

A Comparative Study of Different PV Installations for a Norwegian Net Zero Emission Building Concept

Clara Good¹, Torhildur Kristjansdottir¹, Aoife Houlihan Wiberg¹ and Laurent Georges², Anne Grete Hestnes¹

¹ Norwegian University of Science and Technology (NTNU), Department of Architectural Design, History and Technology, Trondheim (Norway)

² Norwegian University of Science and Technology (NTNU), Department of Energy and Process Engineering, Trondheim (Norway)

Abstract

This paper presents an analysis of how the design of a photovoltaic (PV) system influences the greenhouse gas emissions balance in net zero emission buildings (nZEB). In a zero emission building, the emissions associated both with the energy required in the operation of the building (operational emissions), and the energy used to produce the building materials (embodied emissions), are offset by renewable energy generated on-site. The analysis is applied to a nZEB building concept for a single-family building, developed by the Norwegian Research Centre on Zero Emission Buildings. Previous analyses have shown that the installation of a PV system accounts for a significant share of the embodied emissions of a nZEB. The objective of this paper is to assess how the PV system design influences the embodied and avoided emissions as well as the energy yield. Three different PV technologies and four different module layouts for flat roofs are evaluated. In addition, the influence of two different grid emission factors is studied.

Keywords: zero emission buildings, grid-connected PV, embodied emissions, PV system design

1. Introduction and background

The building industry is a large contributor to global energy demand and greenhouse gas emissions, accounting for about a third of the global energy use (IEA, 2013). To reduce this contribution, the environmental performance of buildings needs to be drastically improved. In order to address this challenge, the concept of zero energy and zero emission buildings has emerged.

At the European level, the revised directive on Energy Performance of Buildings (EPBD) requires that all new buildings should be ‘nearly zero energy buildings’ by 2020 (Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings, 2010). This has led to extensive work on zero energy buildings and their definition, in which Norway plays an active role. As part of this work, the Research Council of Norway has funded the establishment of the Research Centre on Zero Emission Buildings (the ZEB Centre, www.zeb.no). The activities in the ZEB Centre are mainly focused on greenhouse gas emissions related to the building industry, and how these can be reduced.

The overall goal of a net zero emission building (nZEB) is that all emissions related to the energy use for operation as well as embodied emissions from materials should be offset by on-site renewable energy generation. The addition of the word “net” indicates that energy can be exported from and imported to the building, and that the net energy or emission balance is calculated over a specific period of time, usually a year. In practice, this usually means that the building is connected to the energy grid.

1.1. Zero emission buildings

In order to develop concepts and strategies, it is necessary to first establish a sound definition of a nZEB. There is, so far, no commonly accepted definition of a nZEB and how the emissions balance should be calculated (Marszal et al., 2011) (Marszal et al., 2011). A detailed discussion on this topic and a proposed

Norwegian definition of a nZEB is presented in previous publications (Dokka et al., 2013a; Houlihan Wiberg et al., 2014; Kristjansdottir et al., 2013).

The calculation of a life cycle emissions balance is complex and requires a large amount of background data. The level of greenhouse gas emissions that are associated with a unit of energy depends on the composition of the energy mix. The net zero balance of a building therefore depends on the composition of both the energy mix that was used to produce the building materials, and the energy mix that is used in the operation the building. The basic idea of a net zero emission building is that the renewable energy generated on the building site can 'pay back' emissions embodied in the building materials, by replacing energy that would otherwise be imported from the grid. One of the complexities of calculating the emission balance of a building is therefore that it involves estimations of emissions in both different geographic locations and different time periods.

