Life cycle emissions analysis of two nZEB concepts

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The net-zero emissions building (nZEB) performance is investigated for building operation (EO) and embodied emissions in materials (EE) for Norway’s cold climate. nZEB concepts for new residential and office buildings are conceived in order to understand the balance and implications between operational and embodied emissions over the building’s life. The main drivers for the CO₂ equivalent (CO₂e) emissions are revealed for both building concepts through a detailed emissions calculation. The influence of the CO₂e factor for electricity is emphasized and it is shown to have significant impact on the temporal evolution of the overall CO₂e emissions balance. The results show that the criterion for zero emissions in operation is easily reached for both nZEB concepts (independent of the CO₂e factor considered). Embodied emissions are 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. In this particular scenario, the net balance of emissions alone is nonetheless not a sufficient performance indicator for nZEB.

Keywords: buildings, embodied emissions, embodied energy, emissions reduction, greenhouse gas (GHG) emissions, life cycle assessment, net zero, operational emissions, operational energy

Introduction

It is well known that the environmental performance of buildings needs to be drastically improved, especially in terms of energy use and CO₂ equivalent (CO₂e) emissions. In order to address this challenge, the concept of zero energy building has emerged. At the European level, the revised directive on Energy Performance of Buildings (EPBD) (European Parliament, 2010) requires that all new buildings should be nearly zero energy by 2020. Significant efforts to define these net-zero energy buildings have been made: for instance, a review and classification of definitions (Pless & Torcellini, 2010; Torcellini, Pless, & Deru, 2006), the recent REHVA (Federation of European Heating, Ventilation and Air Conditioning Associations) technical definition (Kurnitski et al., 2013), and developments done in the framework of the IEA SHC Task 40 (International Energy Agency, 2008–2013). Marszal et al. (2011) give an overview of existing net-zero energy definitions, while Sartori, Napolitano, and Voss (2012) propose a consistent framework for their definition. In particular, some existing definitions explicitly integrate elements of life cycle analysis (LCA) (Cellura, Guarino, Longo, & Mistretta, 2014; Hernandez & Kenny, 2010).

Given the imperative to minimize the impact of buildings on global warming, some definitions are essentially based on greenhouse gas emissions (GHG), the so-called net-zero emissions building (nZEB). This
means that all CO₂e emissions should be accounted for both the energy use for operation (EO) as well as embodied emissions (EE) from materials and components. Given these ambitious objectives, an array of measures is needed at the level of the building, starting from envelope efficiency to building services, including onsite renewable energy conversion. In practice, only a coherent and coordinated set of these measures will lead to significant emission reduction. This then prompted the need to investigate and develop nZEB concepts. This entails an iterative process where a first proposition of nZEB concept is analysed thoroughly to reveal its strengths and limitations, which ultimately leads to further refinement of the concept.

The first stage of this iterative concept development is presented. As a starting point, the nZEB concept analysis is based on the current available technology, thus reflecting today’s practices in the Norwegian construction sector. A so-called ‘all-electric’ solution has been selected as it is a common strategy often found in the zero energy building community (Voss & Musall, 2012): a well-insulated building envelope is equipped with solar thermal panels and a heat pump to cover the thermal needs (i.e. heating and cooling) and with photovoltaic (PV) panels to produce electricity. Two nZEB concepts are then created by applying this all-electric solution to a typical typology of a new single-family residential building and of a new office building, with two and four storeys, respectively. The goal of this preliminary investigation is to estimate, and thus provide an overview, of the materials and systems that contribute the most to the CO₂e emissions over the building’s lifetime (assumed in this study to be 60 years). The results will provide a benchmark for Nordic conditions (i.e. a cold climate) and a starting point for comparison. It is important to note that the investigated concepts should be considered neither as an absolute optimum nor as an architectural expression of future nZEBs. Nevertheless, they are realistic concepts from a functional point of view.

Previous publications have already reported on the performance of both first-stage nZEB concepts (Dokka, Houlihan Wiberg et al., 2013; Dokka, Kristjansdottir et al., 2013; Houlihan Wiberg et al., 2014; Kristjansdottir et al., 2013). These detailed technical documents provide in-depth information and further explanation. The energy use, EE and total CO₂e emissions for both concepts are well documented.

