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Embodied greenhouse gas emissions from PV systems in Norwegian residential Zero Emission Pilot Buildings

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Abstract

Greenhouse gas (GHG) emissions from the combustion of fossil energy need to be reduced to combat global climate change. For zero energy and zero emission buildings (ZEB), photovoltaic solar energy systems are often installed. When the goal is to build a life cycle zero emission building, all emissions come under scrutiny. Emissions from photovoltaic (PV) energy systems in zero emission buildings have been shown to have a relative large share of material emissions. In this paper, we compare GHG emissions per kWh of electricity and greenhouse gas emission payback times (GPBT) for three residential PV systems in zero emission pilot buildings in Norway. All the buildings have roof mounted PV systems with different design solutions. The objective is to analyse the emission loads and GPBT of these three systems to facilitate for more informed choices of energy systems for zero emission buildings. The results show that the total embodied emissions allocated per square meter of module area are around 150 kg CO_2eq/m^2 to 350 kg CO_2eq/m^2 for the three different systems. Emissions from the mounting systems vary from 10-25 kg CO_2eq/m^2 depending on the material types and quantities used. When modules replace other roofing materials, such as roof tiles, mounting emissions were reduced by approximately 60%. GHG emissions per kWh electricity produced were in the range of 30-120 grams CO_2eq/kWh for the different systems. The system with the lowest emissions was the largest system, which had a simple mounting structure and modules with reused cells. It was found that the GPBT was strongly dependent on the scenario used for electricity grid emissions. By applying a dynamic emission payback scenario with an optimistic reduction of emissions from the European electricity grid, the GPBT was 3-8 years for the different systems. When comparing the emissions with current Norwegian hydropower emissions, of around 20 grams CO_2eq/kWh, it was found that all of the PV system's emissions were higher. When compared to a mainly fossil fuel based grid, all the PV system's emissions are low. This study highlights the importance of reliable emission documentation for PV modules and their mounting structures on the market.

Keywords: zero emission buildings, building integrated photovoltaics, embodied emissions, GPBT, PV system design

1. Introduction

The building industry accounts for approximately one third of global energy use (IEA, 2013) and one fifth of global greenhouse gas emissions (IPCC, 2007). In order to reduce these emissions the concepts of zero energy and zero emission buildings have emerged. The revised directive on energy performance of buildings requires that all new buildings should be 'nearly zero energy buildings' by 2020 (European Parliament, 2010). According to Peterson et al. (2015) zero energy building is defined as "An energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy". Photovoltaic solar energy systems are the most common energy source installed in zero energy buildings (Voss and Musall, 2011). Dokka et al. (2013) presents a definition for Norwegian zero emission greenhouse gas buildings. The concept of a Zero Emission Building is similar to Zero Energy Buildings, except it uses emissions

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of CO_2 equivalents as the balancing indicator instead of primary energy (Sartori et al., 2012). A zero greenhouse gas building (Zero Emission Building – ZEB) can also be referred to as a zero carbon building, ZCB (Hui, 2010). The definition of zero emission buildings (ZEB) presented by Dokka et al. (2013) includes different ambition levels depending on which emissions are included and compensated for. Two fundamental levels are the "ZEB-O" level, which aims to balance out all operational emissions (O) from energy use, and the "ZEB-OM" level, which aims to compensate for both operational emissions (O) and material (M) emissions. Material emissions can also be referred to as embodied emissions. A life cycle zero energy concept has also been introduced by Ramesh et al. (2010) and Cellura et al. (2014). The relative share of embodied energy compared to operational energy is higher in zero energy buildings compared to conventional buildings (Cabeza et al., 2014) (Chau et al., 2015). Life cycle GHG analysis of two Norwegian ZEB concept buildings aiming for the ZEB-OM level is presented in Georges et al. (2015). In order to take the first steps from theoretical concept buildings to real-life pilot buildings, three residential zero emission pilot buildings have been built in Norway. These are the Skarpnes case study with a ZEB-O ambition level, and the Multikomfort and Living Lab buildings both with ZEB-OM ambition levels. Previously, material emission accounting for both of the ZEB-OM pilot buildings have been performed (Kristjansdottir et al., 2016, Inman and Houlihan Wiberg, 2015). The studies showed that the PV systems were a large contributor to embodied emissions for both cases, confirming the results from the concept studies (**Good et al., 2016**, Wiberg et al., 2014, Georges et al., 2015). In these analyses the PV system emission accounting were simplified. Since the PV systems contribute largely to the material emissions in Norwegian ZEBs, it is important to know more about these systems and different emission loads. Can these emissions be reduced? What are the emissions per kWh produced? What are the building integration benefits? And what is their greenhouse gas payback time (GPBT) in years?

The objective of this study is to analyse greenhouse gas emissions from these three PV systems installed in Norwegian ZEB pilot buildings. Further, the goal is to look into their GPBT with different electricity grid emission scenarios. Increased knowledge on emission profiles for different PV systems suitable for Norwegian dwellings will facilitate more informed choices on energy systems for zero emission buildings. The PV systems installed differ in terms of type of modules used, the roof mounting system, geographical location and design. In Norway, there is limited experience with photovoltaics, and there are no standardised solutions for integrating PV modules into roofs. In general, learning from PV pilot systems with regards to mounting solutions, module choices and emissions pay back times, can improve future installations. To follow, we provide an overview of the status of life cycle assessments of PV systems, and provide an introduction to roof integrated PV systems. We then provide a description of the applied method and present the three case studies. Subsequently, we present the results, and discuss and interpret our approach. Finally, we present some concluding remarks.

1.1. Life Cycle Assessment

Life cycle assessment is divided into four main steps: goal and scope definition, inventory analysis, impact assessment, and interpretation. Life cycle assessments often include a sensitivity analysis of important parameters (ISO, 2006). The basic steps of a life cycle assessment for a photovoltaic system are presented in Fthenakis and Kim (2011b). The raw material inputs and manufacturing of PV modules have been well documented through various life cycle assessments (Alsema and de Wild-Scholten, 2006) (Jungbluth, 2005, Jungbluth et al., 2009, Jungbluth et al., 2012, Fthenakis et al., 2011, NREL, 2012). However, according to Peng et al. (2013), life cycle assessments of installed/operating PV systems are limited. In order to increase the comparability, transparency and credibility of the life cycle assessment of photovoltaic electricity, methodological guidelines have been developed by Fthenakis et al. (2011). Fthenakis and Kim (2011b) conclude that the emissions and energy payback times of PV modules are heavily dependent on the type of electricity used to produce the modules. The global PV market share is dominated by China and Taiwan (ISE, 2014). A comparative study of the carbon footprint of PV module production in China and Europe was carried out by Yue et al. (2014). The study revealed that modules produced in China have almost double the emissions compared to modules produced in Europe, with emissions of around 72 grams CO_2 eq/kWh and 37 grams CO_2eq/kWh respectively (for mono-Si modules). This difference is mostly due to the fact that the emission intensity of electricity production in China is significantly higher than in Europe. Yue et al. (2014) apply irradiation levels of 1700 kWh/m^{2}yr and a performance ratio of 0.75. In contrast, documentation of Norwegian produced PV modules has shown that there is a significant benefit from using renewable hydropower in the production of silicon solar modules (Wild-Scholten, 2012). Prospective studies of the life cycle primary energy use of PV modules have been presented in Frischknecht et al. (2015b), Bergesen et al. (2014) and Mann et al. (2014). These studies highlight the expected reduction of material use, as well as expected increases in the efficiencies of PV modules.

1.2. Integrated Roof Mounting Solutions for PV Modules

PV systems may be integrated into building facades or roofs, or may be roof mounted. The three cases studied herein, all have roof mounted PV modules. In building integrated photovoltaic (BIPV) systems, the PV modules are used as part of the building envelope or any other architectural element that is necessary for the proper functioning of the building (SUPSI, 2015). Hence, the PV modules are replacing traditional parts of the building envelope, e.g. the roofing. A BIPV module can therefore not be removed without damaging the physical functions of the building envelope. Integrated systems present possible cost and material savings, as the modules are serving dual purposes (Jelle et al., 2012). Other roof mounting solutions on the market includes semi-integrated PV systems, sometimes referred to as in-roof systems. These solutions are designed to mount PV modules in line with the roof surface, in order to be visibly integrated in the existing roof.

2. Materials and Methods

The life cycle approach used is an attributional approach, focuses on the documentation of greenhouse gas emission burdens from the different life cycles of the PV system. The environmental impact category assessed is global warming potential (GWP) and is based on the IPCC GWP 2007 and IPCC 2013 100-year method, measured in kg CO_2 equivalents (IPCC, 2007) (IPCC, 2013). This assessment follows the methodological guidelines developed by Fthenakis et al. (2011) for the selection of functional unit and service lifetimes. The module degradation is calculated using values given by the producers.