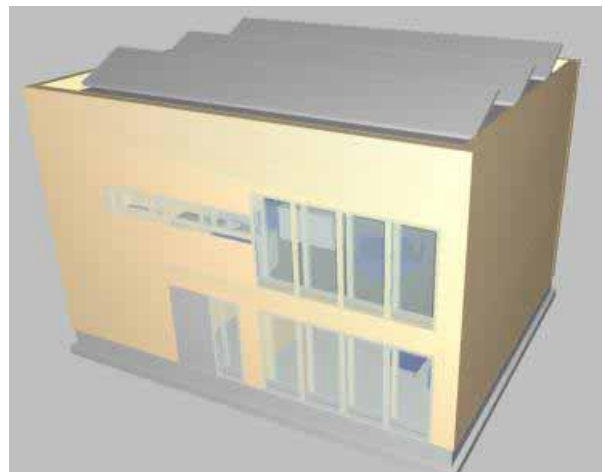
1.2. Residential nZEB concept building

In practice, only a coherent set of measures may lead to the achievement of a zero emission balance, starting from the energy efficiency of the envelope and services to the on-site renewable energy conversion. The need to study the influence of these dynamic measures has led the ZEB Centre to investigate a number of nZEB *concepts models*. As a first step, concept models are based on current available technology, and thus reflects today's practices in the construction sector. The concept models are designed using the nZEB definition suggested by Dokka et al. (2013).

The analysis presented in this paper is based on the ZEB concept model for a single-family house (Houlihan Wiberg et al., 2014) It is a two-storey detached house located in Oslo, Norway. The calculated energy demand and embodied and operational emissions of the building are shown in Tab. 1.

Tab. 1: Main characteristics of the baseline nZEB concept

Building details	
Location	Oslo, Norway
Heated floor area	160 m ²
Roof area	80 m ²
Annual energy demand	[kWh/m² year]
Heating	44.7
Cooling	0.0
Electricity	25.5
Greenhouse gas emissions	[kgCO_{2eq}/m² year]
Embodied emissions	7.2
Total electricity use*	5.1



*Computed using a yearly CO_{2eq} factor of 0.13kg CO_{2eq}/kWh for electricity during the 60-year building lifetime

The concept is solar-based, a strategy often found in the zero energy building community (Voss and Musall, 2012): a well-insulated building envelope is combined with solar thermal collectors and an air-to-water heat pump to cover the heating needs while a grid-connected photovoltaic (PV) system generate enough electricity to reach the zero energy balance. A comprehensive analysis of this concept model is presented by Houlihan Wiberg et al. (2014).

The analysis of the single family concept model showed that the on-site renewable energy sources on the building were able to counterbalance CO_{2eq} emissions from the electricity used during its operation (O) reaching the so-called ZEB-O level (described by Dokka et al., 2013). However, the concept was not able to counterbalance the emissions including embodied emissions of materials (M) defined as the ZEB-OM level.

In the analysis of the emission balance of the ZEB concept building it was also found that the PV modules accounted for 29% of the embodied emissions from the materials – a significant amount (Houlihan Wiberg et al., 2014). The work presented here aims to analyse if this share can be decreased.

1.3. PV technologies

The dominant technology on the PV market today is crystalline silicon solar cells. According to the European Photovoltaic Industry Association (EPIA) mono-crystalline silicon (mono-Si) and polycrystalline silicon (poly-Si) solar modules account for about 85% of the market. Crystalline silicon photovoltaics are mature and robust technologies with efficiencies of commercially available modules ranging from about 11-22%.

Technology developments and increased efficiency have made thin film modules, including amorphous silicon, CdTe (Cadmium Telluride), CIS/CIGS (Cadmium Indium (Gallium) Selenide) and organic solar cells, a real alternative to crystalline silicon. Efficiencies range from 5-13% (EPIA, 2014). Thin film modules can be produced on different substrates, can be made flexible, and can be less sensitive to shading and overheating.

Due to their higher efficiency, crystalline silicon modules require less space than thin film modules to generate the same amount of electricity. Thin film modules, on the other hand, require less energy in the production of the modules.

2. Method

This paper presents an analysis of the net emissions contribution from different PV modules, in order to understand what strategies are most suitable to reach the ZEB-OM balance for the residential concept model. The parameters that are studied are different PV technologies and different module orientations.

The specific purpose of the analysis is to find the PV design solution that will result in the largest net emissions reduction for the concept building, with the restrictions of a limited roof area. In a wider sense, the aim is to investigate which of the PV technologies and designs options that result in the largest amount of energy output per unit of embodied emissions.

To perform such an analysis, it is necessary to know the embodied emissions from the production of the PV modules, and emissions that are avoided when PV electricity replaces electricity from the grid.

