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Lifecycle cost analysis (LCCA) of tailor-made building integrated photovoltaics (BIPV) façade: Solsmaragden case study in Norway

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ABSTRACT

In dense urban areas, the use of building integrated photovoltaics (BIPV) façades are becoming popular and they are bringing many advantageous along with the energy-saving features. However, at the same time, they raise tensions in capital investments and overall returns. "Solsmaragden" is one of such a commercial building, that is integrated with BIPV façade with the peak power of 127.5 kW and owned by Union eiendomsutvikling AS in Norway. In this paper, a lifecycle cost analysis (LCCA) of BIPV façade integrated to "Solsmaragden" is investigated based on on-field recorded data after four years of operation (2016–2019). While formulating LCCA, numerous benefits from system power generation, societal and environmental benefits, and financial gains due to three different end-of-life material recovery approaches were also considered. The result based on the field monitored performance showed that the net present value (NPV), discounted payback period, internal rate of return and levelised cost of energy of the system is equal to 478,934 NOK, 22 years, 6% and 1.28 NOK/kWh, respectively. It is observed that the BIPV system as a building envelope material for different orientations of the building skin could reimburse not only all the investment costs but also become a source of income for the buildings. The results also illustrated that the granted subsidy is substantially covering the societal and environmental benefits of this project.

1. Introduction

A recent report released by the US Energy Information Administration ((EIA), 2019) states that energy consumption of the building sector in the world (which includes both residential and commercial structures) will increase by 65% between 2018 and 2050, from 91 quadrillions to 139 quadrillions Btu. In the same period, renewable energy resources -including solar, wind, and hydroelectric power- will surpass fossil fuels and will be the dominant energy source in the world.

During recent years, there has been an increasing interest in building integrated photovoltaic systems (BIPV) as an alternative for supplying the energy demand of urban areas compared to the other renewable options. BIPV refers to PV systems that not only generate electrical energy but also behave like skin for the buildings (Gholami & Røstvik, 2020; Gholami et al., 2019b). Therefore, the BIPV system must have the properties of conventional building materials such as weather and noise protection, privacy, heat insulation, etc. (Zhang, Wang, & Yang, 2018). The most crucial advantage of BIPV systems compared to other alternatives in urban areas is that the BIPV system is located on the closest distance to the end-user, and it does not need land to produce electricity (Gholami & Røstvik, 2020; Gholami et al., 2019b). Diverse types of BIPV are currently available in the market, such as BIPV tile, foil, module, and solar cell glazing (Jelle, Breivik, & Røkenes, 2012). The BIPV system can function as a building integrated photovoltaics thermal system (BIPVT) and produce both electricity and heat (Agrawal & Tiwari, 2010; Ibrahim, Fudholi, Sopian, Othman, & Ruslan, 2014; Tripathy, Joshi, & Panda, 2017). The configuration and analysis of the BIPVT system are almost the same as the photovoltaic thermal system (PVT) (Gholami et al., 2015a; Gholami et al., 2015b; F Mohammadi, Gholami, & Menhaj, 2016).

The other advantage of the renovation of existing building facades with BIPV systems is the possibility to achieve nearly zero energy building (nZEB), zero energy building (ZEB), or even plus energy building targets (Gholami, H. N. Røstvik, & Müller-Eie, 2019; Sorgato, Schneider, & Rüther, 2018). Taking advantages of building facades with different orientations to expand energy generation throughout a day and aligning the energy production with the energy demand (Brito,

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Nomenclature

BAPV	Building attached photovoltaics
BIPV	Building integrated photovoltaics
BIPVT	Building integrated photovoltaics thermal
C_I	Cash inflows
C_O	Cash outflows
C_{OM}	Operation and maintenance cost
C_{RC}	Inverter replacement cost
CSCC	Country-level societal cost of carbon
C_T	Carbon tax
DPP	Discounted payback period
D_R	Discount rate
E	East
E_G	BIPV annual electricity generation
EIA	US Energy Information Administration
E_{kWh}	Average GHG emission per kWh
EOL	End-of-life
EOL_{FG}	End-of-life financial gains from recovered materials out of BIPV waste
E_T	Electricity tariff
FiT	Feed-in tariff
g	Gram
GHG	Greenhouse gas
GPBT	Greenhouse-gas payback
GSCC	Global-level societal cost of carbon
I_{EMC}	Equivalent envelope material cost
IMF	International Monetary Fund
I_{PIC}	Project investment cost
IRR	Internal rate of return
I_S	Granted subsidies
kg	Kilogram
kW	Kilowatt
kWh	Kilowatt-hour
kWp	Peak power of BIPV system
LCCA	Lifecycle cost analysis
LCOE	Levelised cost of energy
mm	Millimeter
MW	Megawatt
n	Number of the year
N	North
N_{Cn}	Net cash flow of the year
NE	Northeast
NOK	Norwegian krone
NPV	Net present value
NPV_{TC}	NPV of the costs of the system over the system's lifetime
NW	Northwest
nZEB	Nearly zero energy building
O&M	Operation and maintenance
P_{DC}	Saving percentage from power delivery cost
P_{DR}	Degradation rate of BIPV panels
P_{TL}	Electric power transmission and distribution losses ratio
PV	Photovoltaics
PVGIS	Photovoltaic Geographical Information System
PVT	Photovoltaic thermal
Q	Initial investment
RM_C	Recovered materials cost
RM_W	Recovered materials weight
S	South
SCC	Societal cost of carbon
S_{CT}	Saving from carbon tax
SE	Southeast
S_{PB}	Monetized environmental and societal benefit
S_{PD}	Saving from power delivery cost
sq.m	Square meter
S_{TL}	Saving from the electric power transmission and distribution losses
SW	Southwest
T_{EP}	Total electricity generation over the system's lifetime
USD	US dollar
W	West
y	BIPV system's lifetime
Y_{pp}	Payback year
ZEB	Zero energy building
Δ	Difference
°	Degree

Redweik, & Catita, 2013; Freitas & Brito, 2019) as well as the contribution of the system to boost the energy performance of the building skins (Chiu, Hou, Tzeng, & Lai, 2015) are some other privileges of such a building envelope material.

A recent research study conducted by Sánchez-Pantoja et al. (Sánchez-Pantoja, Vidal, Pastor, & society, 2018) reveals that the photovoltaic integration in building facade is aesthetically accepted by society and BIPV technology is also viewed as more positive than building attached photovoltaic (BAPV). BAPV system is a PV system that is added on the building without a direct effect on the structure's function, such as conventional solar cell systems that are generally installed on top of roofs (Barkaszi & Dunlop, 2001). BAPV is also installed often at a distance from the roof itself or as in worst cases at different angles (Kumar, Sudhakar, & Samykano, 2018, 2019, 2020). Moreover, the BIPV system application is not just limited to the buildings and it can be employed in other sections like ships (Esmailian, Gholami, Røstvik, & Menhaj, 2019), trains and busses.

Lifeycle cost analysis (LCCA) empowers the economic assessment of the BIPV system and its alternatives for final selection, based on the factors such as the project's initial costs and monitoring the financial performance of the system throughout its lifetime to reach the minimum cost as well as highest profit. A comprehensive analysis is an analysis that allows the end-users to choose the source of energy for their buildings, considering all consequences of their decision. With regard to BIPV systems, this type of analysis should investigate various aspects and factors such as BIPV role in building material offset (because of their dual functionality as building envelope material and power generator) and environmental and societal advantages.

When it comes to the BIPV economic analysis, many studies have conducted an economic analysis of BIPV systems or various policies which affect the analysis, but very few have quantified or monetised the impact of BIPV systems on the environment and society (Alnaser, 2018; Aste, Del Pero, & Leonforte, 2016; Byrnes, Brown, Foster, & Wagner, 2013; Hammond, Harajli, Jones, & Winnett, 2012; Jing Yang & X.W. Zou, 2015; Osseweijer, Van Den Hurk, Teunissen, & van Sark, 2018; Saretta, Caputo, & Frontini, 2018; Sivanandan, 2009; Sorgato et al., 2018; Wang et al., 2016; Zhang et al., 2018; Gholami et al., 2019a).

All the mentioned studies, neither evaluated the societal and environmental effects of the BIPV system on the economic analysis nor the end-of-life material recovery benefits. Moreover, none of the studies from the literature looked into the reasonable amount of subsidy for the owner of the BIPV systems. Furthermore, the total cost introduced to the economic analysis was generally the sum of both functions of the system (building skins and PV functionality).