2.1. Goal, Scope and Functional Unit

The goal of the assessment is to analyse and compare the different systems with respect to the GHG emission burden per kWh of produced electricity and the greenhouse gas payback time (GPBT) in years. The functional unit is "an averaged kWh of electricity produced per square meter of module area from the systems over a period of 30 years." Life cycle stages include: production of raw materials, manufacture of components, transport to the building site, manufacture of replaced components and simulated energy production with degradation over the service lifetime. Emissions associated with energy used during the installation of the systems are not included, as these emissions are considered to be similar across the different systems. The embodied emissions are calculated according to Equation 1:

Equation 1

$$CO2eq_{embodied} = CO2eq_{modules} + CO2eq_{mounting} + CO2eq_{electric} + CO2eq_{transport}$$

Here, the parameter $CO2eq_{embodied}$ includes the embodied emissions that have gone into the production of the PV modules, the mounting structure, the electric installations (e.g. inverter and cabling) and transport. The transport scenario includes transport to the building site. Figure 1 presents the scope of the analysis. The scope is divided into two main phases based on an estimates service lifetime of 30 years for the PV modules. The first phase, the initial 30-year scenario analysis is based on specific information from the case studies, and then a simplified generic future scenario is used for the replaced system in 30 years time. The end of life stage is not included, as it does not affect the emissions occurring in the next 30 years. In addition, waste treatment of PV modules in the future is highly uncertain.

2.2. GHG Payback Time

The term GHG payback time (GPBT) is defined as the number of years it takes for an energy generation system to “pay back” its embodied emissions through renewable energy generation (C. Reich-Weiser et al., 2008). It is calculated according to Equation 2, whereby ($CO2eq_{avoided(year))}$ (kg CO_2 eq) are the emissions avoided per year due to the production of electricity from the installation. $CO2eq_{avoided(year)}$ is calculated by multiplying the annual production with the average emissions per kWh per year from the local grid.

Equation 2

$$GPBT = \frac{CO2eq_{embodied}}{CO2eq_{avoided(year)}}$$

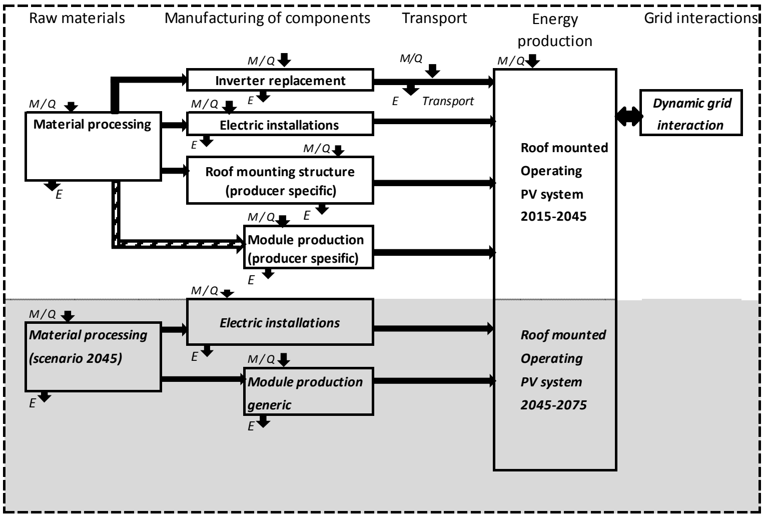

Figure 1 Scope of the analysis, the boxes illustrate what is included in the analysis, M refers to materials, Q refers to energy, and E refers to emissions. The white area refers to the initial specific comparison applied for the first 30 years of the life time, while the grey area refers to a simplified generic scenario applied for the last 30 years of the life time.

2.3. Case Descriptions

The three analysed PV installations in Norway are shown in Figure 2~~Figure 2~~. The three buildings are pilot studies within the Norwegian Research Centre on Zero Emission Buildings. All the buildings have low consumption of energy for space heating due to highly insulated envelopes, and a high heat recovery rate in the ventilation systems. The energy target set for the PV systems studied states that they should provide enough electricity on an average annual basis to cover all electricity consumption of the buildings. Details on the energy concepts for the three case studies can be found in Dokka et al. (2015), Goia et al. (2015) and Nord et al. (2016). For the Multikomfort building and the Living Laboratory, the ambition was set to a ZEB-OM level, whereby the PV systems were dimensioned to provide electricity to compensate for the electricity use from operation, and the embodied emissions from materials over the 60 year service lifetime of the building. We do not include the entire ZEB-OM balance calculations here, but focus only on the PV systems performances. Selected information for the PV systems for each of the buildings is provided in Table 1~~Table 1~~. Table 2 shows details of the installed PV systems. The three case studies represent three different roof mounting systems for the fixing of PV modules.

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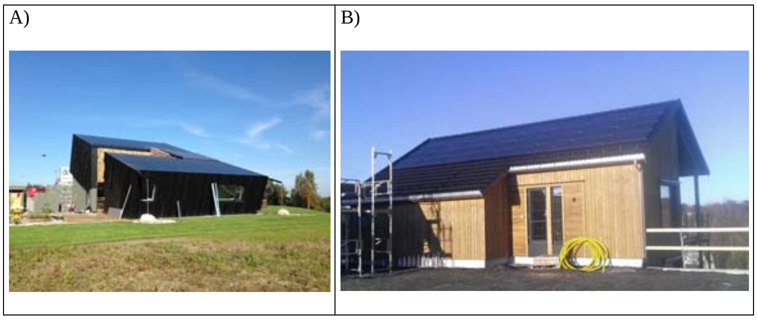

Figure 2 The roof mounted PV system design of the pilot buildings: A) Multikomfort (Kristian Edwards, Snøhetta) B) Skarpnes (Skanska) C) Living Laboratory (Katrine Peck Sze Lim)

Table 1. Building specifications

Description	Unit	A – Multikomfort	B – Skarpnes	C – Living Laboratory
Location	-	Larvik (59°12’N, 10°15’E)	Arendal (58°25’N, 08°43’E)	Trondheim (63°25’N 10°24’E)
Annual average ambient temperature	°C	8	8	5.7
Annual irradiation with optimal tilt angle	kWh/m^2	1182	1182	1120
Annual irradiation on the tilted plane	kWh/m^2	1057	1060	1091
Loss at current angle compared to optimal	kWh/m^2	11 %	10 %	3 %
Year of construction	year	2014	2015	2015
Heated floor area	m^2	202	154	102
Available roof area	m^2	155	106	108
Roof orientation		-45 (south-east)	51 (south-west)	0 (south)
Roof tilt	°	19	32	30
Ratio roof /floor area	m^2/m^2	0.77	0.69	1.06

*Irradiation data from PVGIS (Institute for Energy - Renewable Energy Unit)

2.3.1. Case A: Multikomfort

The Multikomfort case study is shown in Figure 2 A. It is a two-story residential building completed in 2014. It was built as a demonstration building for energy solutions for plus energy buildings. The design of the house is based on Saint-Gobain’s Multi-Comfort concept (Saint-Gobain, 2015). The focus of the concept is both on comfort issues such as indoor air quality and daylight, as well as environmental performance. The photovoltaic modules are from Innotech Solar (ITS) (EcoPlus) and were chosen due to their low carbon profile (Innotech Solar, 2015, ITS, 2012, De Wild-Scholten, 2013). The PV system consists of 91 installed ITS modules. The PV system is grid connected and mounted in a landscape orientation. There are no shading objects in the immediate surroundings of the building. Energy storage is included in the form of a battery bank, with the aim to increase the economic output of the PV system. Previous LCA studies have documented that batteries used in photovoltaic systems may contribute significantly to GHG emissions. This is mainly due to the manufacturing processes used, and the short lifetime of batteries (Beccali et al., 2012, Beccali et al., 2014). In order to compare the three case studies upon the same technological basis it was decided to exclude the batteries used in the Multikomfort house from the system boundary.   A section of the roof construction for the Multikomfort building is shown in Figure ~~Figure~~ 3A and site pictures of the installation and battery bank are shown in Figures 3B and 3C. The PV modules are not integrated in the roof, but are instead mounted on top of bitumen felt. Both the PV modules and the mounting structure can be removed without any impact on the physical functions of the roof. The roof mounting system is named K2 systems (Systems, 2015).

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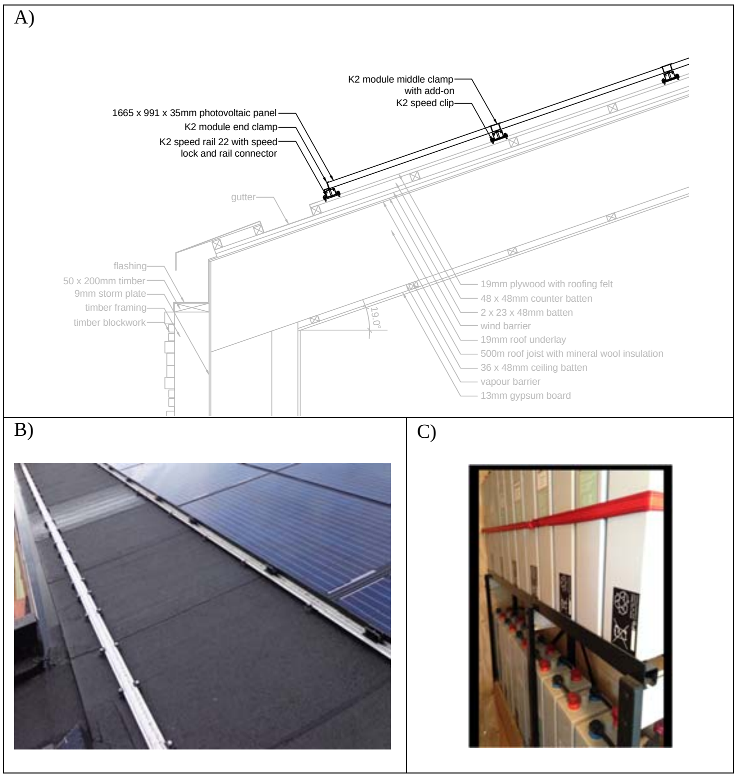

