Vertical perovskite solar cell envelope for the circular economy
A case study using life cycle cost analysis in Europe

Li, Qingxiang; Chen, Ziyue; Li, Xinwei; Brancart, Stijn; Overend, Mauro

DOI
10.1016/j.jclepro.2024.143017

Publication date
2024

Document Version
Final published version

Published in
Journal of Cleaner Production

Journal of Cleaner Production 467 (2024) 143017

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Vertical perovskite solar cell envelope for the circular economy: A case study using life cycle cost analysis in Europe

Qingxiang Li [a,b], Ziyue Chen [c,*], Xinwei Li [a,d], Stijn Brancart [b], Mauro Overend [b]

[a] Architecture, Built Environment and Construction Engineering Department, Politecnico di Milano, Milan, 20100, Italy
[b] Faculty of Architecture and Built Environment, TU Delft, Delft, 2628 BL, the Netherlands
[c] Department of Manufacturing and Civil Engineering, Norwegian University of Science and Technology, Gjøvik, 2815, Norway
[d] Department of Built Environment, Eindhoven University of Technology, Eindhoven, 5612 AZ, the Netherlands

ARTICLE INFO

Handling Editor: Mingzhou Jin

Keywords:
Life cycle cost analysis (LCCA)
Perovskite solar cell
Building integrated photovoltaic (BIPV)
Envelope
Circular economy

ABSTRACT

Recent technological developments make perovskite solar cells (PSCs) particularly suitable for building integrated photovoltaic (BIPV) applications on vertical building envelopes, but the relatively short lifespan of PSCs requires frequent replacement, thereby generating substantial waste. Careful consideration of circularity credentials of this novel technology is therefore essential prior to the extensive implementation of vertical PSCs in building envelopes. This paper provides a circular economy approach for the implementation of PSCs in vertical envelopes and assesses its economic feasibility by life cycle cost analysis in Europe. The process of recycling PSC is developed. The economic performance of PSC envelopes is provided and compared to that of the conventional rigid BIPV system. Uncertainty analysis and sensitivity analysis of economic indicators are then performed to identify the influential parameters. The findings indicate that the PSC envelope has a significant potential for circular BIPV components and that PSCs applied on vertical envelope are economically viable.

1. Introduction

Buildings account for 36% of greenhouse gas (GHG) emissions and 40% of primary energy use in Europe (REN21, 2019). The solar photovoltaic industry has produced several innovations in recent years, in particular for the development of building integrated photovoltaics (BIPV) (Balakumar et al., 2022). The European demand for BIPV is anticipated to grow rapidly in response to the goal of the European Union (EU) to boost renewable energy production from 10% to 27% and the EU Energy Performance of Buildings Directive (Economidou et al., 2020), which mandates all new buildings to be almost zero-energy buildings. Among various photovoltaic technologies, the vertical perovskite solar cell (PSC) envelope is a novel and promising form of BIPV.

Efforts to create a more sustainable built environment are also boosted by the transition from linear economy into circular economy (CE). Building components, and multi-material components such as BIPV, are expected to follow this trend (Hartwell et al., 2021; Van Stijn et al., 2021). The concept of CE for BIPV seeks to employ a judicious use of materials, preserving them at their optimum value for the longest possible duration. This is achieved by establishing a continuous cycle of utilizing, reusing, repairing, and recycling BIPV components. (Jansen et al., 2020). The PSC is an emerging technology which is also promising from a CE perspective because it uses only a small amount of materials and can be readily recycled (Mathur et al., 2020). The thickness of PSC can be 1 mm or less and a self-weight of around 1 kg per square meter. Compared to the conventional PV module which is normally 10 mm thick and 25 kg per square meter self-weight, PSC therefore provides a significant advance in material saving. Moreover, the recycling processes of PSCs have been initially proved both via layer-by-layer and one-step methods.