In BIPV systems, apart from the societal and environmental benefits, there is end-of-life benefit as well. The studies exploring end-of-life benefits are very limited, where they are mostly in line with the conventional photovoltaics (PV). In the PV sector, waste is possible, and it

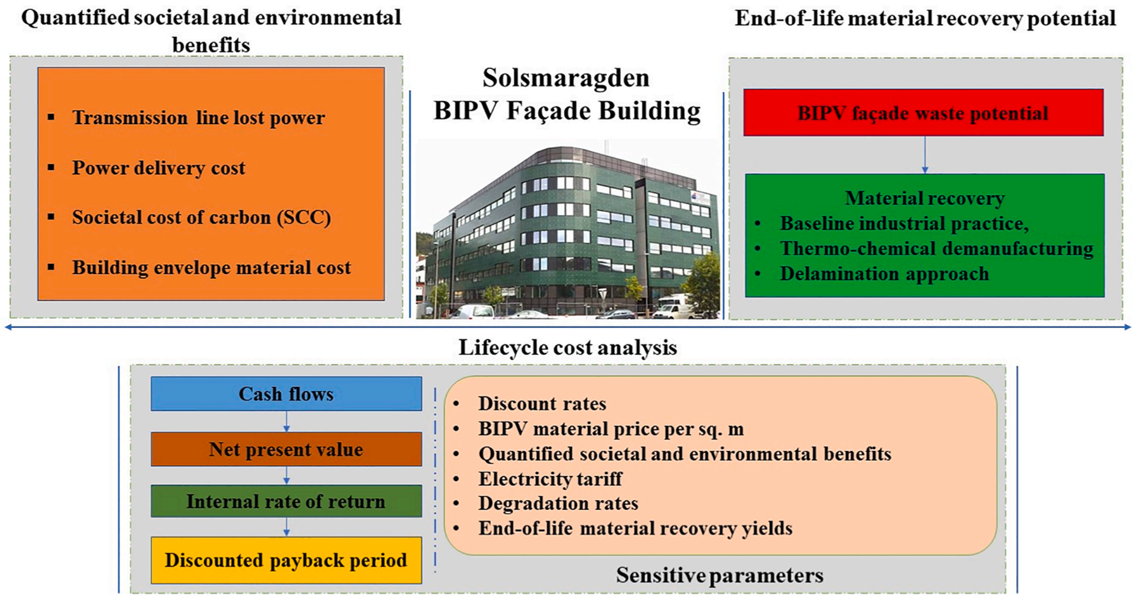

Fig. 1. The proposed methodology for LCCA of BIPV systems.

can be reused as a resource that would positively influence overall economic activity (Gangwar, Kumar, Singh, Jayakumar, & Mathew, 2019). In the PV sector, there are 'in-plant generated waste during manufacturing phase' and 'end-of-life PV modules waste'. It is estimated that by 2030 the generated PV waste would be around 1.7 million tonnes and by 2050 it could even rise up to 60 million tonnes (Gangwar et al., 2019). A recent study highlights that from a PV module weighing 20 kg, approximately 19 kg of useful materials can be recovered. However, this potential is varied based on the demanufacturing or recycling approaches used (Granata, Pagnanelli, Moscardini, Havlik, & Toro, 2014).

The main goal of this study is as follows. First, to determine whether the BIPV system as an alternative to the building envelope materials is economically feasible for the majority of building skin with different orientations or not. Second, to define a methodology to calculate the amount of a rational subsidy for the BIPV systems based on an implemented project.

The hypothesis in this study is that conducting an LCCA considering the societal, environmental and end-of-life material recovery benefits of BIPV system would demonstrate the significant impact of such factors in the BIPV system economic analysis. This research project has, therefore, been defined to accomplish an LCCA of the already implemented BIPV façade system in Norway, and the key contributions are as follows:

- To investigate the lifecycle cost analysis (LCCA) of BIPV façade building that was the first project in the world applying a printed, decoration only, layer on the inside of the front glass of the PV glazing to replicate a green wall.
- Formulation of LCCA considering the societal, environmental, and projected end-of-life material recovery benefits of the system to evaluate whether the allocated incentives, in this case by Enova that is a Norwegian government enterprise responsible for the promotion of environmentally friendly production and consumption of energy, is adequate or not.
- To explore the impact of different end-of-life material recovery approaches on the overall NPV.

The proposed LCCA of BIPV façade integrated system is based on on-field recorded data of the "Solsmaragden" building after four years of BIPV operation (2016–2019). The building is further introduced in Section 3.

This paper is structured in six sections as follows. In Section 2, the methodology and LCCA formulation, along with three different end-of-life material recovery approaches will be presented. In Section 3, the case study will be briefly introduced. The results are depicted in Section 4, with a thorough discussion. A parametric analysis is presented in Section 5. Finally, in Section 6, the conclusions based on the investigated BIPV façade case study is presented.

2. Methodology

This section of the paper addresses the methodology that was applied in order to carry out the LCCA. In our recent study (Gholami et al., 2019b), we proposed a method for lifecycle cost analysis (LCCA) of the BIPV system considering societal and environmental benefits from BIPV systems and for easy understanding of this, the proposed methodology is depicted in Fig. 1.

The proposed method in this study considers the quantified benefits that are as follow:

- saving in transmission line lost power;
- saving in power delivery cost;
- saving in societal cost of carbon (SCC);
- saving in building envelope material cost.
- end-of-life (EOL) financial gains from recovered materials out of BIPV waste

2.1. Input parameters

This section will discuss factors and parameters that need to be defined in order to develop the LCCA for the case studies, which are as follow:

2.1.1. Operation and maintenance (O&M) costs

Once the BIPV system has been implemented, it needs to be carefully maintained and efficiently operated. Compared to other alternatives, the BIPV system has low servicing requirements and maintenance. Annual operation and maintenance (O&M) expense of a BIPV system is assumed to be 0.5% of the initial cost of BIPV system for this study.

2.1.2. Inverter replacement cost

The costs due to the replacement of BIPV inverters (equipment and

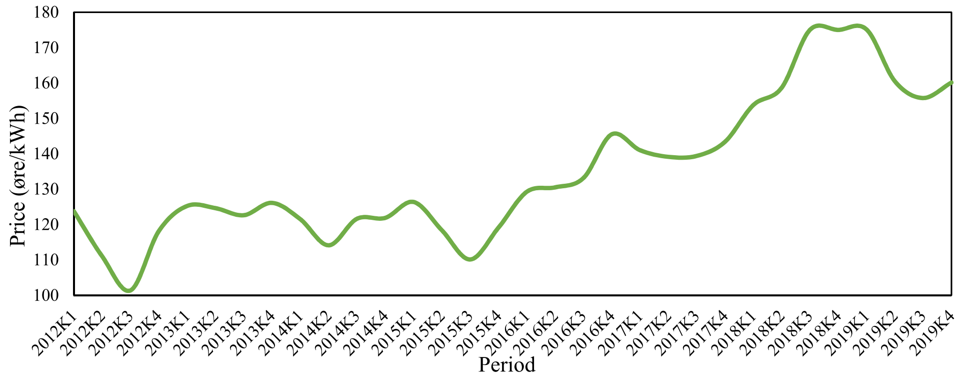

Fig. 2. Seasonal electricity price history of Norway including grid rent and taxes.

labour costs) are 10% of the whole BIPV system's initial cost in this project. The BIPV inverters' practical lifetime is ten to twenty years (Gholami et al., 2019b; Sorgato et al., 2018). Therefore, the replacement cost of BIPV inverters was inserted into the LCCA for the 15th year of operation.

2.1.3. BIPV degradation rate

Regardless of the environment that solar cells of the BIPV system are in, they naturally degrade over time, which is called the BIPV degradation rate. Depending on the material, the BIPV degradation rate varies. Jordan and Kurtz (Jordan & Kurtz, 2013) gathered nearly 2000 degradation rates, measured on individual modules or entire systems from the literature and found that the median degradation rate of solar cells is 0.5% per year. This ratio has been adopted in this study. This input will be further investigated in Section 5.

2.1.4. BIPV Life-time

The lifetime of the BIPV system is currently estimated at around 30 years (Hammond et al., 2012), while new studies state it could be as long as 50 years (Azadian & Radzi, 2013; Cerón, Caamaño-Martín, & Neila, 2013). For this study, the lifetime of the system is considered 30 years.

2.1.5. Building envelope material cost

In the suggested LCCA, what will be inserted into the analysis as an initial cost of the project is the extra imposed cost because of the BIPV secondary function as an energy producer. In other words, the capital cost of a BIPV system should be split between its functions as a building envelope material as well as an electricity generator (Gholami et al., 2019b; Oliver & T.Jackson, 2000) which is what we took into consideration for this study. In this study, The BIPV is a substitute for a glass façade with an average cost of 1 855 NOK per sq.m. (Table 3). Therefore, this value will be deducted from the total BIPV investment. This will be illustrated in details in Section 4, and a parametric analysis of this input will be further investigated in Section 5.

2.1.6. Transmission line lost power

With a BIPV system, the generated electricity will be consumed by the residents of the building or the neighbouring buildings, which leads to the elimination of transmission line losses. According to the World Bank Data (The World Bank Group, 2018), the electrical power transmission loss in Norway is 6%.