In summary, results show that both concepts were able to counterbalance EO, reaching the so-called ZEB-O level. However, neither concept was able to counterbalance the total emissions when EE and EO are combined, a level herein termed ZEB-OM. Nevertheless, it should be noted that these analyses were done considering a specific CO₂e factor for electricity. This yearly averaged factor is relatively low with 132 gCO₂e/kWh and was calculated assuming a fully decarbonized European grid within the next 45 years. In the remainder of this paper, these results and hypotheses will be termed the baseline scenario.

As a continuation, the present paper further discusses the performance of both first-stage nZEB concepts, especially the influence of the CO₂e factor for electricity. In that respect, alternative scenarios for the CO₂e factor for electricity are being considered in order to investigate the robustness of the nZEB concepts. This dependence can be intuitively understood: the electricity consumed by the building or produced by the on-site PV panels will be credited by the selected CO₂e factor so that, using higher factors, credits for the net PV export will counterbalance EE more quickly. Nevertheless, a quantitative assessment of this effect is the outcome reported in this article. Results clearly confirm that the ZEB-O balance is always achievable for both nZEB concepts. However, it was found that EE only prevail over EO in the specific context of low CO₂e factors for electricity where it eventually makes the ZEB-OM balance unsustainable. This is an important conclusion from this paper as it is well known that the selection of CO₂e factors for electricity is prone to a large debate.

**Office and residential concepts**

The initial concepts for both buildings are essentially based on state-of-the-art technologies already available on the market. They are also taken as representative of the current practice in the Norwegian construction sector and in the ZEB community (Snohetta et al., 2012; Thyholt & Dokka, 2012; Thyholt Dokka, & Jenssen, 2012; Voss & Musall, 2012):

- The space-heating demand is limited by using a super-insulated envelope, while the cooling load is restricted by implementing passive strategies properly.
- Energy-efficient building services are applied to minimize the energy use. An air-to-water heat pump is combined with solar thermal collectors through a storage tank so that both systems contribute to cover the thermal load (i.e. domestic hot water and space heating). Energy-efficient lighting and appliances are applied to the office concept.
- A PV system is implemented to offset the EO and EE. From a functional and architectural point of view, it has also been decided to limit the PV installation to the horizontal roof, except for the office concept where the south vertical facade is also used. The solar thermal collectors are less sensitive to shading, therefore they are placed on the south
vertical facade to leave the horizontal roof available for PV.

It should be noted that no effort has been made to minimize the EE through the selection of building materials. This EE optimization will be considered in future work.

Single-family residential and office typologies constitute approximately 40% of the Norwegian building stock. Both building concepts are assumed to be located in Oslo in a flat and open terrain without obstacles.

Table 1 summarizes the main basic characteristics of the residential and office building concepts. Complementary information is given in Tables S1–S5 in the Supplementary File, which can be found online. Furthermore, detailed technical specifications can be found in Dokka, Houlihan Wiberg et al. (2013) and Dokka, Kristjansdottir et al. (2013). Energy demand is calculated according to Norwegian standards, e.g. NS 3031 (Standard Norge, 2007), and normalized according to the heated floor area (BRA). The basis for the emissions calculation is developed below in the Methods section. Results from previous work using the baseline scenario are briefly reported here in order to illustrate some main conclusions.

Table 1 shows that both buildings have a very-low annual energy demand due to the rigorous application of state-of-the-art technologies. The heating demand is indeed relatively low in both building types. There is no active cooling in the residential building, while some mechanical cooling is required for the office. Reduced energy demand combined with energy-efficient supply systems lead to a limited total electricity use for both building concepts. This corresponds to EO that are relatively low. Practically, it can be seen that EE in materials are much higher than EO under this baseline scenario: the EE are the major contributors to the total emissions from the two buildings. It can be seen that PV production in both buildings is able to offset the EO (ZEB-O), but is unable to counterbalance the total emissions when EE are included (ZEB-OM).

**Methods**

The method used to evaluate CO$_2$e emissions and the nZEB balance is presented in the following section. Due to space limitations, not all aspects can be presented in detail. Only the most important elements are presented.

**nZEB definition**

In order to develop and compare concepts for zero emission buildings, it is necessary to have a sound definition of nZEB (for single buildings and also for clusters). No definitive or universal definition currently exists. To address this, the Norwegian ZEB Centre has proposed a consistent version and its main characteristics are introduced below. For a more detailed description of the definition, see Dokka, Sartori, Thyholt, Lien, and Lindberg (2013c).