2.1. Calculation of embodied emissions

The embodied emissions of the materials in the ZEB concept building were calculated to provide an overview of all the materials in the building, e.g. the construction materials in the envelope, the HVAC system and the energy supply system. The objective was to identify the key materials and components in the ZEB residential concept model that contribute the most to the embodied greenhouse gas emissions.

A detailed description of the calculations is available in (Houlihan Wiberg et al., 2014). In this first stage of development of the concept model, only the greenhouse gas emissions contribution to the global warming potential (GWP100) are taken into account as an environmental impact category. Environmental impact assessments are complex and other impact categories should be taken into consideration in further work.

2.2. Embodied emissions of PV modules

Three different technologies were evaluated: monocrystalline silicon (mono-Si), polycrystalline silicon (poly-Si) and CIS thin film. Emissions data from the Ecoinvent database v.2.2 (Swiss Centre for Life Cycle Inventories, 2013) was used for the calculations. The emission data are based on 1 m² of PV panel with frame, and on the following processes in Ecoinvent: Photovoltaic panel, single-Si, at plant/RER/I U (mono-Si); Photovoltaic panel, multi-Si, at plant/RER/I U (polySi); and Photovoltaic panel, CIS, at plant/DE/I U. The age of the inventory data for the modules is from 2006 for the CIS modules and mix of data from 2001, 2004 and 2005 for the silicon based modules (Swiss Centre for Life Cycle Inventories, 2013).

The specific modules for each of the technologies are selected based on the available data on embodied emissions and the energy performance of the modules. The specific modules are chosen to represent an average of each PV technology, and to match the descriptions of the modules given in Ecoinvent. The characteristics of the selected modules are shown in Tab. 2. All modules are assumed to be produced in Western Europe. The materials used for the supporting structures needed on the roof for the PV module integration and the materials needed for the electric photovoltaic production, such as inverters, controlling units and cabling (balance of system) have not been included in the emissions analysis. This amount of emissions is assumed to be similar for the different technologies, but needs further attention. This simplification is also supported by the results from Fthenakis et al. (2011) where it is clear that the modules are the largest emission contributors.

All three module types come with a performance warranty from the producer of 80% of the initial power after 25 years. The expected lifetime of the modules is set to 30 years, with a linear annual degradation of 0.7 % in line with the value suggested for mature technologies in the methodology guidelines developed by (Fthenakis et al., 2011). (Since the producer warranty of the CIS modules is the same as for the silicon modules, the same degradation factor has been used, even though the technology is less mature.)

Tab. 2: Characteristics of the three PV modules used in the simulations. The module dimensions are gathered from producer data sheet and the emissions data from Ecoinvent database (Swiss Centre for Life Cycle Inventories, 2013).

PV technology	Module dimensions	Module area	Rated power	Efficiency	Embodied emissions per m ² of module
Mono-Si	983 x 1476 mm	1.45 m ²	223 W _p	15.4%	199 kg CO ₂ eq/m ²
Poly-Si	970 x 1630 mm	1.58 m ²	210 W _p	13.3%	160 kg CO ₂ eq/m ²
CIS thin film	630 x 1190 mm	0.75 m ²	75 W _p	10.0%	123 kg CO ₂ eq/m ²

2.3. Calculation of emission balance

For a proper assessment of the emissions embodied in the materials, it is important to know the country or region of production of the data in order to know which emission factor has to be used for the electricity mix, e.g. the EU region, Nordic region or Norwegian, as it corresponds to different amounts of CO₂eq.

To assess emissions during the operation phase of the building, as well as the emissions that are avoided due to the use of onsite renewable energy, it is necessary to know the energy mix in the region where the building is located, and how this will likely develop over time. The assumption(s) used in the emission calculation should be clearly stated, e.g. static mix or some predetermined change in the mix at a fixed time or over time.

Since the modules are assumed to generate energy for at least 30 years (Fthenakis et al., 2011), the emissions associated with the electricity from the grid during these 30 years need to be projected. Two scenarios of grid emission factors are used for the analysis. The first one, referred to as the ZEB factor (0.13 kg CO₂eq/kWh), corresponds to a massive de-carbonization of the European grid (in accordance with the EU political goals). It has been developed at the Norwegian ZEB Centre (Graabak and Feilberg, 2011). The second grid factor instead assumes the current EU grid mix (0.45 kg CO₂eq/kWh) as stable and includes LCA elements for the electricity of the grid (Swiss Centre for Life Cycle Inventories, 2013). The significance of these two factors are discussed further in (Georges et al., 2015).