Figure 3. A) Section of the roof construction (adapted from Snøhetta architects), B) Picture of the roof installation, C) Battery bank

2.3.2. Case B: Skarpnes

The Skarpnes case study is shown in Figure 2B. It is a two storey single residential building available on the normal housing market. Skanska is responsible for the energy concept of the building. The building is located in the first zero energy neighbourhood in Norway. The PV system consists of 32 high efficiency modules from SunPower. The modules are mounted in a landscape orientation in four rows on the south-facing part of the pitched roof. The PV array is connected in two strings to one inverter from SMA which is communicating with the grid. There are no shading objects in the immediate surroundings of the building. The installation is a fully building integrated PV system (BIPV). The mounting solution used is Solrif®XL from Schweizer (Schweizer, 2015). The BIPV installation on the Skarpnes building does not cover the full area of the roof, but is integrated in the upper part of the south facing side. The rest of the roof is covered with traditional roof tiles. Hence, the modules are substituting roof tiles in the areas they cover. A section of the roof solution is shown in Figure 4A, and site photographs are given in Figures 4B and 4C.

Figure 4 A) Section of the roof construction (adapted from Roald Rasmussen at Skanska), B) Picture of the roof installation, C) End profile

2.3.3. Case C: Living Lab

The Living Lab building is shown in Figure 2C. The building is located on campus at the Norwegian University of Science and Technology (NTNU) in Trondheim. The purpose of the building is to be a "living laboratory" whereby the performance of the building and its technology is observed and measured, whilst the building is in operation (i.e. when inhabited). The roof of the Living Lab has a saw-tooth shape, and the PV installation is divided between the two tilted roof areas (see 2C), each with 24 PV modules from REC Corp (REC, 2013). The PV installation is south facing with a 30° inclination. The southern-most roof shades the lower part of the northern-most roof during a relatively large part of the year. To minimize the impact of shading as much as possible, the modules are divided into two module strings (one upper and one lower). The module strings are connected to two inverters from SMA which feed into the grid. The roof construction of the Living Lab is shown in Figure 5A, and site pictures are shown in Figures 5B and 5C. The mounting structure replaces the roofing, but the modules, which are mounted on top of a solid board, can be removed without any impact to the building physics. The system applied is from Renusol Solar Mounting Systems (Renusole, 2015). The mounting structure has a 10-year product warranty and an expected reference service lifetime of more than 30 years (Solbes, 2013, Renusol, 2010a, Renusol, 2010b).

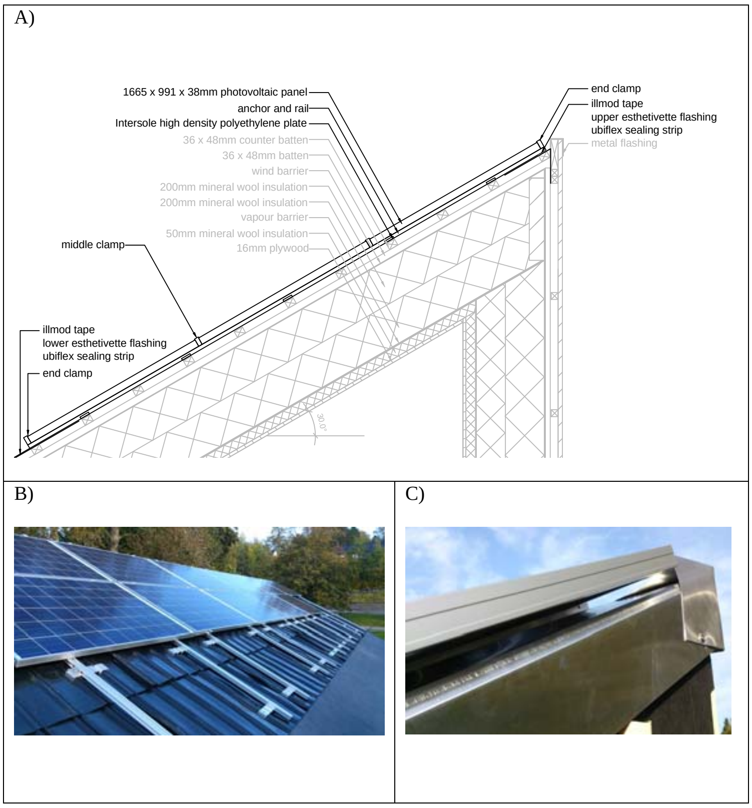

Figure 5. A) Section of the roof construction (adapted from Luca Finocchiaro), B) Photograph of the roof installation, C) End profile

Table 2. Details of the three PV Installations

Description	**Unit**	**A – Multikomfort**	**B – Skarpnes**	**C – Living Lab**
Manufacturer	-	Innotech Solar (ITS)	Sunpower	REC
Type of module	-	Design Black 250	SPR-230NE-BLK-D	REC260PE
Country of PV module production		Sweden (modules) and Germany (cells)	The Philippines	Singapore
Cell technology	-	Poly-Si	Mono-Si (back-contacted)	Poly-Si
Rated power per module	Wp	250	230	260
Efficiency at STC*	%	15.5	18.5	15.8
Module size	m^2	1.65 (1.665 x 0.991)	1.24 (1.559 x 0.798)	1.65 (1.665 x 0.991)
Weight	kg	19	15	18

Number of modules	-	91	32	48
Total module area	m^2	150	40	79
Total rated power	kWp	22.75	7.36	12.48
Total weight of modules	kg	1729	480	864
Inverter		Schneider Electric	1 x SMA Sunny Tripower 7000TL	2 x SMA Sunny Boy 5000TL 21-MS Basic
Number of strings		4	2	4
PV/inverter power ratio		1.15	1.05	1.36
Type of mounting system		BAPV	BIPV	In roof (semi integrated)
Mounting system manufacturer		K2 Systems	Schweizer/ Schweizer	Renusol/ InterSole SE
Place of mounting frame production		Leonberg, Germany	Chemnitz, Germany	Cologne, Germany
Battery storage		24, 42.3 kg Norbat, CFPV 2V 600Ah, OpzV GEL, (China)	No storage	No storage

*STC – standard test conditions: 1000 W/m^2, cell temperature 25°C and AM 1.5 spectrum

2.4. *Inventory Assessment*

The inventory is based on specific data gathered on the installed PV systems. The inventory includes simulations of operational energy performance, module emissions (with frames), the mounting structures, transport, the inverter and other electrical installations (cabling etc.). The background data is obtained from Ecoinvent v.2.2 and v.3.1 (Frischknecht et al., 2007, Weidema et al., 2013). The life cycle analysis tool SimaPro v.8.0.5 (Pre Consultants, 2012) has been applied to access and analyse the Ecoinvent data. Benefits from the reuse or recycling of components are not included. The inventory for the electrical installations is based on specific details relating to the size of the system and weight of the inverters with background data from Ecoinvent.

2.4.1. *Energy Performance of PV Systems*

The energy performance of the three PV systems is evaluated through simulations, using the tool PVsyst (PVSYST SA, 2011.). Site-specific Meteonorm data (Meteotest, 2009) has been used. Annual total solar irradiation for the given locations is given in Table 1. The performance ratio (PR) is defined as the ratio between the final system yield (Yf) divided by the reference yield (Yr) given by Equation 3:

Equation 3

$$PR = \frac{Yf}{Yr}$$

Whereby, Yf is the ratio of the net energy output and the nominal power of the installed array and Yr is the ratio between the total in-plane irradiance and the PV reference irradiance (1000W/m^2).

The performance ratio takes into account array and system losses, such as losses due to shadows, the inverter and wiring (Marion et al., 2005) (PVSYST SA, 2011.). The performance ratio of these three systems was around 0.8, depending on the actual system design in each case. Losses due to snow coverage of the PV modules represent an area of high uncertainty. Snow coverage and the possibility of snow clearing depend not only on the location, but also the orientation, maintenance, type of modules, glazing and frame (Andrews et al., 2013). It is assumed that the modules are covered by 20% snow, between November and February, for all three cases. This assumption is based on discussions with PV consultants and installers in Norway.

Internal energy consumption of the inverters is considered negligible. None of the systems are optimally oriented for their location, which would be around 40-45° and south facing (annual optimisation). The losses in available irradiation, due to non-optimal orientation (not including shading losses), are largest for Multikomfort with around 12%, followed by 9% for Skarpnes and 3% for the Living Lab. Module degradation has been included in accordance with the warranty specified by the producers, as shown in Table 4. However, we apply a service lifetime of 30 years to all of the modules according to Fthenakis et al. (2011). The linear degradation is assumed to extend beyond the 25-year warranty period.