The nZEB definition is characterized by an *ambition level* ranging from low to high in terms of what aspects are included. Table 2 provides an explanation of the different levels of ambition, ranging from the lowest (operational energy excluding plug loads, *e.g.* appliances) to the highest (complete life cycle emissions – based on NS EN 15978; CEN, 2011). In terms of *rules of calculation*, building energy demand...
is calculated according to Norwegian standards (Standard Norge, 2007, 2010, 2012). The lifetime of the building is assumed to be 60 years. Concerning the system boundaries, local renewable electricity will be produced on-site, but off-site renewables (e.g. biofuels) can be used in this electricity production. Thermal energy production for the building or area (i.e. cluster of buildings) can be both on- and off-site, but emissions from the actual energy mix will be used and the total system losses from production to emission in the building will be taken into account. Furthermore, the calculation procedure requires the definition of CO2e factors (discussed below) which correspond to the building lifespan of 60 years. In order to enforce a minimal level of energy efficiency, the criteria for low energy buildings in NS 3700 (Standard Norge, 2010) and NS 3701 (Standard Norge, 2012) are the minimum requirement. In practice, the two nZEB concepts presented here propose to fulfil the more strict requirements of the Norwegian passive house standard (Standard Norge, 2010, 2012).

The mismatch between energy demand of the building(s) and on-site energy production can be considerable on an hourly, daily, weekly and annual basis. This can lead to stresses on the grid and lead to variations in CO2e emissions. However, based on current available methods and data, a simplified approach is to use a yearly averaged factor with no daily, weekly or annual variation. The same factor is used for both the import and export of electricity to/from the building(s), a so-called symmetric weighting (Sartori et al., 2012). Nonetheless, load match factors can be used to estimate the mismatch between demand and production (Sartori et al., 2012). All nZEBs need to comply with the indoor climate requirements in the Norwegian building code (KRD, 2010). In addition, the requirement on local discomfort for Category B in Appendix A in ISO 7730 (CEN, 2005) shall be met.

**Net balance of CO2e emissions**

The emissions calculation essentially begins with a detailed description of the two nZEB concepts. The design of the building envelope and service systems was defined in detail in order to allow a proper evaluation of the loads in operation, as well as EE of the materials (used in the envelope and technical systems). The nZEB balance is essentially composed of three elements:

- **Annual total energy use (Qa)**
  Its evaluation is divided into two consecutive steps. Firstly, energy demand is established (using the current Norwegian regulation as mentioned above). A simulation of the annual heating and cooling demands was done using the software SIMIEN (ProgramByggerne, 2012). Secondly, the system efficiency, including auxiliaries, is computed in order to determine the resulting energy use for each building service. For instance, the efficiency of the thermal systems was evaluated using Polysun (Vela, 2012). Qa is obtained by summing the energy uses of each building service.

- **Annual PV electricity production (Qp)**
  It is evaluated using the software PVsyst (PVsyst SA, 2013) based on a detailed description of the installation.

- **EE in material for the entire building lifetime of n years, EE(n)**
  Following the nZEB definition, n is 60 years. The embodied emissions data include materials for the construction of the building including technical and heating systems as well as emissions from replacements made during the lifetime.

Using symmetric CO2e factors, the net balance (∆E) for an all-electric building can then be formulated in the following way:

\[
\Delta E(n) = EE(n) + \sum_{i=1}^{n} f(i) \times (Q_d - Q_e) \quad (1)
\]

where n is the building lifetime expressed in years (60 years); Qd is the yearly electricity delivered to the building; Qe is the yearly electricity exported to the grid by the building; and f(i) is the yearly averaged CO2e factor in gCO2e/kWh for electricity for year i.

In practice, the difference between Qd and Qe is not computed here. As the CO2e factors are assumed in this study to be symmetrical, this term is consistently replaced by the difference between Qa and Qp:

\[
\Delta E(n) = EE(n) + \sum_{i=1}^{n} f(i) \times (Q_a - Q_p) \quad (2)
\]

If ∆E is negative, then the building has reached the ZEB-OM balance. If the balance is positive, then it fails. If the embodied emissions term EE(n) is removed in equations (1) or (2), it then corresponds to the ZEB-O balance. Accordingly, a building is termed ZEB-O if the balance is negative. Following another terminology, it can also be called a net-positive energy building.