2.4. Evaluation of PV system performance

The energy performance of the PV systems were evaluated using the simulation software PVsyst v5.73 (PVsyst SA, 2011) with Meteonorm meteorological data for Oslo (Meteotest, 2009). The annual irradiation on a horizontal surface in Oslo is around 1000 kWh/m². The simulations were performed as a parametric study of module technology and module orientation. The goal was to assess how the different parameters influence the performance of the system, and which of the systems that provides a better trade-off between energy yield and embodied emissions.

The orientation of a PV system is defined by the tilt angle (the angle between the PV plane and the horizontal) and the azimuth (the cardinal point). Since the sun path changes over the course of a year, the optimal tilt and azimuth may not be the same in summer and winter, and a PV system can therefore be optimised for different times of the year depending on its layout. Generally, the optimal tilt angle increases with the distance from the equator, but so does also the difference between summer and winter. In Oslo, the optimal tilt angle for yearly yield is 40°. However, if a system in Oslo is designed for high output during the summer months, the best angle is around 30°. If the system was instead designed for winter yield, the optimal angle would be approaching 70°.

In the present example, the PV systems are installed on a flat roof. For PV systems installed in rows on a flat roof, self-shading needs to be considered, especially for high latitudes with low sun angles. PV modules that are installed at high tilt angle require a large spacing between the rows to avoid shading. A common solution to this problem is to mount the PV modules at a lower-than-optimal tilt angle to avoid shading. While this results in a lower output from each module, the total number of installed modules is larger.

In the present case, the roof area of the building was set as the design boundary condition for the systems. The reference building has a flat roof with an area of 80 m². There is assumed to be no shading objects, such as

chimneys or pipes, on the roof nor any large buildings or trees in the immediate surroundings. It is further assumed that the total roof area is available for the PV installation. Four alternative design options (or strategies) were developed for the roof, based on the details given above. An overview of the design options is shown in Tab. 3 and Fig. 1.

Tab. 3: The design options for the PV system on the flat roof.

Design option	Azimuth of modules	Tilt angle of modules (°)	Description
A	South	40	Optimal tilt angle and orientation for Oslo. This high tilt requires large row spacing to avoid mutual shading. High energy output for each module, but a low number of modules can fit on the roof.
B	South	15	Lower tilt angle to reduce the required distance. Lower yield per module but more modules can fit on the roof.
C	South/North	15	A development of design option B, where north-facing modules are added in the unused space between the south-facing modules. The rationale of this is to fit as many modules as possible onto the roof, even though the north-facing modules will have very low output for most of the year.
D	East/West	15	The same low tilt angle as in B and C, but modules oriented east/west. The advantages of low self-shading are the same as in B and C, and output is shifted towards autumn and spring.