2.1.7. Power delivery cost

A BIPV system provides a way to reduce or even omit the capital expenditure required to expand the grid's electric network infrastructure or maintenance (Gholami et al., 2019b). Contrary to BIPV systems, other forms of renewable energies like solar farms or wind farms might lead to the necessity of expanding the network infrastructure and even slight changes in the climate at or near the exploited land. Considering a depreciated estimate, generated electricity by a BIPV system can decrease the delivery cost of around 20% of the total electricity price (Gholami et al., 2019b; Institute, 2018). The delivery cost covers expenses for distribution equipment that deals with lower voltages, the transmission costs, charges for installing, operating, and maintaining meters and sensors etc.

2.1.8. Societal cost of carbon (SCC)

The societal cost of carbon (SCC) is the total damage caused by greenhouse gas emissions (GHG) (Dimitris Lazos, 2012). It can be categorised into two groups of country-level SCC (CSCC) and global-level SCC (GSCC) (Ricke, Drouet, Caldeira, & Tavoni, 2018). Some countries like Norway have started to raise taxes on carbon emissions and it is called carbon tax. The value of the carbon tax in Norway is set to be 500 NOK (Group, 2019).

The SCC, which is also called the shadow price of carbon, is a principal measure of the global incremental damage accomplished by GHG emission. A cost–benefit analysis is required to set the optimal amount of GHG emission reduction at the point where this social cost just equals the incremental cost of controlling emissions (Pearce, 2003). The higher cost of SCC would lead to more control. This comparison is based on the assumption that a cost–benefit investigation is the accurate way of regulating climate-change policy. However, many are sceptical and are of the opinion that this is not the case due to the very long-term, potentially catastrophic and irreversible nature of global warming (Pearce, 2003).

A recent study by the International Monetary Fund ((IMF), 2019) concluded that halting global warming to 2°Celsius or less requires immediate policy measures on a demanding scale, like rasing the carbon tax to 75 USD (700 NOK) per ton by 2030. In order to reach a carbon tax of 700 NOK by 2030, a growth rate of 3.5% for the current carbon tax is required. These figures are adopted to this study.

2.1.9. GHG emission

GHG emission from power production depends on the energy source used for production (e.g., coal, gas or water). Practically all electricity generation in Norway is from hydropower due to the substantial hydropower potential. The average GHG emission factor in Norway, which is caused by electricity production, is estimated at 18,9 g/kWh ((NVE), 2019). The country has the lowest GHG emission rate from electricity production in Europe. However, by selling this almost clean energy to Europe and purchasing electricity from other countries with mostly fossil fuel resources, the average GHG emission of electricity consumption raises to more than 100 g/kWh.

From 2008 to 2017 (Larsen, 2019), the GHG emission from the electricity consumption in the Nordic countries has shrunk from 189 g/kWh to 128 g/kWh, which is equal to a decline rate of 4.2% per year. Therefore the average GHG emission of 134 g/kWh for the year 2016 with a decline rate of 4.2% is adjusted and applied in this study.

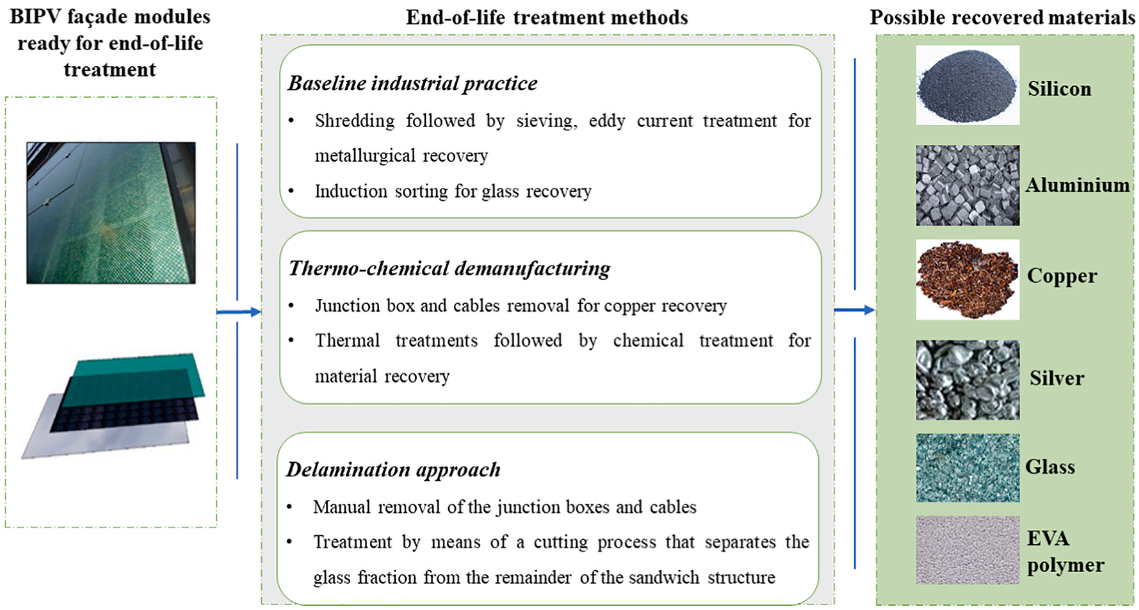

Fig. 3. End-of-life material recovery process for BIPV module.

2.1.10. Electricity tariff and its growth rate

Fig. 2 illustrates the total seasonal price of electricity including grid rent, tax on consumption of electrical energy and value-added tax from 2012 to 2019 for Norway (Holstad, 2019). From the data, it can be calculated that the annual growth rate of electricity is 3.5%. A parametric analysis of this input will be further investigated in Section 5.

2.1.11. Discount rate

The discount rate is the rate of interest a bank charges on its loans and can be represented based on two perspectives of financial (or individual) discount rate and social discount rate (García-Gusano, Espegren, Lind, & Kirkengen, 2016; Gotzens, Heinrichs, Hake, & Allelein, 2018; Steinbach & Staniaszek, 2015). Although it changes from country to country, a discount rate of 3% has been applied to this study (Gotzens et al., 2018). A parametric analysis of this input is also investigated in Section 5.

2.2. End-of-life modelling of BIPV façade

There are currently three major demanufacturing strategies for crystalline modules and these include baseline industrial practice, thermo-chemical demanufacturing, and delamination approach (Gangwar et al., 2019). Fig. 3 illustrates the end-of-life material recovery process for BIPV modules. Each process has different procedures for demanufacturing the PV or BIPV modules and yields of recovered materials are different. But most of the methods will follow a strategy and at the first step glass materials are recovered by using organic solvents; then other essential materials like silver, copper, aluminium, and EVA polymer are recovered (Kang, Yoo, Lee, Boo, & Ryu, 2012). The cost of recycling and the market value for recovered materials vary. Taking the end-of-life material recovery benefits into account in the LCCA would definitely have a significant impact on the overall revenues.

In baseline industrial practice, the BIPV waste is directly put under the shredding process without having any preliminary removal of junction boxes. The crushed BIPV from the shredder is further treated using various metallurgical and induction sorter techniques to recover the materials (Duflou, Peeters, Altamirano, Bracquene, & Dewulf, 2018). In thermo-chemical demanufacturing process, the BIPV end-of-life modules are treated in a different manner when compared to the baseline industrial practice. In this process, the junction boxes and cables are first separated. The reminder waste is processed under thermal treatments followed by chemical treatments for material recovery (Gangwar et al., 2019; Huang et al., 2017; Park, Kim, Cho, Lee, & Park, 2016). In the delamination approach also, the junction boxes and cables are removed from the BIPV end-of-life modules using the manual process. The reminder BIPV waste goes to the cutting process where the glass fraction is separated from the PV cell. The leftover solar PV cell and EVA polymer are then treated by thermal approaches to recover the materials (Duflou et al., 2018).

Using the above-discussed EOL methods for BIPV module waste, the reusable materials can be recovered. These materials can be sold in the market and they can replace the virgin materials in many applications.

2.3. LCCA formulation

The aim of the proposed LCCA is to consider the multi-functional performance of the BIPV system, as well as end-of-life material recovery benefits and the societal and environmental factors. Therefore, the following analysis is presented (Gholami et al., 2019b).

The basis of the suggested LCCA is three financial tools which are net present value (NPV), internal rate of return (IRR) and discounted payback period (DPP). (Eicker, Demir, & Gürlich, 2015; Eiffert, 2003; Gholami et al., 2019b).

NPV can be formulated as follows in Equation (1):

$$\mathrm{NPV} = \sum\nolimits_{n=1}^{y} (C_I - C_O)(1 + D_R)^{-n} \tag{1}$$

C_I and C_O stand for cash inflows and cash outflows. D_R, y, and n, represent discount rate, BIPV lifespan and the number of the year, respectively.

C_I is the gained money from the BIPV system, such as the income from the electricity production, financial gains from EOL and the granted subsidy from Enova. C_O is the spent money on the system, such as investment, inverter replacement cost and O&M cost.

The initial investment, Q, is calculated as follows:

$$Q = I_{\mathrm{PIC}} - \mathrm{I}_{\mathrm{EMC}} - I_S \tag{2}$$

I_{PIC}, I_{EMC} and I_S represent project initial investment cost, equivalent building envelope material cost and granted subsidies, respectively.