Table 4. Product and power warranties of the three types of PV modules (Innotech Solar, 2013, SunPower Corp., 2012, REC Group, 2013)

Module	ITS	SunPower	REC
Product warranty	12 years	25 years	10 years
Performance, warranty, initial degradation	At least 97% of initial power after the first year	At least 95% of initial power for the first 5 years	At least 97% of initial power after the first year
Performance, warranty, annual degradation	No more than 0.7% (at least 80.2% after 25 years)	No more than 0.4% per year (at least 87% after 25 years).	No more than 0.7% (at least 80.2% after 25 years)

The energy output with degradation accounted for, E' (kWh/m^2, year), is calculated according to equation (4) where E (kWh) is the first year energy yield, d_{int} (-) is the initial degradation, d_{lin} (-) is the linear degradation, A_{PV} (m^2) is the module area, t_{int} (years) is the time of initial degradation, and t (years) is the module lifetime.

Equation 4

$$E' = \frac{E \cdot d_{int}}{A_{PV} \cdot t} \cdot \frac{1 - {d_{lin}}^{t-t_{int}}}{1 - d_{lin}}$$

PV module efficiency is dependent on the operating temperatures, decreasing with increased temperatures (M.A. Green, 1992). In a building integrated PV system, it is more difficult to assure good ventilation of the modules, resulting in higher temperatures than in free standing systems. This factor is taken into account in the simulations, whereby the Skarpnes system is considered fully integrated, the Multi- comfort and Living Lab systems are building adapted and semi-integrated respectively, and therefore have some degree of ventilation. The rear ventilation of the modules is taken into account by changing the thermal loss factor in the simulation program. The fully integrated system was simulated with a thermal loss factor of 15 W/m^{2}K, and the semi-integrated and building adapted systems were simulated with a thermal loss factor of 20 W/m^{2}K, as per the recommendations in the program (PVSYST SA, 2011.) When calculating the CO_2 avoided in the GPBT, we apply the dynamic production profiles per year, including the degradation of the modules. The PV energy performance, in the replacement scenario, is assessed in a simplified way, due to the large uncertainties in future module performance.

2.4.2. Module emissions

PV module emissions are sensitive to the local energy source at the production site of the main material inputs (Fthenakis and Kim, 2011a, Yue et al., 2014). It is assumed likely that single- Si module production emissions are within the range of 100-300 kg CO_2 eq/m^2 based on previous analyses (Jungbluth et al., 2012, Frischknecht et al., 2015a, Fthenakis et al., 2011, Fthenakis and Kim, 2011a). Life cycle emissions from the SunPower modules have been thoroughly documented in Fthenakis et al. (2012). According to that previous study, the SunPower life cycle emissions are 281 kg CO_2 eq/m^2 based on Philippine production, which is to the authors' knowledge the case for the modules used in Skarpnes. According to ITS, the emissions from the ITS modules are 80% lower than that from conventional crystalline modules, due to the optimization process of unused cells from other manufacturers (ITS, 2012). Emissions from the ITS modules have been documented with a simplified carbon footprint analysis by Wild-Scholten (2013), a study that is not comparable to a complete LCA study. Thus, we use module emissions data from the Ecoinvent database to resemble the ITS modules: "Photovoltaic panel, multi-Si, at plant/RER/I." We make the following adjustment in the Ecoinvent process to resemble the use of secondary cells in the ITS modules: "50% reduction in the use of primary cells for the baseline scenario, based on ITS (2012), Wild-Scholten (2013) and (Ecoinvent, 2013)." We apply emission data based on the

Ecoinvent database directly for the REC module (Photovoltaic panel, multi-Si, at plant/RER/I) with 210 kg CO_2 $_{eq}$/m^2 (Ecoinvent, 2013). REC was unable to provide specific emission data for their modules. Since the modules are the largest fraction of the PV system inventory, we have carried out a sensitivity analysis based on assumptions for "best case" and "worst case" scenarios for module emissions. The sensitivity analysis for the SunPower modules is based on differences in production locations as presented in the paper by Fthenakis et al. (2012). The " best case" is based on Norwegian production and the "worst case" is based on Malaysian production, whilst the baseline is Philippine production. The sensitivity for the REC modules is based on a Monte Carlo analysis performed in SimaPro v.8.0.5 of the Ecoinvent data, resulting in a normal distribution with a standard deviation (SD) of 16.8 kg CO_2 eq/m^2 (Ecoinvent, 2013) (Pre Consultants, 2012). The "best case" is -2 x SD, the "worst case" +2x SD, whilst the mean value is the baseline scenario. Finally, the sensitivity for the ITS modules is based on different assumptions of the amount of primary cells used. The "best case" is based on a scenario were 75% of the cells are reused, whilst the baseline assumes 50% reused cells, and the "worst case" assumes that no cells are reused. The ITS scenarios are inspired by the production methods of the ITS modules (ITS, 2012) (De Wild-Scholten, 2013). The sensitivities are given in Table 3.

Table 3 Module emission scenarios

Module	Best case kg $CO_{2\,eq}$/m^2	Baseline kg $CO_{2\,eq}$/m^2	Worst case kg $CO_{2\,eq}$/m^2
SunPower	200	281	307
ITS	89	130	210
REC	176	210	244

Table 4 Material inventory for the roof mounting structures, given per m^2 of PV

Material	Unit	A – Multikomfort	B – Skarpnes	C – Living Lab
Aluminium	kg	1.02	2.1	2.12
Glass fibre reinforced polyamide	kg	0.06	n/a	n/a
Polyethylene	kg	n/a	1.08	2.84
Polyurethane Foam	kg	n/a	0.68	0.28
Rubber	kg	n/a	1.2	n/a
Sealing Tape (alu PE)	kg	n/a	n/a	1.34
Steel	kg	0.07	0.19	n/a
Zinc plated steel	kg	0.05	n/a	n/a
Wood	m^3	n/a	0.004	0.002

2.4.3. Mounting structures

All materials used for the sake of mounting the PV modules have been included. The mounting material inventory is given in Table 4. The PV roof mounting structures consist of rails, clamps, sealing materials and other components. In some cases, for their installation in or onto the roof, additional timber battens were necessary, and flashings were required for the edges of the roof, for reasons of building physics and/or aesthetics. Material quantities for the Schweizer system were obtained directly from (Jungbluth et al., 2007). For the Living Laboratory and Multikomfort case studies, the inventory was gathered from technical datasheets for the system and system descriptions. Aluminium is used in all three of the mounting structures, because of the lack of specific information concerning the type and location of aluminium used, we have included a sensitivity analysis for aluminium emissions based on the Ecoinvent database: "best case" 1.4 kg CO_2 eq/kg (secondary), "baseline" 8.4 kg CO_2 eq/kg (production mix) and "worst case" 22.8 kg CO_2 eq/kg (alloy based on Chinese electricity). For the "best case" emission scenario, we include a possible building integration benefit by subtracting emissions of the roofing material avoided, for the "baseline" and "worst case" scenarios the building integration benefits are not included.

2.4.4. Transport

To calculate transport emissions of the components used, the production factory has been located using product information from the manufacturer and factory inspection certificates. The online route explorer tool SeaRates (SeaRates, 2015) has been used to calculate distances. Three transport scenarios have been modelled: "best case" by ship, "baseline" by ship and truck and "worst case" only by trucks. Transport emission data is based on Ecoinvent EURO 5 truck (Ecoinvent, 2013) and Ecoinvent Transoceanic Ship.

2.4.5. Electricity Grid Factor Scenario

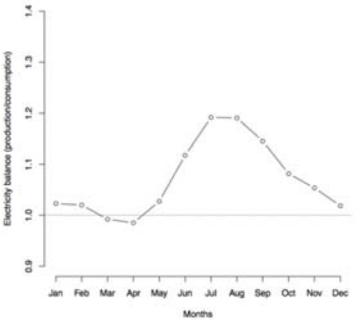

Figure 6 Average monthly power balance for Norway, 2006-2015 (import lower than 1, export higher than 1)

To calculate the greenhouse gas payback time (GPBT) in years, a reference value for the local grid is necessary to calculate the avoided emissions. Future dynamic grid emission scenarios are complex and we apply annual averages in our analysis. Currently around 97% of the electricity production in Norway stems from hydropower (NVE, 2013). The emissions of CO_2 eq/kWh from Norwegian Hydropower have been calculated to be around 20 grams CO_2 eq/kWh (low voltage) by Ecoinvent (2010). Figure 6 shows the average monthly power balance for Norway, (production/consumption) based on hourly production and consumption statistics from 2006-2014 (Statnett, 2015). From these statistics we see that Norway is normally exporting electricity. However, Norway has been, on average, sensitive to the import of electricity during the spring months. Norway is connected to the European electricity grid and the transfer capacity between Norway and Europe will increase in the near future (Statnett, 2013). Graabak and Feilberg (2011) and Graabak et al. (2014) previously developed scenarios for emission profiles in 2010, 2020, 2030, 2040 and 2050, for the emissions of electricity production in Europe. One of the scenarios developed is the "ultra-green" scenario, which assumes the European electricity grid in 2050 will be nearly emission free. In this scenario, it is assumed that Norway is fully integrated with the European electricity grid. Initial emissions for this scenario are documented as 361 grams CO_2 eq/kWh. We have interpolated the **hourly profiles** of the ultra-green scenario for each year towards 2050; the results are shown in Figure 7. From this figure we see seasonal variations **due to the dynamics of electricity production and consumptions patterns modelled in the scenario by Graabak and Feilberg (2011)**. We also see the decreasing trend towards 2050. We apply this future scenario for our baseline GPBT calculations, starting from year 2015. Graabak and Feilberg (2011) also developed a simplified "worst case" scenario, the "red" scenario, with low emission reductions due to a higher demand and lower increase in renewable energy production. The "red" scenario estimates emissions from the grid to be 224 grams CO_2 eq/kWh in 2050, in contrast to the ultra-green scenario which predicts an optimistic 30 gram average.