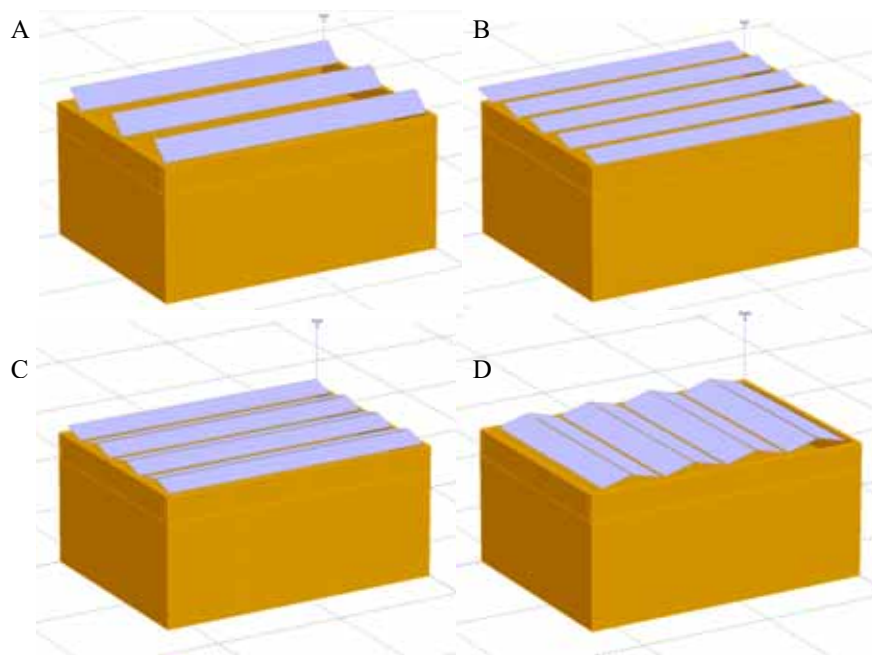


Fig. 1: Design options A to D. Images from PVsyst (2011).

The minimum required distance between the PV module rows to avoid shading were calculated with the real dimensions of the modules, and are therefore different for the three module technologies. The sun height in Mid-February (15°) is as the worst case scenario. Since the insolation in November to February accounts for about 2-8% of the annual insolation, this is seen as a reasonable simplification.

The rows of modules are assumed to be one module high and equally spaced over the length of the roof. As many modules as possible were fit in each row. Because of the different dimensions of the modules, the number of modules and the size of the system are different for each technology.

The crystalline silicon modules are mounted in landscape position to make best use of the three bypass diodes in the modules. Shading of the lower edge, for example from snow pileup, will thereby have a limited influence on the output power. The thin film module, on the other hand, was placed in portrait orientation since this limits

the effects of shading for this technology. The strategy for the rest of the system design (e.g. string layout and choice of inverter) has been to keep it as similar as possible between the alternative designs.

Each of the design options A-D was simulated with the three different PV technologies mono-Si, poly-Si and CIS. The details of each simulated case are presented in Tab. 4

Tab. 4: Detailed data for the design options using different PV technologies

Design option	PV technology	Total no of modules	Total module area (m ²)	Total power (kW _p)
A	Si-mono	21	30.5	4.7
A	Si-poly	18	28.5	3.8
A	CIS	32	24.0	2.4
B	Si-mono	28	40.6	6.2
B	Si-poly	24	37.9	5.0
B	CIS	48	36.0	3.6
C	Si-mono	49	71.1	10.9
C	Si-poly	42	66.4	8.8
C	CIS	80	60.0	6.0
D	Si-mono	40	58.0	8.9
D	Si-poly	32	50.6	6.7
D	CIS	84	63.0	6.3

3. Results

The yearly energy output of the system alternatives was calculated and compared to the energy delivered to the building from the grid. The results are shown for the first generation year (i.e. without module degradation) in Fig. 2. The mono-Si modules have the highest yield for all the design options. Design option C has the clearly highest energy yield for mono-Si and poly-Si modules, while design option D has a slightly higher yield for the CIS modules. These results are a direct reflection of the size of the systems in terms of installed W_p (Watt peak) (see Tab. 4).

Three systems are able to generate enough energy to cover the energy use of the building, i.e. the energy otherwise delivered from the electricity grid. These are design option C with mono-Si and poly-Si, and design option D with mono-Si modules.

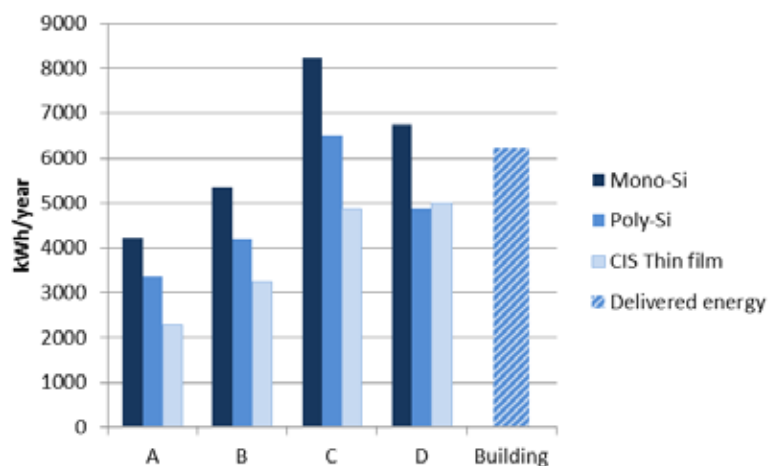


Fig. 2. The energy yield of the systems for the first year of generation (i.e. without degradation), compared to the energy used by the building (delivered from the grid).