**CO2e factors for electricity**

The annual CO2e factor f(i) for electricity thus plays an important role in the nZEB balance, as shown in equation (2), and has been deliberately kept dependent on the year i.

The baseline case considers a specific and constant factor of 132 gCO2e/kWh. This factor has been
established based on several considerations (Graabak & Feilberg, 2011). Essentially, it assumes that the Nordic and European grids will be strongly interconnected and that an average European mix is consistent (based on the EU-27 plus Switzerland, Norway and the Balkans). Furthermore, in line with the long-term political goals for the electricity in Europe (ECF, 2010; European Commission, 2011), an ambitious 90% reduction of the CO2e emissions is assumed for 2050. Accordingly, a realistic scenario termed ‘ZEB Ultra-Green’ has been established. It corresponds to a coherent set of measures taken on the energy systems to reach this ambitious objective. The scenario enables creating input data (e.g. electricity demand, energy prices, renewable energy sources (RES) deployment and non-RES production capacities until 2050) that are subsequently used to investigate the future electricity production mix until 2050. This is done using the analytical tool EMPS, a stochastic optimization model for hydrothermal electricity markets (Wolfgang et al., 2009). Most of the methodology and data inputs are from the EU-FP7 project SUSPLAN (2011) including important sources for input data like World Energy Outlook from the IEA and reports from Eurelectric. Extrapolating this trend beyond 2050, it leads to a fully decarbonized grid after 45 years. Assuming a constant annual electricity use in the building during its 60-year lifetime, it leads a 60-year average factor of 132 gCO2e/kWh. This concept is illustrated in Figure 1: using the ZEB Ultra-Green scenario, the annual factor starts at 361 gCO2e/kWh and decreases linearly to zero in 45 years; the ZEB baseline factor is then the 60-year average of this annual factor.

As an objective of the present paper is to investigate the robustness of the two nZEB concepts with regard to the CO2e factor for electricity, alternatives to the baseline scenario are introduced. Firstly, the UCTE (i.e. Union for the Coordination of the Transmission of Electricity) emission factor is assumed throughout the lifetime of the building to have a high value of 531 gCO2e/kWh. This is a factor that is originally based on studies for EN 15603 (CEN, 2013) and adapted in Ecoinvent to integrate elements of life cycle assessment (Swiss Center for Life Cycle Inventories). Secondly, another alternative is to assume that the European grid will not be globally improved. Starting at the same magnitude as the ZEB Ultra-Green factor of today (i.e. f(0)), the factor of 361 gCO2e/kWh will be taken constant throughout the building lifetime. Finally, the current five-year average of the Norwegian grid is taken for the entire building lifetime. This leads to an extremely low CO2e factor of 38 gCO2e/kWh (due to 98% hydroelectricity production in Norway). By definition, this approach ignores completely the exchange of electricity between Norway and its neighbours. In summary, the different factors, listed in Table 3, reflect potential technical and political contexts in which future nZEBs will have to play.

### Description of emission accounting from material use

The evaluation of the ZEB-OM balance requires a calculation of EE in materials and components (see equation 2). In both cases, the functional unit is 1 m² of heated floor area (BRA) over the 60-year estimated lifetime of the building. The results are presented for emissions on an annual basis, where the functional unit of 1 m² is divided by the building lifetime. The intention of these analyses was not to minimize the EE. Instead, it is to document EE using the usual building materials and components including those associated with the ventilation system and renewable energy system (including the PV panels and solar thermal units).

The boundaries for the analyses are limited to the extraction of raw materials and the manufacturing of the main products and materials needed. Replacement...
of new materials over the lifetime has also been included. The calculations are based on the principles of environmental assessment through life cycle analysis. The analysis focuses on modules A1–A3 from the standard EN 15978 (CEN, 2011), which include material inputs to gate. The use phases B1 and B4, replacement of new materials over the lifetime of the building, have also been included. The estimated service lifetime of the different inputs is mainly based on product category rules for different materials and components.