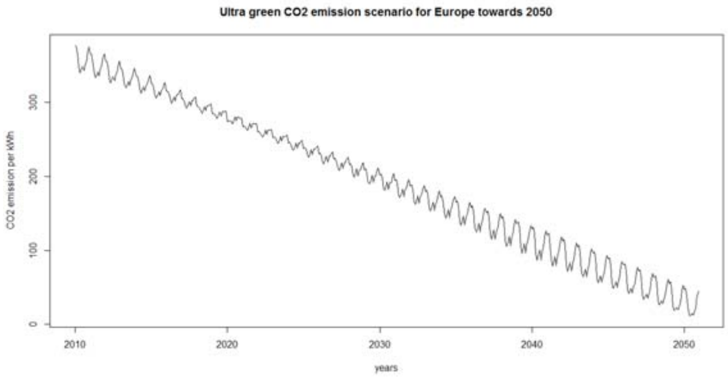

Figure 7 Ultra-green scenario for emissions per kWh electricity in Europe towards 2050 (Graabak and Feilberg, 2011)

Dokka et al. (2013) present a Norwegian "ZEB emission factor" that is based on averaged emissions from the "ultra–green" scenario towards 2050, resulting in emissions of 132 grams CO_2 eq/kWh. For the sensitivity assessment, we include the ZEB emission factor and the "red" scenario.

2.5. System Replacement Scenario 2045

Within the PV industry there is a continuous development for new technologies and material use, as well as efficiencies for PV modules (NREL, 2016). For our case studies the building service lifetime is estimated to be 60 years, thus the PV system needs to be replaced once. To increase our long term perspective we include a replacement scenario for the Skarpnes system. We assume that the replaced technology for the PV modules is the same, mono-Si. Frischknecht et al. (2015b) developed scenarios for life cycle emissions from future mono-Si and CdTe modules. They developed three different scenarios: "business as usual", "realistic improvement" and "optimistic improvement". The efficiency of the replaced single-Si modules is expected to be 22.9, 25.2 and 27.6% in the different scenarios, respectively. We have chosen the realistic improvement scenario and set the module efficiency to 25.2%. The embodied emissions per m^2 of module are expected to decrease by 65%, based on (Frischknecht et al., 2015b). It is assumed that future modules will be produced in Asia, with initial emissions resembling the Malaysian production of SunPower modules (300 kg CO_2 eq/m^2), as documented by (Fthenakis et al., 2012). This estimates replacement module emissions at 100 kg $CO_{2\,eq}$/m^2. It is assumed that there are no emissions from mounting structures; the PV modules are fully integrated. Transport distances are assumed to be the same. It is assumed that the inverter, electrical installations and transport emissions are also reduced by 65%, (Frischknecht et al., 2015b). The degradation profile is based on data from SunPower (SunPower Corp., 2012). The production yield calculations are further based on irradiation and efficiency. For the future scenario we calculate greenhouse gas emissions per kWh produced, and the GPBT with the ZEB-factor and "red" scenario.

3. Results

3.1. Production yield

In Figure 8, the simulated production yield from the different systems is shown, in terms of both the annual energy production per module area, and per floor area of the buildings. The figure also shows the total annual power yield from the systems. The yield from the Multikomfort system is the highest, since this is the largest system.

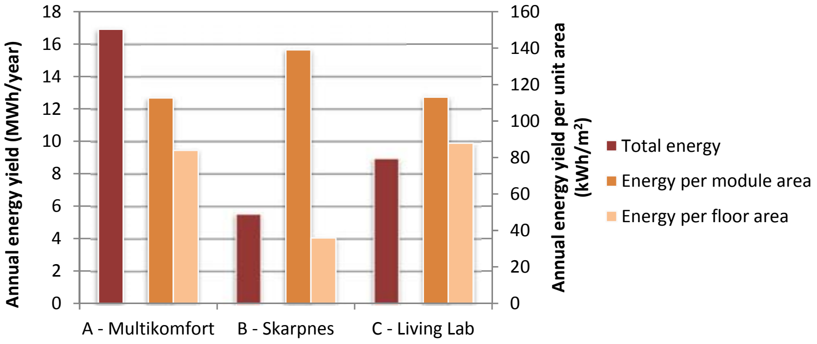

Figure 8. Simulation results for the total annual the energy yield per year (left axis) is shown together with the annual yield normalized per square meter module area and per square meter heated floor area (right axis).

The normalised values for Multikomfort and the Living Laboratory are approximately equal, both with respect to energy yield per square meter module area and heated floor area. The irradiation (see Table 1) is slightly higher for the Living Lab than Multikomfort, but the Living Lab's system is also significantly influenced by self-shading, resulting in a similar energy output between the two buildings. Skarpnes has a smaller production in relation to heated floor area, but a higher energy production performance per square meter due to the higher efficiency of the mono-Si modules. The monthly energy yield for the first year of the three systems is shown in Figure 9. The Skarpnes system has the highest specific output during the whole year. The energy yield from Multikomfort is slightly higher during the autumn months compared to the Living Lab, due to the difference in tilt angles.

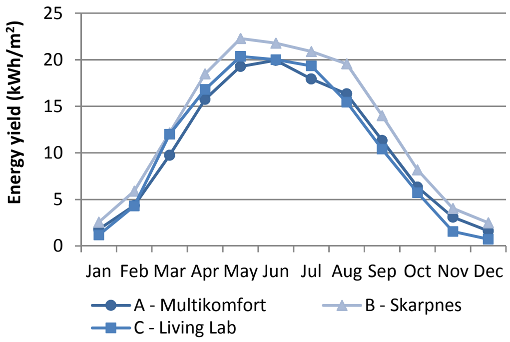

Figure 9. Simulations results for the monthly yield for the first year energy per square meter module area

3.2. Emissions from Mounting structures

The emission loads for the different mounting structures are shown in Figure 10 for the baseline aluminium scenario. The K2 System applied in the Multikomfort building, has less than half of the emissions compared to the Schweizer and the Renusol systems. Between Schweizer and Renusol, the difference is less significant. The Living Lab and Skarpnes mounting systems have a larger material demand, which drives up emissions compared to the simpler K2 BAPV system. BIPV systems reduce the demand for traditional roofing material, because the system replaces the roofing materials in the areas where the PV is installed. The avoided emissions associated with this will depend on the type of roofing avoided. In the Skarpnes case, cement roof tiles are used. By applying the emission factor for roof tiles from Ecoinvent, 13 kg $CO_{2\,eq}/m^2$, (Ecoinvent, 2010) the Skarpnes mounting structure emissions are reduced by around 60%. The emissions for the Living Lab are reduced by approximately

3 kg CO_2 eq/m^2 due to the avoidance of bitumen felt (Ecoinvent, 2010), but still has the largest amount of GHG emissions compared to the two other cases.

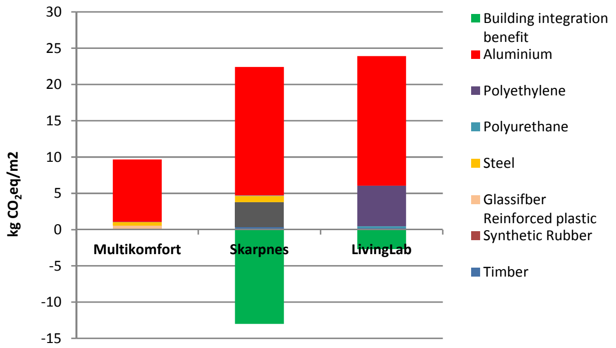

Figure 10. Emissions in kg $CO_{2\ eq}$/m^2 for the different materials for the roof mounting structures and building integration benefits

3.3. Emissions per square meter module area and kWh

In Figure 11, we present the results for the total embodied emissions allocated per square meter module area, including the sensitivity scenarios for module, transport and mounting aluminium emissions. The module emissions are the largest contributor, followed by the mounting structures and inverters. Total embodied emissions for the baseline scenario are around 150 kg CO_2eq/m^2 for Multikomfort, 350 kg CO_2eq/m^2 for Skarpnes and around 280 kg CO_2eq/m^2 for the Living Lab.