C_I in year n can be calculated as shown in Equation (3) :

$$C_I = (E_T \times E_G) + EOL_{FG} \tag{3}$$

E_T represents electricity tariff and E_G stands for BIPV annual

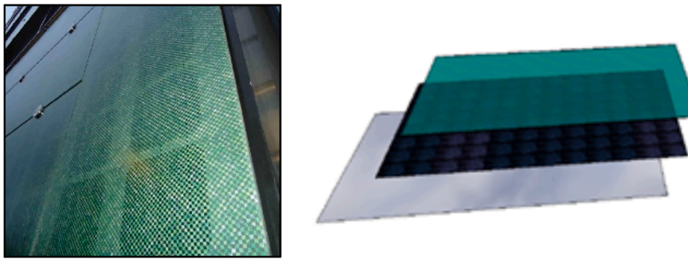

Fig. 4. a). Green pattern colouration of the BIPV front glass; b). Structure of Issol BIPV panel.

electricity generation. EOL_{FG} represents the end-of-life financial gains from recovered materials out of BIPV waste which is estimated using Equation (4):

$$EOL_{FG} = \sum_{w=1}^{n} RM_C \times RM_W \tag{4}$$

Where RM_C and RM_W stand for the recovered materials cost and the weight of the recovered materials in kg, respectively.

E_{Gn} of each year can be formulated, as shown in Equation (5):

$$E_{Gn} = E_{G1} \times (1 - P_{DR})^n \tag{5}$$

P_{DR} stands for the degradation rate of BIPV panels. The monetised environmental and societal benefit, S_{PB}, can be calculated using Equation (6):

$$S_{PB} = S_{TL} + S_{PD} + S_{CT} \tag{6}$$

S_{TL} stands for the electric power transmission and distribution losses. S_{PD} represents saving from power delivery cost. S_{CT} is saving from carbon tax. S_{TL}, S_{PD}, S_{CT} can be calculated by Equations (7–9):

$$S_{TL} = \mathrm{P}_{TL} \times E_T \times E_G \tag{7}$$

$$S_{PD} = \mathrm{P}_{DC} \times E_T \times E_G \tag{8}$$

$$S_{CT} = \mathrm{C}_T \times E_{kWh} \times E_G \tag{9}$$

P_{TL} represents the electric power transmission and distribution losses ratio (in percent). P_{DC} stands for saving percentage from power delivery cost. C_T indicates carbon tax and finally, E_{kWh} shows average *GHG* emission per kWh. C_O of the BIPV in year *n* can be shown as in Equation (10) :

$$C_O = C_{OM} + C_{RC}(ifn = 15) \tag{10}$$

C_{OM} indicates the cost of operation and maintenance and C_{RC} stands for the inverter replacement cost. N_{Cn}, the net cash flow of the year *n*, is the difference of the cash inflows and outflows in a given period and can be calculated as follows:

$$N_{Cn} = C_I - C_O \tag{11}$$

The cumulative *NPV* is computable as indicated in the following formula:

$$\begin{aligned} \mathrm{NPV} &= -Q + N_{C1}/(1 + D_R)^1 + N_{C2}/(1 + D_R)^2 + \cdots + N_{Cy}/(1 + D_R)^y \\ &= -Q + \sum_{n=1}^{y} N_{Cn}/(1 + D_R)^n \end{aligned} \tag{12}$$

D_R stands for the discount rate. The *DPP* can be calculated from Equation (13):

$$\sum_{n=1}^{Ypp} N_{Cn}/(1 + D_R)^n = Q \tag{13}$$

Finally, the internal rate of return can be found out by Equation (14):

$$-Q + \sum_{n=1}^{y} N_{Cn}/(1 + IRR)^n = 0 \tag{14}$$

3. Description of Solsmaragden BIPV façade building

The “Solsmaragden” is a commercial building owned by Union eiendomsutvikling AS and holds office space for around 450 people (8650 sq.m.). The building is located in Grønland, 3045 Drammen, west of Oslo, Norway. The geographic coordinate of the building is 59.74° N, 10.19 ° E.

The project was the first project in the world that applied a printed,

Fig. 5. Solsmaragden building skin from different perspectives (Energibygget Drammen).

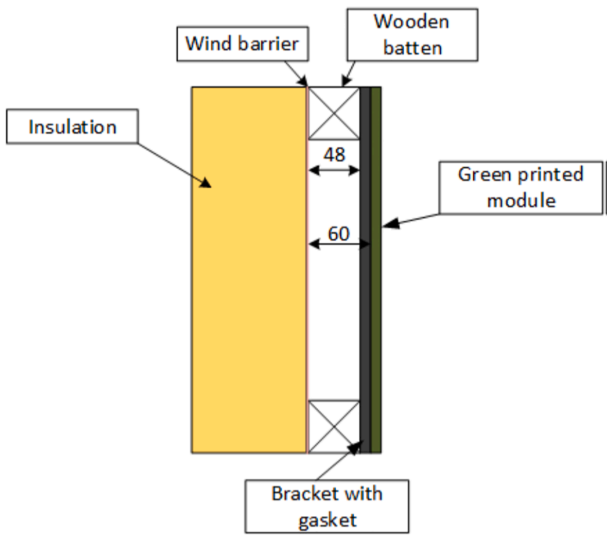

Fig. 6. The cross-section of the south facade in Solsmaragden BIPV building (dimension unit is mm) (Frivold, 2018).

decoration only layer on the inside of the front glass of the PV glazing. The objective of the project was to replicate a green wall according to the requirements of the architects.

The tailor-made BIPV panels, together with glass cladding has been used for most of the building façades of this project. The facade modules consist of 4 mm glass with a printed layer on the inside of the front glass of the PV glazing, a layer of standard 6″ mono-crystalline silicon solar cells and another layer of 4 (mm) glass, which are laminated together (frameless glass-glass configuration). The cell efficiency is 20% and the printed green colour reduces the cells' overall efficiency by 17%. Therefore, the efficiency of the BIPV panels is 16.6%.

The front glass has been printed on the inside with a pattern of green colour as can be seen in detail in Fig. 4.a and the structure of the BIPV panels is also demonstrated in Fig. 4.b (Frivold, 2018).

The project was a collaboration between the building owner Union eiendomsutvikling AS, the project architect LOF architects AS, the Norwegian PV supplier Solenergi FUSen AS, the Belgium company ISSOL sa/nv and installed by the building contractor Strøm Gundersen AS. The material choice and installation method is in compliance with national standard safety requirements for a glass façade, which ensures that panels will not fall in the case of glass breakage. Fig. 5 shows the building's skin from different perspectives.