The EE calculations for both the residential and office cases used the Intergovernmental Panel on Climate Change (IPCC) Global Warming Potential 2007, 100-year scenario for CO2e emissions, in the LCA Software tool, SimaPro version 7.3 (PRé Consultant, 2012) and with data from the life cycle inventory database Ecoinvent Version 2.2 (Swiss Center for Life Cycle Inventories, 2010). Length, area and volume of different materials and components have been exported from the REVIT/BIM (Autodesk, 2011) model to Excel, and then the quantities have been used to calculate EE. The material and components contained in the BIM output correspond to the category in the Norwegian standard NS 3451 (Standard Norge, 2009).

The material inputs are mainly based on environmental data from the Ecoinvent database version 2.2, but in the case of the office concept, environmental product declarations (EPD) have also been used for the facade and floor materials. The decision to use mostly Ecoinvent processes was based on the need to have a consistent and transparent methodology behind the emissions data for the materials. Using this database, such as Ecoinvent, the emission factors are taken locally for each specific material from its own country or region of production. For EE, emissions factors are thus dependent on the current emission factor of the electricity consumption mix in each respective country (or region). As it is difficult to ascertain how these local factors will evolve in the next 60 years, they are assumed to remain constant throughout the lifetime of the building. This hypothesis only affects the emissions related to the replacement of material. Except for EE in PV, this framework of calculation will not be changed in the remainder of the article.

An important methodological aspect is related to the evaluation of the EE related to the PV panels. As shown in Figure 2, they have the most dominant contribution to CO2e emissions for both building...
concepts. The emission data for PV are based on the process for a ‘Photovoltaic panel, single-Si, at plant/ RER/’ from the Ecoinvent database. The estimated service lifetime for the solar PV panels is 30 years and is based on guidelines from the IEA for the LCA of electricity from PV panels (IEA). It should be noted that the service lifetime for PV panels is uncertain and is highly dependent on the quality of the actual PV panels used. In the baseline scenario, the solar cells were estimated to be produced in a 50% more efficient way in 30 years (SENSE, 2008). Furthermore, mainly the UCTE electricity mix has been used. Nevertheless, in the present work, the methodology has been adapted to account for different CO2e factors of Table 3 in a more consistent way. These factors indeed influence EE through the 144 kWh of the electricity used in the production chain for 1 m² of the PV panels:

- When PV is installed for the first time at the building construction (year \( t_0 \)), the CO2e factor to compute EE in PV is equivalent to the factor for operational energy at year \( t_0 \): \( f(0) \) using terminology in equations (1) and (2). The only exception will be for the Norwegian electricity mix where it is still assumed that PV is manufactured in continental Europe. In this case, the UCTE factor has been preferably chosen.

- For the replacement after 30 years, the EE in the PV are estimated by taking the CO2e factor value at that particular year (i.e. \( t_0 + 30 \) years): \( f(30) \) using terminology in equations (1) and (2). This has an impact when factors are dynamic, as for the ZEB Ultra-Green (scenario 1.b in Table 3).

Given this new framework of evaluation, the resulting EE in PV are reported in Table 4.

| CO2e factor used for operational energy | Number | First PV installation \( (t_0) \) (kgCO2e/m²) | Replacement PV \( (t_0 + 30 \) year) (kgCO2e/m²) |
|----------------------------------------|--------|----------------------------------------|----------------------------------------|
| ZEB baseline                           | 1.a    | 1474                                   | 1474                                   |
| ZEB Ultra-Green                         | 1.b    | 180.9                                  | 145.7                                  |
| UCTE current                           | 2      | 199.0                                  | 199.0                                  |
| ZEB current EU                         | 3      | 180.9                                  | 180.9                                  |
| NO current                             | 4      | 199.0b                                 | 199.0b                                 |

Notes: “In this particular table, the embodied emissions are normalized by m² of PV panel.

nZEB balance over the entire building lifetime

The CO2e emissions of the residential building are reported in Figure 3 as a function of the CO2e factor considered for electricity. In each case, the PV electricity is able to offset the EO. For a typical two-storey single-family house, it is possible to achieve a ZEB-O level (Houlihan Wiberg et al., 2014). In this case, the building can be labelled as a net-positive energy house (i.e. energy produced on-site with PV exceeds the total electricity use). The relative contribution of EE to the total CO2e emissions strongly depends on the CO2e factor chosen for electricity: EE dominates EO with low CO2e factors, while high factors lead to the opposite case. In terms of balance of emissions, the conclusions are now different: the ZEB residential building is able to reach the ZEB-OM (operational and embodied) balance as a function of the CO2e factor. For high factors such as the UCTE and the ZEB current European Union (EU) (i.e. scenarios 2 and 3 in Table 3), the ZEB-OM level is reached. However, this objective is not met for lower factors. When a European electricity mix is considered, then the ZEB-OM level is reached as a function the evolution of the CO2e factor over the next 60 years. If factors remain high, then the balance is reached but it will not be reached if the European grid is massively decarbonized.