The embodied emissions of the PV modules in the different systems are shown in Fig. 3. The embodied emissions per heated floor area EE_{fl} (kg CO_{2eq}/m² heated floor area) are calculated according to (eq. 1), where

A_{PV} is the installed PV area, EE_{PV} the embodied emissions per area of PV module (kg CO_{2eq}/m² installed PV) and A_{fl} the heated floor area (m²).

$$EE_{fl} = \frac{A_{PV} \cdot EE_{PV}}{A_{fl}} \quad (\text{eq. 1})$$

The mono-Si systems have the highest embodied emissions of the three technologies due to the more energy demanding production. Design option C for mono-Si and poly-Si modules and design option D for the CIS module have the highest amount of embodied emissions since these system are largest in terms of PV area (see also Tab. 3).

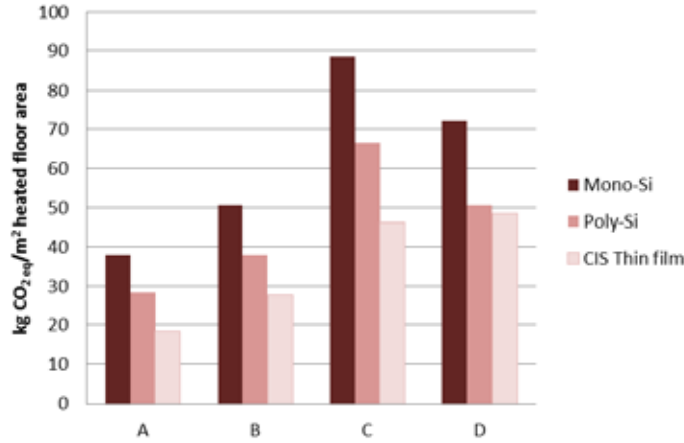


Fig. 3: The embodied emissions of the systems per m² of heated floor area of the building

As Fig. 4 shows, the design options with the highest total yield are not the ones with the highest specific yield of the modules. The specific yield is the energy output per installed power unit of the PV modules, here expressed as kWh per kW_p. While Fig. 4 shows only the specific yield of the mono-Si modules as an example, the tendency is the same for all module types. As the figure shows, the performance of the modules is highest for design option A. The specific yield of the north facing modules in design option C is about 70% of that of the modules in design option A.

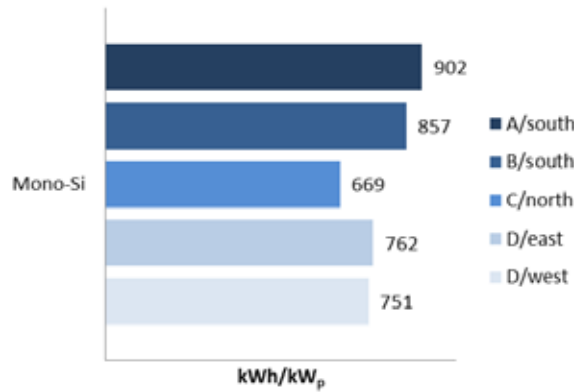


Fig. 4: The specific yield (kWh/kW_p) of the PV in the different design options (mono-Si modules used as an example).

Fig. 5 presents results related to the first emissions category. It is expressed as the embodied emissions that can be assigned to every unit of energy that the systems yield during their lifetime, here denoted EE_{energy} (kg CO_{2eq}/kWh). It is calculated according to (eq. 2), where $E_{PV,lifetime}$ (kWh) is the total amount of energy generated during the lifetime of the modules (here assumed to be 30 years) including the effects of PV module degradation.

$$EE_e = \frac{A_{PV} \cdot EE_{PV}}{E_{PV,lifetime}} \quad (\text{eq. 2})$$

The CIS modules, which have the lowest embodied emissions per area unit, also have the lowest amount of embodied emissions per unit of energy. The CIS modules can therefore be said to yield the “cleanest” energy in terms of CO₂ emissions. This corresponds to earlier findings (Fthenakis et al., 2011).