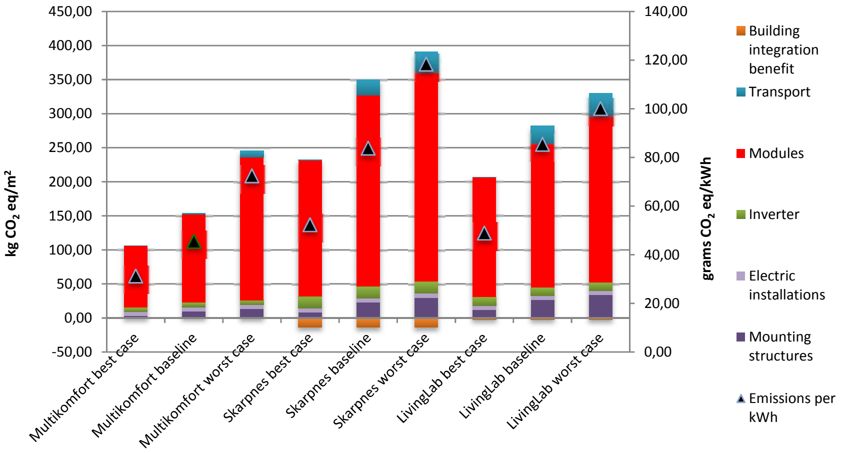

Figure 11 Emissions loads from the systems in kg $CO_{2\ eq}$/m^2 and GHG emissions per kWh produced over the service lifetime of 30 years, including best, baseline and worst case scenarios

From this figure, we see that the GHG emissions per kWh for the different systems range from around 30 to 120 gCO_{2eq}/kWh. Emissions per kWh produced are lowest for Multikomfort. Emissions per kWh for Skarpnes and the Living Lab cases are similar. The sensitivity assessment shows that there can be a significant difference between system emissions per kWh. With emissions ranging from around 50 grams to 120 grams for the Skarpnes system, 30-70 grams for the Multikomfort system and 50-100 grams for the Living Lab.

3.4. Greenhouse gas payback time (GPBT)

In Figure 12, we show the dynamics of the emission payback scenario per square meter of module area for the different systems. The production profiles and cumulated avoided emissions are very similar for the Living Lab and Multikomfort systems, giving similar efficiencies. For the baseline scenario, embodied emissions and the “ultra-green” electricity emission scenario have payback times of around 3, 7 and 8 years for the Multikomfort, Living Lab and Skarpnes respectively. We also see from Figure 12 that Skarpnes gives larger emissions avoided per year due to higher module efficiency. When applying the “red” scenario; the GPBT is reduced to around 6 years for both the Living Lab and Skarpnes. With the current averaged Norwegian ZEB factor of 132 grams CO_2 eq/kWh, the GPBT increases to 8, 15 and 18 years respectively.

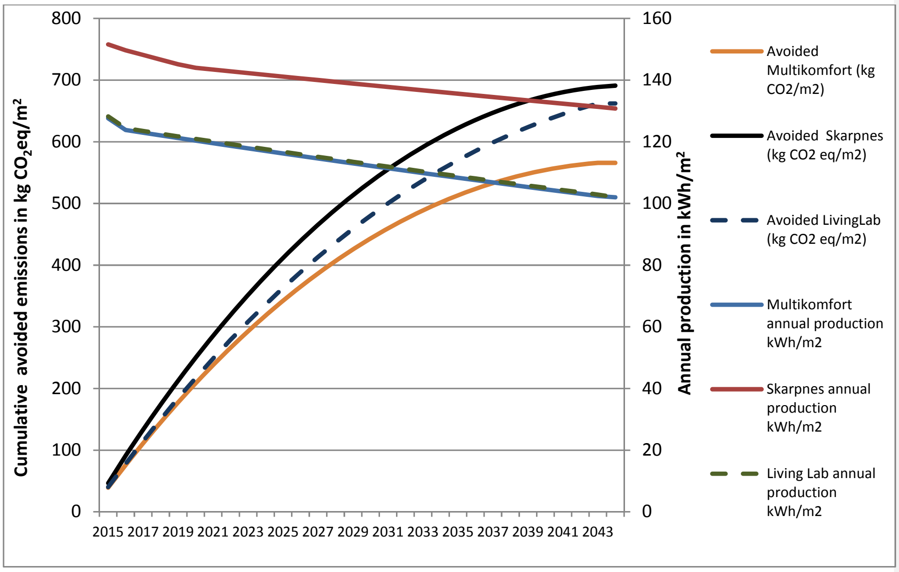

Figure 12 Annual average productions with degradation and corresponding cumulative avoided emissions based on the “ultra-green” scenario

For the replacement scenario from 2045-2075, the emissions per kWh are around 20 gram CO_2 eq/kWh for the Skarpnes system, with annual production yields of around 220 kWh/m^2. In the "ultra-green" emission scenario, the emissions are not payed back, but for the "red" scenario emissions are payed back within two years. When using the ZEB emission factor emissions are payed back within three years.

4. Discussion

From our analysis, we see that the life cycle emissions from the PV systems analysed have lower emissions compared to fossil fuels, thus confirming previous studies (NREL, 2013). We also see that there are significant differences between the systems, with respect to emissions from the modules and mounting structures. However, we also saw a wide range of emission loads within the best and worst case scenarios, thus it is challenging to make any decisive comparative conclusions. The GPBT varies significantly according to which scenario is applied, according to the avoided emissions in the grid. In the “ultra-green” scenario we saw that it takes 8 years to payback emissions from the Skarpnes system, but in the "red" scenario we saw a GPBT of 6 years for the same system. The simplified, static ZEB emission factor scenario gave us a GPBT of up to 15 years. Emissions can be paid back if PV system emissions are lower than the grid emissions. If we consider only an isolated Norwegian hydropower grid, which would have emissions of approximately 20 grams CO_2eq/kWh, (Ecoinvent, 2010) then the PV systems emissions are not payed back. This uncertainty emphasizes the need for careful consideration, between the grid interaction and related system boundaries, when choosing energy systems for buildings. Even though module emissions represent the largest fraction of emissions from PV systems, the mounting structures also contribute significantly. From our analysis we saw that with proper integration of PV systems, we can reduce the use of roofing materials, and thus reduce building material emissions. With large-scale implementation of solar home systems, mounting emissions become more significant, even though they seem small when viewed on an individual building basis. Therefore, minimizing mounting structure emissions with proper integration is beneficial. Based on our simplified future emission scenario, emissions from electricity, from PV systems are likely to be significantly reduced. At the same time, a payback calculation becomes more irrelevant in a scenario where the grid becomes nearly emission free.

Emissions from the SunPower modules have been thoroughly documented, while for the REC modules, emission data was not available. For the Multikomfort case, emissions from the module scenarios were low, due to the use of reused cells in the ITS modules. The allocation procedures for emission burdens, when using secondary or waste material, can be challenging. We therefore made a simplification, in that there were no emission loads from the reused cells, which is debatable. Comparing different life cycle studies is challenging, as different methods and reporting formats are used by different authors, thus reducing comparability. When installing a PV system, it is preferable to have proper knowledge of the emission burdens of the installed modules. In some cases, we encountered difficulties in gaining specific data from producers, a challenge that may be resolved in the future. According to (Fraunhofer, 2012) ~~Fraunhofer (2012)~~ the end of life benefits of recycling, especially glass and aluminium can have significant influence on the overall life cycle impact of PV modules. These potential benefits have not been included.

With regards to the battery storage, the Multikomfort system is more self-sufficient and possibly gains a better economic output. We have not included the impact from the batteries. This is an aspect that requires further investigation. We have limited our analysis to GHG emissions, mainly due to the fact that the pilot case studies have focused on a zero emission GHG balance. Looking also into the primary energy balance of the different systems would be of interest. Nevertheless, previous studies have shown that cumulative energy demand and greenhouse gas emissions often correlate (Huijbregts et al., 2006).

Service lifetime is an important parameter for emission burden accounting; in a scenario with a shorter service lifetime, emissions per kWh are increased. The replacement of possible defect modules has not been taken into account, which is also an aspect that could increase service lifetime emissions.

Currently, there is a lack of guidelines for good BIPV practice in Norway. In cold climates, shading caused by snow, needs to be considered. How much this influences a system is difficult to know, without site-specific measurement. None of the systems are optimally oriented for their location, which would be around 40-45° and south facing (annual optimisation). Optimal orientation would have resulted in lower emissions per kWh.

From historical statistics of the Norwegian export profile for electricity, it can be argued that producing electricity in the spring months gives an extra benefit for the Norwegian electricity grid. Production in the summer months is considered to have a lesser value, as it could lead to lower prices. With the high availability of hydropower in Norway, one could argue that PV system installations are not necessary. As a result, PV systems should be prioritised in areas with higher solar irradiation and electricity grids based on fossil energy. In contrast, a large fraction of Europe's electricity is produced from fossil fuels, emphasising a general need for the increased electricity production from renewable energy sources, and therein PV systems (Eurostat, 2015).

From the "ultra-green" emission scenario in Figure 7, and the Norwegian export-import sensitivity analysis in Figure 6, we get a picture of the seasonal grid production and emission sensitivities. Essentially, the emissions are higher in the winter and lower in the summer. As an area for further study, it would be interesting to include a month-by-month emission payback profile of the systems, combining energy demand and generation on an hourly basis. There are plans to measure the energy outputs of the systems, which will bring insight into the real operational performance of the PV systems in a Norwegian context.