The performance of the office building is reported in Figure 4. Similar to the residential case, the ZEB-O balance is always reached for the office building which can then also be labelled as a net-positive energy building. However, the ZEB-OM level cannot be met except in one scenario. Only the high CO2e factor of the current UCTE mix (i.e. 531 gCO2e/kWh) manages to counterbalance the total building emissions. Reaching the ZEB-OM balance is much more critical for the office building.

In the case where the electricity consumed is exclusively produced in Norway (i.e. using the current Norwegian CO2e factor) and the building products such as PV originate from the European continent, then the PV electricity production cannot payback for its own EE. In other words, it would be inconsistent to manufacture PV using ‘high-carbon’ electricity to offset electricity in a national electricity grid that is basically already ‘green’. This shows that the selection of CO2e factors is of prime importance to assess the performance of nZEBs. Furthermore, the question of
whether EE is dominant or not over EO, directly depends on this CO₂e factor.

**Dynamics of CO₂e emissions over time**

The temporal evolution of the cumulative CO₂e emissions over the building lifetime deserves investigation. From a mathematical point of view, it is possible to plot the ZEB-OM balance formulated by equation (2), \( \Delta E(n) \), for \( n \) between 0 and 60 years. For instance, this term is reported on Figure 5 for the residential building. At the beginning \( (t_0) \), only EE of the materials are present (obviously because the building has not yet become operational). Then, for each passing year, more electricity is produced by PV than the amount of electricity used to operate the building. The CO₂e credit for this net electricity export from PV progressively decreases the initial carbon debt (due to EE). In practice, the higher the CO₂e factor for electricity, the quicker this debt is repaid. Over the building’s lifetime, some building components will require replacement and their respective EE are therefore added to the balance. This can be seen in Figure 5 where the different curves have several discontinuities. For instance, the largest increase is induced by the PV replacement after 30 years.
Using the UCTE mix or the ZEB current EU mix, the ZEB-OM is reached after 16 and 26 years, respectively. Furthermore, there is now a fundamental difference between the ZEB baseline CO₂e factor and the dynamic ZEB Ultra-Green factor (scenarios 1.a and 1.b of Table 3, respectively). They have almost the same starting point in Figure 5 and finish at almost at the same level. Nevertheless, the dynamic scenario starts with a high factor which is, by definition, equivalent to the ZEB current EU mix (scenario 3). The offset of emissions generated by the extra PV production is therefore important at the beginning of the building lifetime. Nevertheless, this contribution converges progressively towards zero while the EU grid is massively decarbonized (i.e. the CO₂e factor for electricity becomes negligible). Most of the positive impact of PV on the nZEB balance is performed during the first 30 years. At the end, the behaviour becomes similar to the Norwegian electricity mix, characteristic for low CO₂e factors. Finally, by definition of the nZEB balance (developed in equation 2), Figure 5 can also be used to investigate the influence of the building lifetime (i.e. the nZEB balancing period) which is basically taken at 60 years..for instance, it is here shown for lifetimes between 0 and 60 years.

**Discussion**

The present study assumes symmetrical emission factors. Yearly averaged CO₂e factors were assumed, although these factors vary in practice within this period of time. The PV installation has been limited to the flat roof plus the south facade for the office building case. Results are therefore discussed for this specific context. Although simplified, this framework of analysis is nevertheless representative for most of the current existing research on nZEBs worldwide.

For the ZEB-O level, both the residential and office concepts manage unconditionally to reach this ambition level. In fact, they both are net-positive energy buildings with a net electricity export to the grid. Both concepts are indeed based on an all-electric approach so that all energy exchanges through the building boundary are only performed using electricity. In the nZEB balancing method (equation 2), the ZEB-O level is then independent of the CO₂e factor for electricity, \( f(i) \). Consequently, a proper assessment of the CO₂e factors or their future evolution in time is not required. The confidence level in the conclusions on the ZEB-O level is thus high.