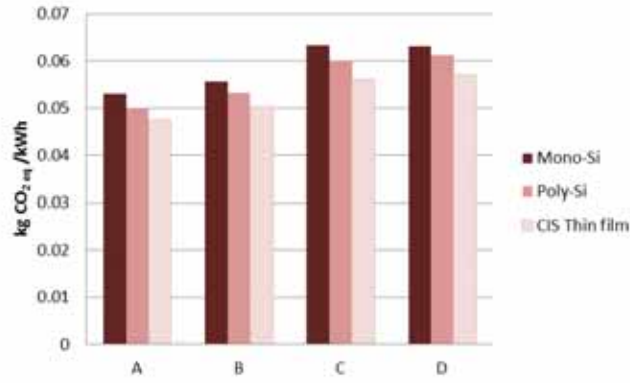


Fig. 5: Amount of embodied emissions per unit of energy output for the different system alternatives (kgCO₂-eq/kWh) during its lifetime (30 year lifetime is assumed for all module types.)

The result when the two grid factors are applied to the energy yield of the PV modules is shown in Fig. 6. The upper (positive) bars are the same as in Fig. 3, i.e. the embodied emissions per heated floor area. The lower (negative) bars represent the avoided emissions, $EE_{avoided}$ (kg CO₂-eq/m² heated floor area). They avoided emissions are calculated according to (eq. 3), where EE_{grid} (kg CO₂-eq/kWh) as described in Section 2.3.

$$EE_{avoided} = \frac{E_{PV,lifetime} \cdot EE_{grid}}{A_{fl}} \quad (\text{eq. 3})$$

As Fig. 6 shows, the avoided emissions are much larger when the EU grid factor is used (the embodied emissions are independent of the grid factor). The EU grid factor represents a grid with higher associated emissions than the ZEB grid factor, i.e. a lower share of renewable energy. This means that the electricity in the grid represented by the ZEB factor is already relatively “green”, and consequently the effect of replacing it with renewable energy is smaller in terms of avoided emissions.

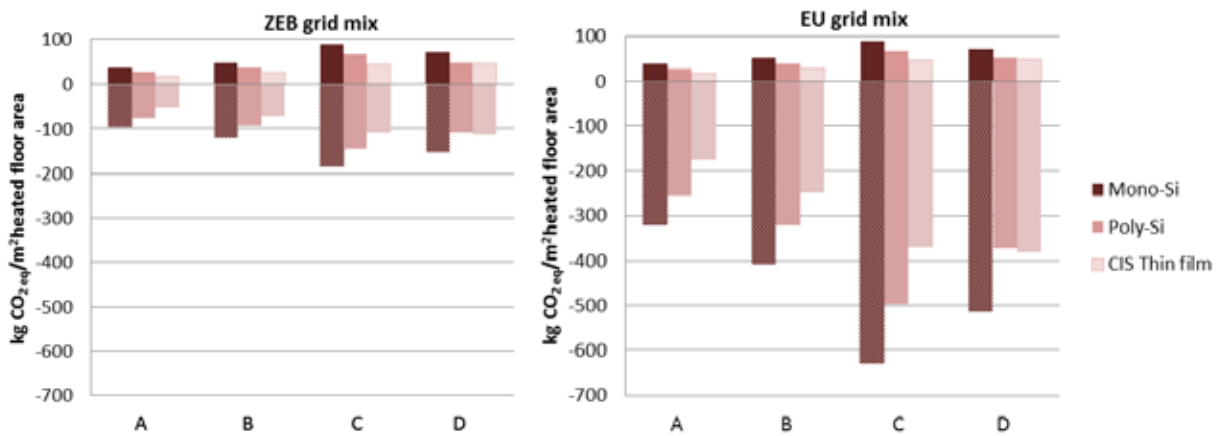


Fig. 6: The embodied energy of the PV system (positive on the vertical axis) and the avoided emissions from the grid (negative on the vertical axis) of the systems for two different grid mixes. The values are shown per m² heated floor area. The avoided emissions are cumulative values for the 30 year lifetime of the PV system..

The net contribution to reduce emissions from the different systems is found by subtracting the lower bar from the upper in Fig. 6. The system with the largest net emissions reduction is design option C with mono-Si modules, which results in 15 3001 kg CO₂-eq avoided emissions during the system lifetime with the ZEB grid factor, and 86 500 tons CO₂-eq with the EU grid factor.