5. Conclusions

We have looked at the emissions of GHG and GPBT for three different PV systems installed in Norwegian Zero Emission Buildings for an estimated service lifetime of 30 years. These systems are referred to as the

Multikomfort, Skarpnes and Living Lab. We have included a simplified future scenario, whereby one of the PV systems is replaced after 30 years. Total embodied emissions, allocated per square meter of module area, for the baseline scenario are around 150 kg CO_2 eq/m^2 for Multikomfort, 350 kg CO_2 eq/m^2 for Skarpnes and around 280 kg CO_2 eq/m^2 for the Living Lab. The simplest mounting system showed emission of around 10 kg CO_2/m^2, whilst the other, more complex systems showed emissions from around 20-25 kg CO_2 eq/m^2. A building integration benefit, where roof tiles were replaced with PV modules, reduced mounting system emissions by around 60%. We also see that module emissions have the largest proportion of emissions from the three different systems, stressing the need for reliable data on PV module production. Emissions per kWh produced, showed that the lowest emissions originated from the Multikomfort system which had approximately 45 grams CO_2 eq/kWh, and around 80-85 grams for the other two systems. Emissions from the Multikomfort system are lowest, due to the use of reused cells in the modules, combined with the large dimension of the system, and the simple roof mounting structure. The sensitivity analysis showed that there are large variations in emissions, with the total span from around 30 to 120 grams CO_2 eq/kWh. The GPBT is very sensitive to the grid scenario for emissions. The baseline scenario "ultra-green", showed emission payback times of 3, 7 and 8 years respectively. The GBPT is decreased to around 6 years, if the "red" scenario for emissions from the grid is used for the Living Lab and Skarpnes cases. A constant emission factor, namely the Norwegian "ZEB factor" of 132 grams CO_2 eq/kWh showed payback times of 8, 15 and 18 years for the three systems. If we assume Norwegian hydropower emissions of 20 grams CO_2eq/kWh, as an average for local grid emissions, then the modules do not payback emissions within their 30 year service lifetime. Furthermore, when looking 30 years into the future, the emissions from the Skarpnes system are likely to be reduced from around 80 to 20 grams CO_2 eq/kWh.

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7. References

ALSEMA, E. & DE WILD-SCHOLTEN, M. Environmental impacts of crystalline silicon photovoltaic module production. 13th CIRP International Conference on Life cycle Engineering, , 2006 Leuven, Belgium.

ANDREWS, R. W., POLLARD, A. & PEARCE, J. M. 2013. The effects of snowfall on solar photovoltaic performance. *Solar Energy,* 92**,** 84-97.

BECCALI, M., CELLURA, M., FINOCCHIARO, P., GUARINO, F., LONGO, S. & NOCKE, B. 2012. Life cycle assessment performance comparison of small solar thermal cooling systems with conventional plants assisted with photovoltaics. *Energy Procedia,* 30**,** 893-903.

BECCALI, M., CELLURA, M., FINOCCHIARO, P., GUARINO, F., LONGO, S. & NOCKE, B. 2014. Life cycle performance assessment of small solar thermal cooling systems and conventional plants assisted with photovoltaics. *Solar Energy,* 104**,** 93-102.

BERGESEN, J. D., HEATH, G. A., GIBON, T. & SUH, S. 2014. Thin-Film Photovoltaic Power Generation Offers Decreasing Greenhouse Gas Emissions and Increasing Environmental Co-benefits in the Long Term. *Environmental science & technology,* 48**,** 9834-9843.

C. REICH-WEISER, D. DORNFELD & HORNE, S. 2008. *Greenhouse Gas Return on Investment: A New Metric for Energy Technology, in: Green Manufacturing and Sustainable Manufacturing Partnership.*

CABEZA, L. F., RINCÓN, L., VILARIÑO, V., PÉREZ, G. & CASTELL, A. 2014. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renewable and sustainable energy reviews,* 29**,** 394-416.

CELLURA, M., GUARINO, F., LONGO, S. & MISTRETTA, M. 2014. Energy life-cycle approach in Net zero energy buildings balance: Operation and embodied energy of an Italian case study. *Energy and Buildings,* 72**,** 371-381.

CHAU, C., LEUNG, T. & NG, W. 2015. A review on life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings. *Applied Energy,* 143**,** 395-413.

DE WILD-SCHOLTEN, M. 2013. Certificate of simplified carbon foot print of Innotech solar PV modules. *In:* SMARTGREENSCANS (ed.).

DOKKA, T. H., BERGGREN, B. & LASSEN, N. 2015. Comparison of five zero and plus energy projects in Sweden and Norway, A technical review. *Passivhus Norden, Sustainable Cities and Buildings.* Cobenhagen, Denmark.

DOKKA, T. H., SARTORI, I., TYHOLT, M., LIEN, K. & BYSKOV LINDBERG, K. 2013. A Norwegian zero emission building definition. *Passivhus Norden.* Gothenburg, Sweden.

ECOINVENT 2010 Ecoincent database v.2.2. www.ecoinvent.org: Swiss Centre for Life Cycle Inventories, Zürich, Switzerland.

ECOINVENT 2013. Ecoinvent database version 3.1. *In:* CENTRE, E. (ed.). www.ecoinvent.org, Zurich, Switzerland.

EUROPEAN PARLIAMENT 2010. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. *Directive 2010/31/EU.* Brussels.

EUROSTAT 2015. Environmental data centre on natural resources. http://ec.europa.eu/eurostat/web/environmental-data-centre-on-natural-resources/natural-resources/energy-resources: European Commision.

FRAUNHOFER 2012. Executive Summary: Life Cycle Assessment (LCA) screening of the Maltha recycling process for Si-PV modules. IPB Department Life Cycle Engineering (GaBi).

FRISCHKNECHT, R., ITTEN, R., WYSS, F., BLANC, I., HEATH, G., RAUGEI, M., SINHA, P. & WADE, A. 2015a. Life cycle assessment of future photovoltaic electricity production from residential-scale systems operated in Europe, Subtask 2.0 "LCA", IEA-PVPS Task 12.

FRISCHKNECHT, R., ITTEN, R., WYSS, F., BLANC, I., HEATH, G., RAUGEI, M., SINHA, P. & WADE, A. 2015b. Life cycle assessment of future photovoltaic electricity production from residential-scale systems operated in Europe, Subtask 2.0 "LCA", IEA-PVPS Task 12.

FRISCHKNECHT, R., JUNGBLUTH, N., H.-J., A., DOKA, G., HECK, T., HELLWEG, S., HISCHIER, R., NEMECEK, T., REBITZER, G., M., S. & WERNET, G. 2007. Overview and Methodology. ecoinvent report No. 1. Dübendorf: Swiss Centre for Life Cycle Inventories

FTHENAKIS, V., BETITA, R., SHIELDS, M., VINJE, R. & BLUNDEN, J. 2012. Life cycle analysis of high-performance monocrystalline silicon photovoltaic systems: energy payback times and net energy production value. *27th European Photovoltaic Solar Energy Conference and Exhibition.*

FTHENAKIS, V., FRISCHKNECHT, R., RAUGEI, M., KIM, H., ALSEMA, E., HELD, M. & DE WILD-SCHOLTEN, M. 2011. Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity: IEA PVPS Task 12.: International Energy Agency.

FTHENAKIS, V. & KIM, H. C. 2011a. Photovoltaics: Life-cycle analyses. *Solar Energy,* 85**,** 1609-1628.

FTHENAKIS, V. M. & KIM, H. C. 2011b. Photovoltaics: Life-cycle analyses. *Solar Energy,* 85**,** 1609-1628.

GEORGES, L., HAASE, M., HOULIHAN WIBERG, A., KRISTJANSDOTTIR, T. & RISHOLT, B. 2015. Life cycle emissions analysis of two nZEB concepts. *Building Research & Information,* 43**,** 82-93.

GOIA, F., FINOCCHIARO, L. & GUSTAVSEN, A. 2015. The ZEB Living Laboratory at the Norwegian University of Science and Technology: a zero emission house for engineering and social science experiments. *Passivhus Norden Conference, Sustainable Cities and Buildings.* Copenhagen, Denmark.

GOOD, C., KRISTJANSDOTTÍR, T., HOULIHAN WIBERG, A., GEORGES, L. & HESTNES, A. G. 2016. Influence of PV technology and system design on the emission balance of a net zero emission building concept. *Solar Energy,* 130**,** 89-100.

GRAABAK, I., BAKKEN, B. H. & FEILBERG, N. 2014. Zero Emission Building and Conversion Factors between Electricity Consumption and Emissions of Greenhouse Gases in a Long Term Perspective. *Environmental and Climate Technologies,* 13**,** 12-19.

GRAABAK, I. & FEILBERG, N. 2011. CO2 emission in different scenarios of electricity generation in europe. Technical report, SINTEF Energy Research.

HUI, S. C. Zero energy and zero carbon buildings: myths and facts. Proceedings of the International Conference on Intelligent Systems, Structures and Facilities (ISSF2010): Intelligent Infrastructure and Buildings, 2010. 15-25.

HUIJBREGTS, M. A. J., ROMBOUTS, L., HELLWEG, S., FRISCHKNECHT, R., HENDRIKS, J. & VAN DE MEENT, D. 2006. Is Cumulative Fossil Energy Demand a Useful Indicator for the Environmental Performance of Products? *Environmental Science & Technology,* 40**,** 641-648.

IEA 2013. IEA Online Data Services. Available at: http://data.iea.org/ieastore/statslisting.asp.

INMAN, M. & HOULIHAN WIBERG, A. 2015. Life Cycle GHG Emissions of Material Use in the Living Laboratory Norway: SINTEF Building and Infrastructure

INNOTECH SOLAR 2013. Warranty Conditions – August 2013. Innotech Solar.

INNOTECH SOLAR. 2015. *Green Energy* [Online]. Innotech Solar webpage. Available: http://www.innotechsolar.com/en/company/green-energy.html [Accessed 27 May 2015].