![Figure 5](image)

*Figure 5* Evolution of cumulated CO₂e emissions during the 60-year lifetime of the residential building. This also corresponds to the evolution of the nZEB balance, \( \Delta E(n) \), of equation (2), where \( n = 0 - 60 \).
For the ZEB-OM level, the performance of the residential and office concepts is more complicated and depends upon the specificity of the scenario. The comparison of EE with EO introduces a large complexity into the analysis:

- The CO₂e factor for electricity cannot be neglected anymore in the ZEB-OM balance (equation 2) and this has several important dimensions. Firstly, different energy carriers are used to produce materials, which means the difference between their respective CO₂e factors is important. It also raises the question of the definition used for CO₂e factors. Which processes do they include? For instance, are the EE for the energy infrastructure accounted for, or are the CO₂e factors only based on operational energy? Secondly, materials and components can be produced at different geographic locations, which entails a need to account for the actual CO₂e factors for these material processes. Thirdly, emissions are released at different times so that the evolution of CO₂e factors is also important. CO₂e factors are realistically expected to decrease during the 60-year lifetime as depicted by the ZEB Ultra-Green scenario. This long 60-year lifespan also makes replacement scenarios complex. Building components, energy supply and electricity production systems will most probably see their performance improving in the next 60 years, either in terms of energy efficiency or of EE.

- A long balancing period is required when comparing EE with EO. The common nZEB balance based on the building’s physical boundaries may become problematic when used as the main performance index for a nZEB. If the CO₂e factor for the electricity remains unchanged and high, this balance still makes sense as the on-site electricity production will continue to substitute a ‘polluting’ production unit of the grid electricity mix. The better the emissions balance of the nZEB, the better it is for the overall grid and the society. However, if the electricity CO₂e factor significantly decreases in the next decades, then the ZEB-OM may not be reached as the on-site electricity production would contribute less to the balance of emissions from EE and EO. Based on the assumptions from the present work, the contribution of the PV replacement after 30 years combined with relatively low CO₂e factors for operational electricity would not be useful as electricity from the grid would be ‘greener’ than the processes to produce the PV panels. Nevertheless, with a low carbon grid, a failure to balance the CO₂e emissions does not necessarily mean that the nZEB does not meet its objectives. In practice, the grid energy systems and nZEBs cannot be decoupled artificially (by setting the boundary for the emissions balance to the building’s physical extent). Collectively nZEBs are most probably part of the solution to reach this ‘greener’ electricity production. This is partly due to their on-site renewable energy conversion but also due to their high energy efficiency and the flexibility they could provide to the grid. The interest in nZEBs is to contribute to the shift to a low carbon society rather than to optimize a single building (isolated in a fossil fuel society). A true holistic approach should then consider the strong interaction between nZEBs and the energy systems of the grid.

As coherent nZEB concepts are developed, a key challenge is to investigate the robustness of these concepts against uncertainties. This is more important than proposing accurate scenarios of the future operating conditions for these buildings. In this respect, results can be discussed in the following way:

- The inclusion of uncertainties in the CO₂e emissions accounting has shown a significant change in the concept’s performance. Firstly, in terms of emissions efficiency, the relative importance of EO and EE is changing. A fully decarbonized grid in future, the ZEB default CO₂e factor (i.e. Ultra-Green scenario) presents a risk of handicap energy-efficient measures to reduce operational energy. High CO₂e factors would handicap efforts to reduce EE. Secondly, in terms of balance of emissions, each building concept has a net export of electricity so that the higher the CO₂e factor for electricity during operation, the easier it is to counterbalance EE. With high CO₂e factors, results show that the residential concept manages to reach the ZEB-OM, while this balance is almost never reached by the office concept. This difference is explained by two factors: the EE of the office concept are higher than the residential building and the office has four floors while the residential building only has two. Consequently, when considering emissions normalized by the reference building area, the offset emissions from PV production are thus significantly lower for the office building. In parallel, the office building’s EE are higher while its EO have the same order of magnitude as for the residential case. Finally, in the context of a highly decarbonized grid (i.e. with a low CO₂e factor), it is questionable practice to assess the nZEB performance only on the basis of a balance of emissions that neglects other energy systems from the grid. Whatever balancing methodology is followed, the current article clearly shows that EE in materials should always be minimized. This is more a matter of efficiency than a requirement to reach the CO₂e emissions balance.
The choice of materials and components can make a substantial reduction in a building’s life cycle energy use (Himpe et al., 2013; Thormark, 2006). In order to minimize EE, efforts should be made to reduce the amount of materials and to choose recycled as well as robust materials (i.e., longer service life). Low carbon material could also be used, e.g., emissions from Norwegian low carbon concrete (B35) are about 20% lower than for the concrete used in the baseline study (NorBeton, 2012). Another focus should be on using recycled steel and choosing insulation materials with low emissions. Furthermore, the bearing structure could be optimized with respect to EE by looking at alternative design and material solutions. Finally, a single-crystal-type PV can be replaced with poly-crystal silicon type as well as ribbon and amorphous silicon types characterized by lower EE (Himpe et al., 2013).