The project is a combination of BIPV (façade-mounted) and BAPV

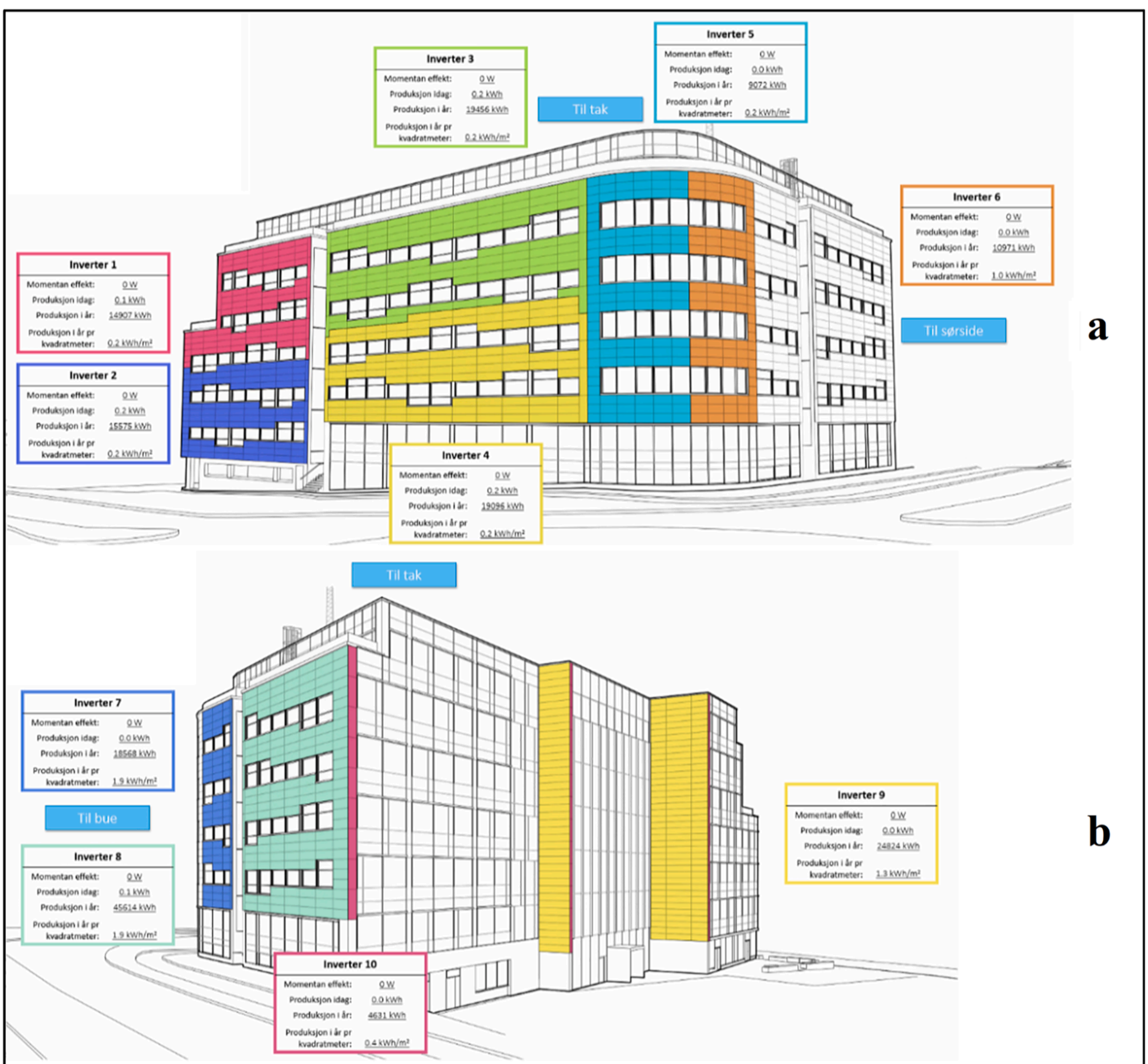

Fig. 7. Different strings of BIPV panels on the building skin (screenshot from the monitoring app).

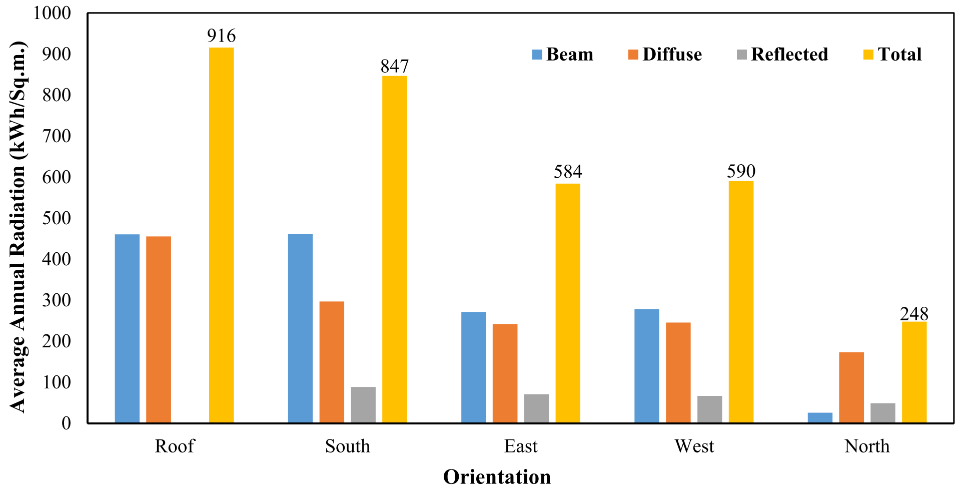

Fig. 8. Average Annual radiation on different orientations of the building skins.

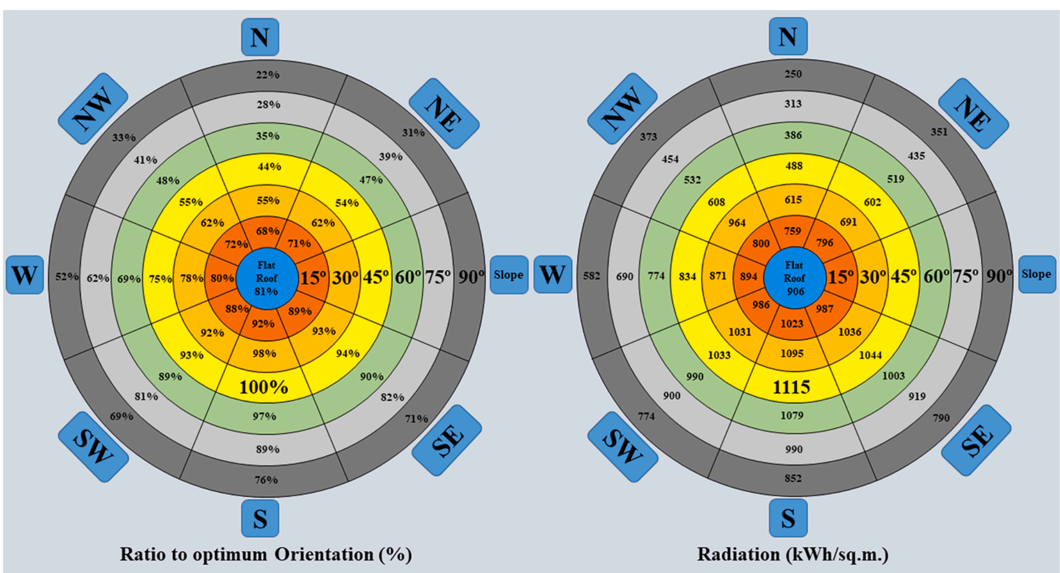

Fig. 9. Annual solar potential of building skins with different tilts and orientations in Drammen, Norway.

(roof-mounted). The focus of this study is on the BIPV system. The entire BIPV façade consists of in total of 1011 panels (1146 sq.m.) with the peak power of 127.5 kW$_P$ and the estimated annual production of 55.5 MWh/sq.m. The integration of BIPV and their cross section is shown in Fig. 6. The architectural integration of BIPV modules demanded 26 different shapes of PV panels (from 55 WP (15 cells) to 170 W$_P$ (48 cells)). The BIPV strings are connected to 10 SMA inverters.

Fig. 7 describes the configuration of the inverters on the building skin. The direction of the panels is toward the south, east, west and south-west. The total area of the BIPV on the west, south, south-west and east facade is 523, 462, 125, and 36 square meters, respectively.

4. Results and discussion

The analysis was done in Excel and the data together with the formulation and method is publicly available in the Mendeley database. The starting date for the system evaluation is the beginning of 2016. Considering a 30-year lifetime, it is expected that the system operates until 2046.

Fig. 8 presents the average annual geographical irradiation potential on building skins at the site. The analysis and calculated amounts are based on the hourly incident radiation data between 2005 and 2016 from the Photovoltaic Geographical Information System (PVGIS) (PVGIS, 2017).

As can be seen from Fig. 8, the reflected radiation component of the roof area – which is the reflection of the direct and diffuse radiation on the ground of the objects on the ground – on the database is zero. The way the database assumes is that the roof of the building has no view of the other surfaces around it and therefore, no reflection from other objects in the area will be hit by the building roof. Because of the climate of the location, the contribution of the diffuse radiation – which are the sunlights that has been dispersed or scattered by particles in the atmosphere and still made their way down to the surface – is significant and its contribution in terms of the east, west and roof area of the building is almost equal to the direct radiation– which is solar radiation coming on a straight line from the sun down to the surface of the earth. In terms of the north façade, almost 70% of the radiation is from the diffuse radiation component.

Fig. 9 illustrates the solar irradiance potential on different orientations of building skins with different tilt in the Solsmaragden site and for the year 2016. The data has been extracted from PVGIS ((PVGIS), 2017) . The solar irradiance values for the east and west facades with different

Table 1
Inverter capacities and production on the building skin.

Direction	Inverter number	Inverter Model	Inverter Capacity (kW)	BIPV Orientation	Area (sq. m.)	Peak Power (W_p)	Annual production (kWh)				Total (kWh)	Average annual production (kWh/sq. m.)
							2016	2017	2018	2019		
Bow view	1	STP 10,000 TL-20	10	West	113.5	12,630	3,910	3,782	3,558	3,658	14,907	33
	2	STP 10,000 TL-20	10	West	126.7	14,100	4,085	3,951	3,717	3,822	15,575	31
	3	STP 12,000 TL-20	12	West	140.2	15,600	5,103	4,936	4,643	4,774	19,456	35
	4	STP 12,000 TL-20	12	West	142.2	15,820	5,008	4,844	4,557	4,686	19,096	34
South direction	5	STP 6000 TL-20	6	South-west	66.6	7,410	2,379	2,301	2,165	2,226	9,072	34
	6	STP 5000 TL-20	5	South-west	57.9	6,440	2,877	2,783	2,618	2,692	10,971	47
	7	STP 6000 TL-20	6	South	77.5	8,620	4,870	4,710	4,431	4,556	18,568	60
	8	STP 15,000 TL-10	15	South	190.0	21,140	11,963	11,572	10,886	11,193	45,614	60
	9	STP 20,000 TL-30	20	South	194.7	21,660	6,510	6,298	5,925	6,092	24,824	32
	10	SB 3000 TL-21	3	East	36.4	4,050	1,215	1,175	1,105	1,136	4,631	32

Table 2
BIPV annual performance.