The emissions payback times of the systems, i.e. the number of years that they need to be in operation before the embodied emissions are off-set by reduced emissions, have been calculated based on the data presented in Fig. 6. The emissions payback times of the systems with the ZEB grid factor ranges between 11-14 years, the longest time is for the larger crystalline silicon systems, and the shortest time is for the small CIS systems. If only the north facing modules in design option C are considered, the payback time is 17 years for the mono-Si

modules. If the EU grid factor is applied instead, the emissions payback time is reduced to 3-4 years for all the systems.

4. Discussion

The analysis presented in this paper involves a number of simplifications, generalisations and uncertainties. The embodied emissions of the PV modules are gathered from the Ecoinvent database (Swiss Centre for Life Cycle Inventories, 2013), which is one of the most comprehensive databases on environmental impact data. However, the work with collecting data from such a database is inevitably time consuming, and in some cases the data can be around 10 years old. This is unproblematic in some sectors, but the PV manufacturing industry has gone through a significant development during this time, and the validity of the data in today's industry can perhaps be questioned. In addition to the technological development, a large part of the PV manufacturing industry has moved from Europe to Asia, in particular to China. The location of the production plants influences the embodied emissions of the products, since these depend on what kind of energy sources that are being used in the factories. Environmental impact data from individual producers is hard to come by, and when available might be difficult to validate. It is difficult to make any clear statement on how the development in the PV industry would influence the results presented here, but this will be the subject of further study.

Another uncertainty that has a large influence on the results is the choice of electricity grid factor. As the calculations have shown, the net positive effect of installing a PV system in terms of reduced CO_{2eq} emissions depends to a high degree on the electricity it replaces. An installation in a location where the grid mix has a large share of fossil energy can therefore be seen as more beneficial than installing the same system in a location with a more renewable energy mix. Further discussion on this topic is referred to in (Georges et al., 2015).

While the results clearly show that the net reduction in emissions is directly related to the size of the system in kW_p – which in itself is an unsurprising result -- the benefit of increasing the systems size by mounting modules with north-facing orientation can be questioned. As a total system, design option C for the mono-Si modules has the highest total yield and the highest value of net emissions reductions. However, the north-facing modules in this system has a yield that is only 70% of the south facing ones, and a payback time of 17 years when the ZEB grid factor is used (the payback time was, however, only 4 years with use of the EU grid factor). This is over half the expected lifetime of the PV modules.

5. Conclusions

An analysis of the different PV installations for a Norwegian nZEB concept building developed by the ZEB Centre has been presented. The PV systems were evaluated based on their contribution to the emission balance of the building, which represents the results of the relationship between the embodied greenhouse gas emissions (kg CO_{2eq}) and the energy yield (kWh) of the systems. The analysed parameters include the choice of PV technology (mono-Si, poly-Si and CIS) and the orientation of the modules. The design boundary for the entire installation was the 80 m² flat roof of the building. The emission balance was calculated with two different energy grid factors: the ZEB factor assuming a large decarbonisation of the EU electricity grid (0.13 kg CO_{2eq}) and the current EU factor (0.45 kg CO_{2eq}).

Design option A, with optimally inclined and oriented modules (40° south-facing), had the highest energy yield per installed module (kWh/kW_p). The CIS modules had the highest ratio between energy output per module and embodied emissions. Nevertheless, due to the limited installation area available on the roof, the most favourable systems to reach a zero emission balance were found to be the ones with the highest energy density, i.e. energy output per roof area. These were the systems with a high number of modules at low inclination (design options C and D), and modules with highest efficiency (mono-Si). It should be noted that these systems were also the systems with the highest amount of embodied emissions, and the lowest energy yield per module. Design option C also included the north facing modules.

The net emissions reduction was calculated by subtracting the embodied emissions of the PV module from the amount of avoided emissions during its lifetime. The calculations with two grid emission factors also show that the value of a PV installation is more evident if the grid electricity it replaces is more carbon-intensive.

The analysis presented here has shown that a PV system can be optimised in several ways and that it is important to consider the embodied emissions, as well as the energy performance, in the design of net zero emission buildings.

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