Conclusions

nZEB concepts are examined for new residential and office buildings using state-of-the-art technologies already available on the market. Using the Norwegian context and a realistic nZEB definition, the performance in terms of CO₂e emissions is estimated for two typical building typologies. The main objective is to minimize the total CO₂e emissions related to EO (operational energy) and, ultimately, EE (embodied energy) in materials and installations. A key finding is the influence of the scenarios for CO₂e factors of the electricity supply on the performance of these nZEB concepts. The preliminary conclusions of this large research effort are as follows:

- For both the residential and office building concepts, it is possible to reach the ZEB-O balance independently of the CO₂e factors. In this case, the building can be labelled as a net-positive energy building (i.e., the energy produced on-site with PV is higher than the total electricity demand).

- Although the calculation of EE has considerable uncertainties, preliminary results clearly indicate that they contribute significantly to the total CO₂e emissions and therefore they deserve to be minimized. EE even dominates EO when a low CO₂e factor is considered.

- When EE are taken into account, achieving the ZEB-OM balance is more challenging and critical. In practice, a low CO₂e factor (e.g., 132 gCO₂e/kWh) would not achieve the ZEB-OM balance for both the residential and office building concepts. In this scenario, it is difficult for the PV production to offset the EE (as they are mainly computed using the today’s high emission factors). The use of a ZEB-OM balance alone as the main nZEB performance index in a low-carbon society may nevertheless be problematic. The philosophy behind this balance of emissions is essentially valid in the context of a nZEB (equipped with on-site renewable energy conversion) placed in a high-carbon environment (i.e., high CO₂e factor for electricity).

- Both nZEB concepts can be further improved. Present investigations show that there is no reason to limit this improvement to specific performance aspects (e.g., EE reduction) and neglect others (e.g., better energy efficiency in operation). The improvement should then continue to follow a holistic approach: it should simultaneously promote energy-efficiency measures, flexibility to the electricity grid (such as demand-side management), minimization of EE as well as increased renewable energy conversion. Specifically, energy demand may indeed be further reduced (especially from appliances, auxiliaries and lighting), thermal systems with higher seasonal performance investigated, and EE reduced through the use of advanced ‘green’ materials.

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Supplementary files

Further detailed information containing tables mentioned in this article can be found in the online supplemental file at http://dx.doi.org/10.1080/09613218.2015.955755

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Endnotes

1. The total annual energy use (Q.) and the annual PV electricity production (Q.pv) have been assumed to be constant throughout the lifetime of the building. It is a usual but strong hypothesis. For instance, it assumes that the climate will not significantly change over the next 60 years and that the building use is normalized and will also be constant.

2. Several efforts are performed to reduce the CO₂e emissions: energy efficiency (among other by a large deployment of ZEBs), a very high share of power production from non-fossil sources (RES and nuclear), and increased transmission capacity between the region and countries to enable large quantities of electricity to be transported between regions and countries.

3. It includes all GHGs, which means CO₂, CH₄, N₂O, HFC, PFC, SF₆, and all CFC and HCFC and other substances with a GWP according to table T52 of the technical summary of the IPCC (2007) report.

4. When analysing emissions over the entire building lifetime, the present calculation method does not provide any difference between the results computed using constant or dynamic CO₂e factors. Therefore, cases 1a and 1b of Table 3 are here merged into a single category termed the ZEB Ultra-Green scenario.

5. Except for the baseline scenario 1a of Table 3, which is intrinsically based on a 60-year building lifetime.

6. For instance, EE from PV panels have been evaluated using different EU electricity mixes. What would be the result if the production of PV panels is in China?