Year	Total production (kWh)	Building self-consumption		Sold electricity to the grid	
		kWh	of total	kWh	of total
2016	95,460	93,697	98%	1763	2%
2017	92,340	91,317	99%	1023	1%
2018	86,870	84,407	97%	2463	3%
2019	89,320	87,353	98%	1967	2%

orientations were almost the same (with a maximum 1% variation). The optimum angle to gain the maximum solar irradiance for this location is the azimuth angle (the angle of the BIPV modules relative to the direction due south, in which −90° is east, 0° is south and 90° is west) of zero degrees, and the slope (the angle of the BIPV modules from the horizontal plane) of 45°. The annual solar irradiance of this orientation in 2016 was recorded 1115 kWh per square meter.

Table 1 presents information about the system configuration and production through each inverter during the first four years of operation (2016–2019).

The average annual production of the solar BIPV system in the building based on the production data of the past four years is equal to 40 kWh per square meter of the BIPV area. The average annual irradiance on the BIPV system is equal to 707 kWh per square meter without taking the shading effect into account (can be calculated from Fig. 8).

Table 2 shows the total annual electricity production by the BIPV (walls) and BAPV (roof) systems. The total electricity production of both systems was estimated to contribute 23% of the annual building energy consumption and the rest will be supplied by the grid. In this study, which is only assessing the BIPV system, it has been presumed that the building consumes all the produced electricity by the BIPV.

Table 3 shows the cost breakdown for this BIPV project. The BIPV project ended up by the total investment of 4,625,794 NOK for an active area of 1146 sq.m. of BIPV panels (total investment of 4,036 NOK/sq. m.). The building also received 1,553,236 NOK support from Enova for the BIPV project.

The glass façade costs are based on the quotations. Contractor surcharge is the fee that the main contractor is charging to manage and control the entire Engineering, procurement and construction (EPC) project. After BIPV project implementation, some costs did not fall into the defined categories and were added to the "Other costs."

The recovered materials from end-of-life of BIPV waste after the 30th year lead to financial gains and these gains are estimated as per the Equation (4). Before the financial gain's estimation, the possible BIPV waste potential need to be identified based on the weight of the PV module. The BIPV façade weight is 20.5 kg per sq.m. and 1146 sq.m. of BIPV façade is installed, which accounts for a cumulative weight of 23.5 tonnes. The weight of recovered materials varies depending on EOL approaches. The percentages of materials recovery yields, which are based on the industrial data (WEEE treatment plant in the Flemish region of Belgium) as well as the literature support (Duflou et al., 2018; Gangwar et al., 2019; Huang et al., 2017; Kang et al., 2012) are provided in Table 4. The recovered materials in all the three EOL methods, as well as the financial gains, are estimated and presented in Table 5 with their NPV values.

Fig. 10 shows the cumulative NPV of the BIPV system based on three scenarios of initial investment and also NPV of the façade if the glass option was selected. Therefore, four scenarios have been evaluated for this project as follows (without taking the EOL benefits into account):

Scenario-A: Gross investment, which is the total invested money by the client without taking the Enova support and BIPV function as a building envelope material into consideration (4,625,794 NOK);

Scenario-B: Net investment without Enova support, which is the total invested money by the client considering the system functionality as a building envelope material (an alternative for glass façade) but without

Table 3
BIPV project estimated cost breakdown.

Gross estimated cost	BIPV Facade		Glass facade		Δ	
	Total Cost (NOK)	Cost/sq.m.(NOK)	Total Cost (NOK)	Cost/sq.m. (NOK)	Total Cost (NOK)	Cost/sq.m.(NOK)
Facade panel delivery	2,767,590	2,415	655,512	572	2,112,078	1,843
Mounting system	435,480	380	435,480	380	0	0
Mounting labor	665,826	581	665,826	581	0	0
Elect. job and equipment	461,838	403	0	0	461,838	403
Lift	184,506	161	184,506	161	0	0
Contractor surcharge	0	0	184,506	161	−184,506	−161
Other costs	110,554	96.47	0	0	110,554	96.47
Sum	**4,625,794**	**4,036**	**2,125,830**	**1,855**	**2,499,964**	**2,181**

Table 4
Percentage of material recovery yields .

Material types	Recovery yields		
	Baseline industrial practice	Thermo-chemical demanufacturing	Delamination approach
Silicon	74%	95%	100%
Almunium	78.1%	86%	86%
Copper	34.7%	85%	95%
Silver	35%	74%	95%
EVA	55%	90%	95%
Glass	89.6%	98%	98%

taking the Enova support into the evaluation (4,625,794 NOK − 2,125,830 NOK = 2,499,964NOK);

Scenario-C: Net investment with Enova support, which is the total invested money by the client by taking the system functionality as a building envelope material (an alternative for glass façade) and the Enova support into the evaluation (4,625,794 NOK − 2,125,830 NOK − 1,553,236 NOK = 946,728NOK);

Scenario-D: Glass façade option (2,125,830 NOK).

By taking the subsidy granted by the Enova into the calculation, the cumulative NPV of the BIPV system becomes positive, with the total value of 478,934 NOK (0.48 Million NOK, see Fig. 10). It means the BIPV system could reimburse not only the invested money but also become a source of income for the building. It is also found out that with a subsidy equal to 1,074,301 NOK, the cumulative NPV of the BIPV system would become Zero. On the other hand and in terms of the glass façade option,

Table 5
BIPV end-of-life material recovery potential and their NPV.

Materials types	Material composition (kg/tonne)	Material recovery potential from BIPV system waste (kg)	Total recovered materials (kg)		
			Baseline industrial practice (P1)	Thermo-chemical demanufacturing(P2)	Delamination approach (P3)
Silicon	18.2	427.6	316.4	406.2	427.6
Aluminium	20.1	472.2	368.8	406.1	406.1
Copper	19.9	467.5	162.2	397.4	444.1
Silver	1.2	29.1	10.2	21.6	27.7
EVA	45.2	1,061.9	530.9	955.7	1,008.8
Glass	895.4	21,035.6	18,847.9	20,614.9	20,614.9
Total weight	1,000.0	23,493.9	20,236.5	22,801.9	22,929.2
NPV of total financial gains (NOK)	–	–	108,514	201,095	242,468

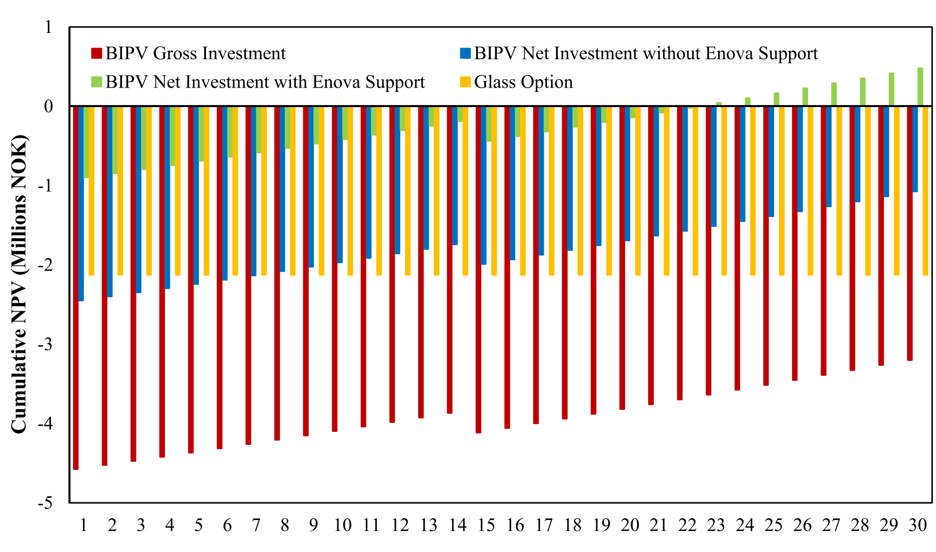

Fig. 10. The cumulative NPV of investment for different scenarios (without EOL benefits).

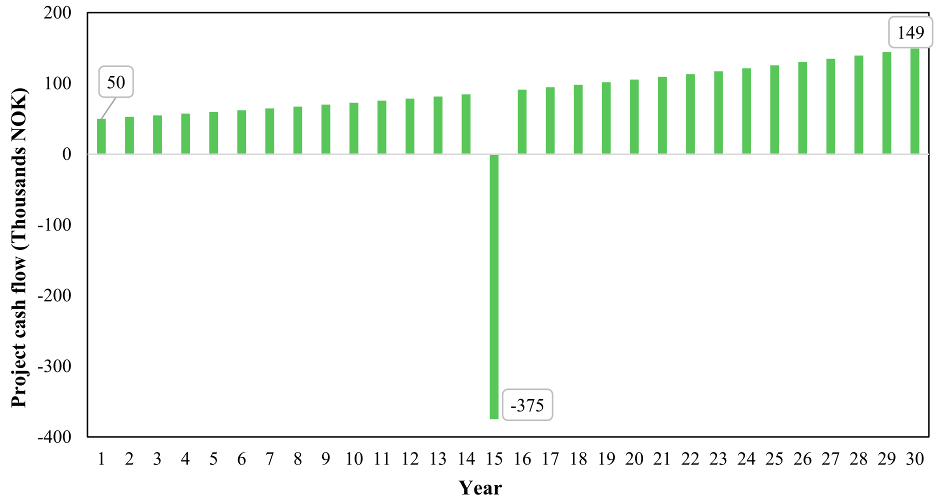

Fig. 11. BIPV cash flow without investment and EOL benefits.