INSTITUTE FOR ENERGY - RENEWABLE ENERGY UNIT. *Photovoltaic Geographical Information System (PVGIS)* [Online]. European Commission, Joint Research Centre. [Accessed 31 January 2013].

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Formatted: Norwegian (Bokmål)

IPCC 2007. Climate Change, 2007. The Physical Science Basis, Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). *In:* SOLOMON, S., QIN, D., MANNING, M., MARQUIS, M., AVERYT, K., M., M., TIGNOR, B., LEROY MILLER, HENRY, J. & Z. CHEN (eds.). Cambridge University Press; Cambridge (United Kingdom): IPCC.

IPCC 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; . *In:* STOCHKER, T. F., QIN, D., PLATTNER, G.-K., TIGNOR, M., ALLEN, S. K., BOSCHUNG, J., NAUELS, A., XIA, Y., BEX, V. & MIDGLEY, P. M. (eds.).

ISE 2014. Photovoltaics report. Technical Report MSU-CSE-00-2. Institute for Solar Energy Systems, Freiburg, Germany.

ISO 2006. Environmental management – life cycle assessment – principles and framework International Organization for Standardization.

ITS 2012. CO2 Study on ITS-Modules: 80% lower CO2 emissions. Innotech Solar

JELLE, B. P., BREIVIK, C. & DROLSUM RØKENES, H. 2012. Building integrated photovoltaic products: A state-of-the-art review and future research opportunities. *Solar Energy Materials and Solar Cells,* 100**,** 69-96.

JUNGBLUTH, N. 2005. Life cycle assessment of crystalline photovoltaics in the swiss ecoinvent database. *Progress in photovoltaics: Research and applications,* 13**,** 429-446.

JUNGBLUTH, N., STUCKI, M., FLURY, K., FRISCHKNECHT, R. & BÜSSER, S. 2012. Life Cycle Inventories of Photovoltaics,. ESU-services Ltd on behalf of the Swiss Federal Office of Energy SFO.

JUNGBLUTH, N., STUCKI, M. & FRISCHKNECHT, R. 2009. Photovoltaics, contribution to ecoinvent version 2.1. Technical Report Ecoinvent report No 6-XII. Swiss Centre for Life Cycle Inventories, Dubendorf, Switzerland.

JUNGBLUTH, N., TUCHSCHMID, M. & DONES, R. 2007. Photovoltaics. Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. Ecoinvent report No. 6-XII, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, .

KRISTJANSDOTTIR, T., ANDRESEN, I., AMUNDSEN, H. & GOOD, C. 2016. Design phase calculation of greenhouse gas emissions for a Zero emission residential pilot building. *SBE 16 - International Conference on Sustainable Built Environment.* Hamburg, Germany.

M.A. GREEN 1992. *Solar cells : operating principles, technology and system applications,* University of New South Wales, Kensington.

MANN, S. A., DE WILD-SCHOLTEN, M. J., FTHENAKIS, V. M., VAN SARK, W. G. J. H. M. & SINKE, W. C. 2014. The energy payback time of advanced crystalline silicon PV modules in 2020: a prospective study. *Progress in Photovoltaics: Research and Applications,* 22**,** 1180-1194.

MARION, B., ADELSTEIN, J., BOYLE, K., HAYDEN, H., HAMMOND, B., FLETCHER, T., CANADA, B., NARANG, D., SHUGAR, D., WENGER, H., KIMBER, A., MITCHELL, L., RICH, G. & TOWNSEND, G. 2005. Performance Parameters for Grid-Connected PV Systems *IEEE Photovoltaics Specialists Conference and Exhibition* Lake Buena Vista, Florida: National Renewable Energy Laboratory.

METEOTEST 2009. Meteonorm Database.

NORD, N., QVISTGAARD, L. H. & CAO, G. 2016. Identifying key design parameters of the integrated energy system for a residential Zero Emission Building in Norway. *Renewable Energy,* 87**,** 1076-1087.

NREL 2012. Life cycle greenhouse gas emissions from solar photovoltaics. Technical Report NREL/FS-6A20-56487.: National Renewable Energy Laboratory, Denver, Colorado, U.S.

NREL 2013. Life Cycle Greenhouse Gas Emissions from Electricity Generation. Denver, Colarado. : National Renewable Energy Laboratory.

NREL 2016. Research Cell Efficiency Records [Online]. National Center for Photovoltaics at the National Renewable Energy Laboratory, U.S Department of Energy.

NVE 2013. Production and consumption of electric energy in 2012 *ENERGY IN NORWAY.* http://www.nve.no/Global/Energi/Analyser/Energi%20i%20Norge%20folder/FOLDE2013.pdf: Norwegian Water Resources and Energy Directorate

PENG, J., LU, L. & YANG, H. 2013. Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems. *Renewable and Sustainable Energy Reviews,* 19**,** 255-274.

PETERSON, K., TORCELLINI, P., GRANT, R., TAYLOR, C., PUNJABI, S., DIAMOND, R., COLKER, R., MOY, G. & KENNETT, E. 2015. A Common Definition for Zero Energy Buildings. U.S Department of energy, Energy Efficiency and Renewable Energy

PRE CONSULTANTS 2012. SimaPro version 8.0.5. Netherland. .

PVSYST SA 2011. . PV-syst 5.73, Photovoltaic System Software *In:* GENEVA, U. O. (ed.). In: MERMOUD, A. (ed.) 5.73

RAMESH, T., PRAKASH, R. & SHUKLA, K. 2010. Life cycle energy analysis of buildings: An overview. *Energy and Buildings,* 42**,** 1592-1600.

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Formatted: Norwegian (Bokmål)

Formatted: Norwegian (Bokmål)

Formatted: Norwegian (Bokmål)

REC 2013. High performance solar modules REC peak energy series. *In:* GROUP, R. (ed.) *www.recgroup.com*.

REC GROUP 2013. Real Life, Real Security (Warranty factsheet). REC Group.

RENUSOL 2010a. Renusol Solar Mounting Systems: Installation Guide Intersole SE. Germany.

RENUSOL 2010b. Renusol Solar Mounting Systems: Intersole SE In-Roof System.

RENUSOLE. 2015. *Renusole Solar Mounting systems, Installation Manual Intersole SE and Picture Manual Intersole SE* [Online]. http://www.renusol.com/en/download.html. [Accessed June 2015].

SAINT-GOBAIN. 2015. *Saint-Gobain Multi-Comfort concept* [Online]. http://www.isover.co.uk/saint-gobain-multi-comfort. [Accessed January 2015 2015].

SARTORI, I., NAPOLITANO, A. & VOSS, K. 2012. Net zero energy buildings: A consistent definition framework. *Energy and Buildings,* 48**,** 220-232.

SCHWEIZER. 2015. *Installation Manual Solrif® XL / D* [Online]. https://www.schweizer-metallbau.ch/en/produkte/photovoltaik-systems/technical-documents.html,. [Accessed June 2015].

SEARATES 2015. www.Searates.com. SeaRates LP

SOLBES 2013. ZEB Living Lab Takintegrert PV-system. Tilbud for leveranse og installasjon. (Roof integrated PV system, offer on deliverables and installations).

STATNETT 2013. National plan for the next generation main grid. http://www.statnett.no/Global/Dokumenter/Prosjekter/Nettutviklingsplan%202013/Statnett-Nettutviklingsplan2013-engelsk_03korr.pdf: Statnett, .

STATNETT. 2015. *Power situation* [Online]. http://www.statnett.no/Drift-og-marked/Kraftmarkedet/Kraftsituasjonen/.

SUNPOWER CORP. 2012. Sunpower limited product and power warranty for PV modules. Online: SunPower Corp.

SUPSI. 2015. *Building Integrated Photovoltaic Systems* [Online]. http://www.bipv.ch/index.php/en/about-en-top: The University of Applied Sciences and Arts of Southern Switzerland. [Accessed June 2015].

SYSTEMS, K. 2015. *Brochure material, installation manual and image brochure* [Online]. http://www.k2-systems.uk.com/downloads/product-information.html,. [Accessed June 2015.

VOSS, K. & MUSALL, E. 2011. *Net Zero Energy Buildings,* Germany, Detail

WEIDEMA, B. P., BAUER, C., HISCHIER, R., MUTEL, C., NEMECEK, T., REINHARD, J., VADENBO, C. & WERNET, G. 2013. Overview and methodology. Data quality guideline for the ecoinvent database version 3. St. Gallen: Swiss Centre for Life Cycle Inventories.

WIBERG, A. H., GEORGES, L., DOKKA, T. H., HAASE, M., TIME, B., LIEN, A. G., MELLEGÅRD, S. & MALTHA, M. 2014. A net zero emission concept analysis of a single-family house. *Energy and Buildings,* 74**,** 101-110.

WILD-SCHOLTEN, M. D. 2013. Certificate of simplified carbon foot print of Innotech solar PVmodules. SmartGreenScans.

WILD-SCHOLTEN, R. G. A. M. D. 2012. Energy payback time and carbon footprint of elkem solar silicon®. *EU PVSEC Proceedings.* Frankfurt, Germany

YUE, D., YOU, F. & DARLING, S. B. 2014. Domestic and overseas manufacturing scenarios of silicon-based photovoltaics: Life cycle energy and environmental comparative analysis. *Solar Energy,* 105**,** 669-678.

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