conclusions. It proves that previous conclusions as regards the ZEB concept performance were robust. It is nevertheless important to note that ZEB-OM is almost reached when the ZEB Ultra-Green CO_{2eq} factor is used. The magnitude of EE and EO is also significantly improved. In the ZEB Ultra-Green scenario (i.e. low-carbon grid), EE in materials can be dominant and the largest improvement is due their reduction..

DISCUSSION AND CONCLUSION

The results from the switch to specific Norwegian EPD data show a significant reduction in total EE for materials from 7.2 to 5.8 $kgCO_{2eq}/m^2$ per year. The EE data are extracted from publicly available Norwegian EPDs that are performed according to EN 15804. However, it should be noted that these calculations reflect cradle to gate emissions (A1-A3) and replacement (B4) but do not reflect the even greater potential if calculated for cradle to grave emissions where the longer term benefits of wood as a carbon store can be seen. It should be made clear that emissions related to transport from cradle to factory gate (A2) are accounted for in our calculations but those emissions related to transport from gate to construction site (A4) have not been included. The true benefits of using specific data for those products produced in Norway would be seen if the system boundary is extended to include transport emissions.

It should also be noted that the results for the Norwegian EPD switch are based on the emission factor calculated using the CO_{2eq} factor for the Nordel mix compared to a much higher value used for RER or average European mix, which can result in a significant reduction in emissions as can be seen in the case of concrete where the much lower CO_{2eq} factor for the Nordel mix is used in the calculations. Even if the calculation of embodied emission has uncertainties, preliminary results indicate significant reduction of EE by replacing generic data with specific data from EPDs.

As regards the PV installation, the net emissions reduction was largest for the design alternative with north and south facing modules at low tilt angles (i.e. design “C”). However, the benefit of installing low-performing north facing modules in order to reach an emission balance can be questioned, since the performance of these modules was low. The highest net emissions reduction was found to result from the largest PV system with the highest efficiency modules (system C with mono-Si modules), even though this system also resulted in the highest amount of EE.

The CO_{2eq} factor considered for the electricity imported and exported to the grid has a large influence on the net ZEB balance. For instance, the ZEB-OM balance is not reached in the context of a low-carbon grid which corresponds either to the Norwegian grid connected to the future de-carbonisation European grid, or to the current situation with a Norwegian grid that has some transmission capacity to Nordic countries, but are only to a limited degree connected to the European grid. In this context, the EE can be higher than the emissions for the building operation during the 60 year lifetime. On the contrary, if the emission factor grid electricity is relatively high, a scenario corresponding to a Norwegian grid fully connected to a European grid without de-carbonization, the ZEB-OM balance is reached and the emissions for building operation dominate over EE.

Finally, this paper investigates the influence of using Norwegian emission data (from EPDs), using different CO_{2eq} factors (for electricity in the operational phase) and electricity load from household appliances (using data for household appliances and hot-fed machines) on the overall ZEB residential building performance. This sensitivity analysis showed that the previous conclusions about the performance of the ZEB residential concept were essential correct. The ZEB-OM is difficult to reach in the context of a low-carbon electricity grid, even though improvements proposed in the paper managed to get close to the strict balance of emissions.

When discussing the performance of ZEB, one should be very careful as this performance is not only limited to a balance of CO_{2eq} emissions. In fact, the overall ZEB performance is the combination of its energy efficiency, reduced EE and emissions for building operation, on-site renewable energy conversion, flexibility offered to the electricity grid (e.g. grid interaction), as well as, balance of CO_{2eq} emissions. By the way, in the context of a low-carbon grid, it is not because the ZEB-OM balance is not reached that the interest into the ZEB concept is essentially lost. For instance, ZEBs are considered necessarily to shift to this low-carbon grid due to their high energy efficiency, onsite renewables and the flexibility they can provide to the grid.

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