Table 6
The IRR and DPP values of the different Scenarios.

Scenario	DPP	IRR without EOL	IRR with EOL-P1	IRR with EOL-P2	IRR with EOL-P3
A	NA	−4%	−3%	−3%	−3%
B	NA	0%	0%	0%	0%
C	22	6%	7%	8%	9%
D	NA	NA	NA	NA	NA

the cumulative NPV of the system will be −2,125,830 NOK.

The BIPV systems' cash flow during its lifetime can be seen in Fig. 11. The cash flow of the project is the same for all the Scenarios because it deals with electricity production, electricity tariff, etc., and the types of scenarios do not affect them. As can be seen from Fig. 11, the cash flow of the system increases slightly from 50,000 NOK to 149,000 NOK for the entire lifetime except year 15 in which the cash flow becomes negative because of the replacement cost of the inverter.

Table 6 shows the IRR and DPP of the defined scenarios for this project. Even without Enova support, the IRR would be equal to zero. It means that the BIPV system can recoup the extra investment as a consequence of choosing the BIPV system instead of the glass option with a discount rate of zero. In other words, the DPP of the BIPV system with a discount rate of zero in the second Scenario would be 30 years. However, all of these economic analyses and IRR and DPP calculations are meaningful if the case is an active façade (such as a BIPV facade). In terms of passive facades (such as a glass façade) as can be seen from Table 6, discussing IRR and DPP is pointless.

Another important implication from this study is that the BIPV system as an envelope material for a significant portion of a building's skin, even in a climate and an urban area like Oslo (with lower solar irradiance and cheaper electricity price compared to many other European countries), is economically feasible. This fact has recently led to an expeditious development of the business model of BIPV technology and it is about to be recognised soon as a building envelope material for the entire building skins in competition with other alternatives such as brick, wood, stone, metals, etc.

Fig. 12 presents and sums up all the factors involved in the LCAA and economic analysis of this project. The total carbon saving from the BIPV system of this building over a 30-years lifetime is equal to 105 Tons of CO2. It is apparent from Fig. 12 that the Enova support greatly covers the societal and environmental benefits of the BIPV system which has been quantified (saving in transmission loss, saving in power delivery cost and carbon tax).

What is interesting in Fig. 12 is that for every BIPV project, such a graph could be plotted, and then decision-makers could discuss and decide on the amount of incentive or subsidy. The graph varies from country to country or even from project to project, but the principles are the same.

Fig. 12 is also a useful tool to calculate the levelised cost of energy (LCOE) for the defined Scenarios. LCOE is often referred to as a convenient summary measure of the overall competitiveness of electricity-generating technologies (EIA, 2016; Farshad Mohammadi, Gholami,

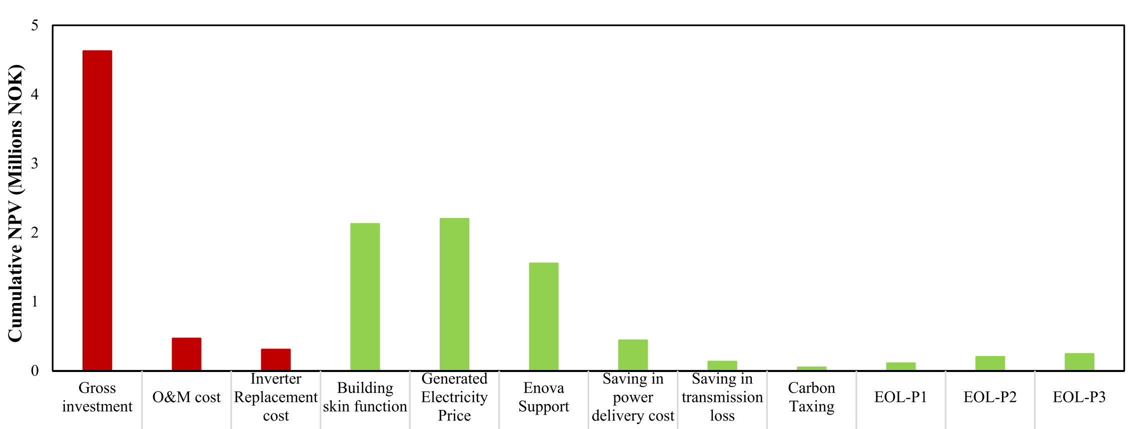

Fig. 12. The absolute cumulative NPV of different items for this project.

Table 7
The LCOE of Scenarios.

Scenario	NPV_{TC}	LCOE without EOL	LCOE with EOL-P1	LCOE with EOL-P2	LCOE with EOL-P3
A	5,397,924	4.03	3.95	3.88	3.85
B	3,272,094	2.45	2.36	2.30	2.26
C	1,718,858	1.28	1.20	1.13	1.10
D	2,125,830	NA	NA	NA	NA

Gharehpetian, & Hosseinian, 2017). In terms of BIPV technology, LCOE is a term that describes the cost of the power produced by the BIPV systems over the lifetime of the system, which is 30 years in this study.

The following Equation (15) can be used to calculate the LCOE:

$$\text{LCOE} = NPV_{TC}/T_{EP} \tag{15}$$

NPV_{TC} and T_{EP} represent the net present value of the costs of the system over its lifetime and total electricity generation over its lifetime, respectively.

The LCOE of the Scenarios is presented in Table 7. Since the electricity generation for Scenario D is Zero, the LCOE is not computable for this Scenario.

As mentioned earlier, all the electricity generated by the BIPV system is consumed by the building. Therefore, the total cost of electricity per kWh for end-user in Norway (Fig. 2) is inserted in the LCCA as the electricity price.

Fig. 13 presents the history of the cost breakdown of electricity for end-users in Norway (Holstad, 2019). Unfortunately, there is no feed-in tariff (FiT is a fixed electricity price that is paid to renewable energy producers for each unit of energy produced and injected into the electricity grid as an economic policy to promote active investment in renewable energy sources) for PV and BIPV on residential and commercial buildings in Norway. Generally, the reference price for the surplus energy of the end-users injected into the power grid is the "Electricity price excl. taxes". This value for the winter season of 2019 as an example is 46.8 Øre per kWh (each NOK is 100 Øre) or 0.468 NOK while the total electricity price per kWh for the end-user is equal to 160.1 Øre (1.6 NOK). Therefore, when it comes to countries with no FiT (such as Norway), it is crucial to design the BIPV system in a way that the building consumes as much as possible of the electricity production.

For this particular project, two reasons made the system economically viable; the Enova subsidy and the self-consumption of the generated electricity by the building. The calculation shows that the Enova subsidy is equal to 1.16 NOK per kWh. In other words, Enova has paid 1.16 NOK/kWh for the total electricity production of the BIPV system during the system's lifetime (30 years) in advance.

Table 8 shows the information of the system in terms of different lifetimes of the system. The inverter replacement cost is added to the calculation for every 15th years of the system operation. It means that in terms of the estimated lifetime of 30, 40 and 50 years, the inverter replacement cost has been taken into calculation for the year 15, 15 and 30, 15, 30 and 45, respectively. The degradation rate is also considered 0.5% per year for all cases. As can be seen from Table 8, with a 50 years lifetime, the BIPV system would be economically feasible even without Enova support.

5. Parametric analysis

A parametric analysis is carried out for this project to figure out how much the cumulative net present value of the implemented BIPV system would fluctuate if the input parameters change. For this purpose, Scenario-C has been chosen as a reference.

Fig. 14 depicts the parametric analysis of various inputs on the output. The relationship between the discount rate and NPV is a nonlinear concave relationship and the cumulative NPV of the project varies from one Million NOK to minus 320 Thousand NOK if the discount

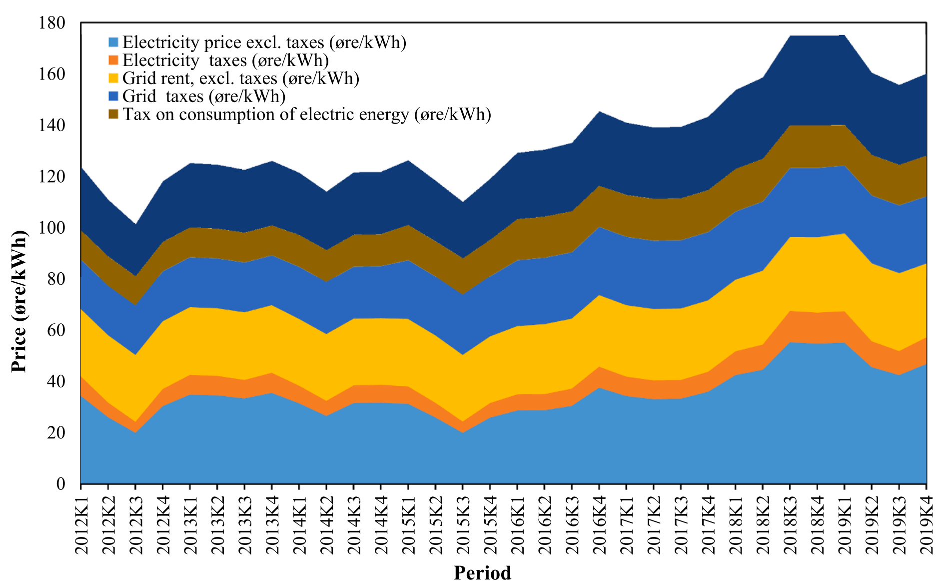

Fig. 13. Cost breakdown of electricity for end-users in Norway.

Table 8
The result of the LCCA for system's different lifetime (without EOL benefits).

System estimated lifetime	30 years				40 years				50 years			
	A	B	C	D	A	B	C	D	A	B	C	D
Cumulative NPV ($10^3 NOK$)	−3,200	−1,074	+479	−2,126	−2,749	−624	+929	−2,126	−2,209	−83	+1,470	−2,126
IRR (%)	−4	0	+6	NA	−1	+2	+7	NA	+1	+3	+8	NA
DPP (year)	NA	NA	22	NA	NA	NA	22	NA	NA	NA	22	NA

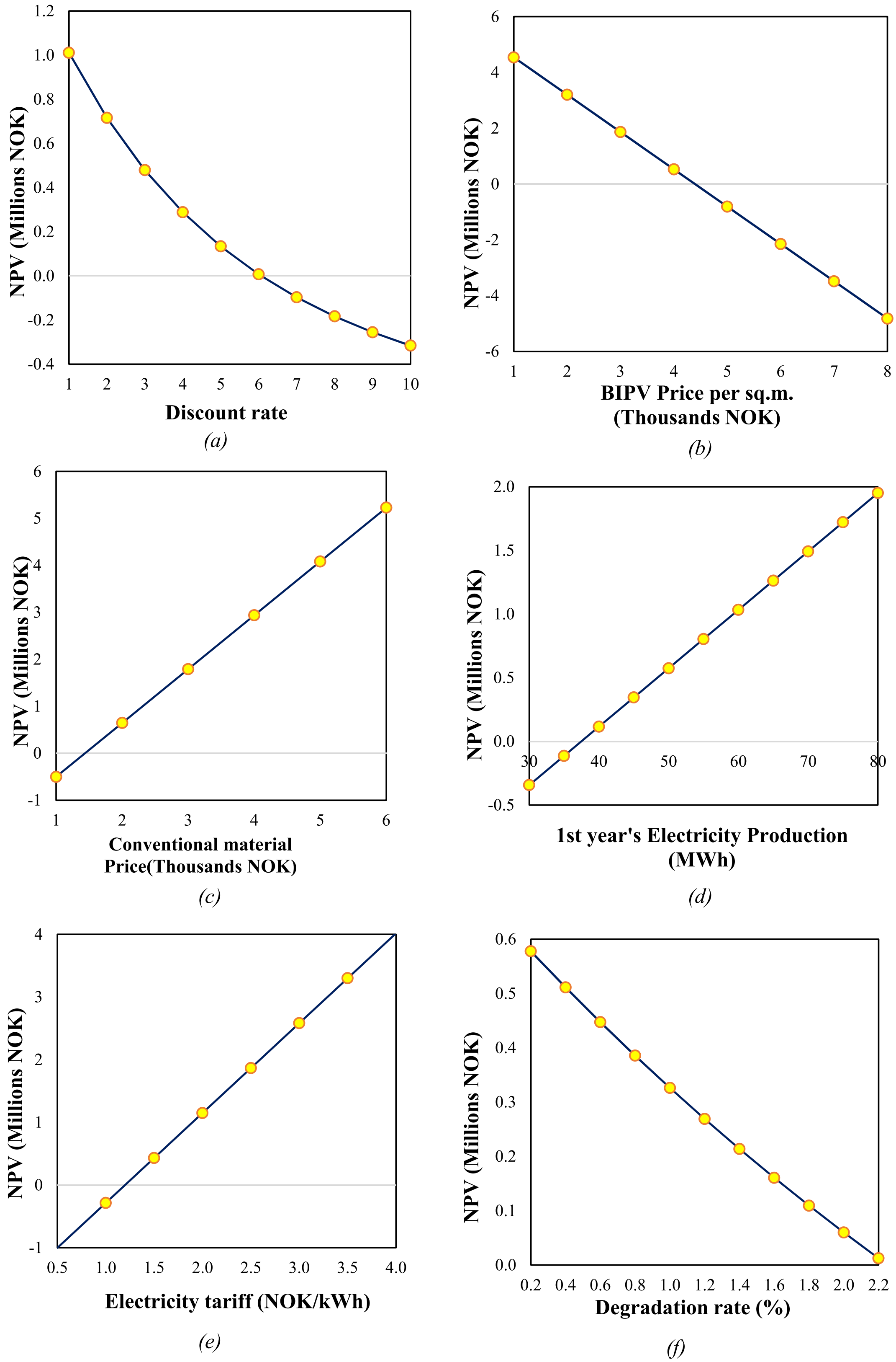

Fig. 14. Cumulative NPV of the BIPV under variation of different parameters: (a) discount rate; (b) BIPV price; (c) conventional material price; (d) BIPV Production; (e) electricity tariff; (f) degradation rate.

rate varies from 1% to 10%.

As can be predicted, the relationship between the BIPV price and cumulative NPV is a negative linear relationship. The cumulative NPV varies from minus 4.8 Million NOK to 4.5 Million NOK when the BIPV investment changes from 8 Million NOK to one Million NOK.

The relationship between the cumulative NPV and the conventional building envelope material price, BIPV electricity production and electricity tariff are all positive linear relationships with different growth rates. Finally, the relationship between the degradation rate and NPV is a nonlinear concave relationship.

From Fig. 14, it can be seen that by a D_R of 6%, the NPV will be equal to Zero and it can increase to one million NOK if D_R drops to 1%. Moreover, the NPV of the BIPV system is equal to zero, where BIPV system price is 4,486 NOK per sq.m. The NPV can vary between 4,540,042 NOK and −4,822,065 if the BIPV system varies from 1,000 NOK per sq.m. to 8,000 NMOK per sq.m. (with a slope of −1,337)

Furthermore, The NPV of the system rises from −500,896 NOK to 5,229,104 NOK if the conventional material prive moves from 1,000 NOK per sq.m. to 6,000 NOK per sq.m. (with a slope of + 1,146)

The slop for the system electricity production of the first year against NPV of the BIPV system is + 45,877. It means that if the system electricity production of the first-year increases from 30 MWh to 85 MWh, the cumulative NPV will grow from −34,3179 NOK to + 2,180,049 NOK.

As it is predictable, a minor change in the electricity tariff leads to a significant variation to the cumulative NPV of the system. By rising the electricity tariff from 0.5 NOK per kWh to 3 NOK per kWh, the NPV grows from −1,002,454 NOK to 2,582,706 with a slope of 1,000,000.

In terms of degradation rate, the NPV of the system drops from 577,719 NOK to 59,961 NOK if the degradation rate rises from 0.2% to 2%.

6. Conclusion

This paper dealt with LCCA of a 127.5 kW_P of BIPV façade system with the estimated annual production of 55.5 MWh/sq.m in Drammen, Norway that had received a subsidy from the government. The paper analysed the system's economic performance based on the monitored data after four years of operation and explained the effect of the subsidy on the LCCA of such a system.

The LCCA indices, including NPV, DPP, IRR and LCOE were computed. The provided output demonstrated that the case study system is economically feasible with a DPP of 22 years, IRR of 6%, cumulative NPV of 478,934 NOK and LCOE of 1.28 NOK/kWh. Furthermore, with an average annual solar irradiance on the system of 707 kWh/sq.m., the average annual electricity production of the system, based on the monitored data, is 40 kWh/sq.m.

The analysis also proved the importance of incentives for BIPV projects in Norway because of the lack of such FiT schemes today. It was perceived that the LCOE without Enova support would become more than the network electricity tariff (2.45 NOK/sq.m.)

A parametric analysis also done in this study showed the effect of various input parameters on the system's output, which was defined as the cumulative NPV of the BIPV system over the lifetime of the system. The examined input parameters were discount rate, BIPV price, conventional building envelope material price, BIPV electricity Production, electricity tariff and degradation rate.

This study can not only help end-users as well as architects to acknowledge a BIPV system as a suitable option for the building skins in Norway (as well as other Nordic countries), but also steer governments or decision-makers to promote the technology by rational subsidies and incentives as an alternative solution to the FiT approach.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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