Meanwhile, the PSC is also regarded as an ideal next generation material for solar cells in vertical BIPV systems within high-density urban cities (Giuliano et al., 2021). Thus far, rooftop BIPV systems show the highest implementation rate in the existing projects, but vertical envelopes are the largest sun-harvesting areas (Chen et al., 2022). In fact, solar energy is a significant resource that falls on the envelopes of buildings in urban areas when the rooftop area makes up a limited portion of the overall building envelope (Verberne et al., 2014). Tall buildings have a large envelope-to-roof ratio which makes up for the fact that solar radiation intensity is lower on a vertical surface than it is on a horizontal one. As a result, annual total energy production on vertical

* Corresponding author.
E-mail address: ziyue.chen@ntnu.no (Z. Chen).

https://doi.org/10.1016/j.jclepro.2024.143017
Received 30 January 2024; Received in revised form 27 May 2024; Accepted 23 June 2024
Available online 25 June 2024

BIPV envelopes is likely to be higher. Most vertical building envelopes are currently not used for the

the production of power. The principal barrier is mainly the nature of PV modules. Currently, monocrystalline and polycrystalline silicon, which constitute the majority of BIPV modules (Biyik et al., 2017), are bulky due to the heavy frame and glass facesheet. The risk of detachment of vertical PV panels in windy conditions poses a significant safety concern when used in high-rise buildings, representing a critical flaw that warrants investigation and further attention (Osorio-Aravena et al., 2021). Furthermore, the power conversion efficiency (PCE) decreases significantly under shadow conditions, resulting in low energy production (Shukla et al., 2018). These shortcomings hinder the adoption of BIPV systems applied on the vertical building envelopes.

The PSC largely addresses these issues and its desirable properties make it attractive for future use of vertical BIPV envelope (Bing et al., 2022). Firstly, PSC panels are lightweight, thereby making it easier to mount by boding them directly to the envelope without the need for additional substructure. In addition, PSC panels regulate color, thereby offering a wide variety of aesthetic options (Chen et al., 2021). Additionally, PSCs perform better at power conversion under diffuse and low-intensity light than they do under the normal air mass 1.5 global spectrum (Zhu and Li, 2020). They are also preferred to silicon solar cells for vertical envelopes in densely populated cities since they outperform the silicon counterparts in low light and diffuse light conditions (Zhu et al., 2019, 2020). However, to investigate PSC's potential for the vertical BIPV envelope, it is first essential to investigate the economic feasibility.

Lifecycle cost analysis (LCCA) represents a comprehensive approach in evaluating the anticipated total incremental cost associated with the creation, manufacturing, utilization, and eventual retirement of a particular item over its lifecycle (Fuller, 2010). With the development of recycling technology, calculation methods were provided to calculate LCCA from CE perspective (Jansen et al., 2020). Gholami, Hassan et al. (2020) analyzed the economic viability of silicon PV panels on vertical BIPV envelopes in Norway using case studies of commercial buildings. Weerasinghe et al. (2021) evaluated the financial benefit of 45 BIPV systems in different countries. The research highlighted the BIPVs' building envelope functions. A BIPV system is an inherent part of the building's exterior materials that transforms solar energy to electricity. BIPV is applied to change building envelope materials. The initial cost was compensated by a reduction of building material cost and labor cost while replacing the BIPV systems. Aste et al. (2016) undertook an assessment on a university BIPV project, which has been in operation over 13 years, and showed that there was no substantial performance reduction with time. It is therefore necessary to evaluate the economic sustainability of the vertical PSC envelope taking into consideration CE in order to guide decision-makers.

While numerous device architectures have been proposed for PSCs, with some demonstrating impressive PCEs in laboratory settings, there remains a critical gap in the literature regarding the feasibility of scaling these technologies for industrial-level production. As such, this study has chosen to focus on the most prevalent PSC architecture approaching commercialization. In particular this paper aims at establishing the economic viability of vertical PSC envelope from the perspective of CE by LCCA methodology. The results are compared to the economic performance of current silicon BIPV systems. The paper consists of an investigation of the circularity of perovskite solar cell, in Section 2; followed by, we provide a description of a vertical BIPV project with conventional silicon PV panels as a benchmark case study in this study, in Section 3, which introduces the current BIPV system and the design of PSC envelope; Section 4 presents the LCCA methodology with the input parameters and economic indicators as well as detailed recycling process of PSC with the benefits and costs. Economic results with uncertainty and sensitivity analysis are shown in Section 5; Ending with the implications and limitations in Section 6.

2. Circular vertical perovskite solar cell envelope

The application of PSCs in BIPV projects has attracted a great deal of research and development over the past decade due to their lightweight, colorful appearance, and advantageous power conversion efficiency (PCE) under low-intensity conditions, shown in Fig. 1.

2.1. Architecture of perovskite solar cell

The PSC architecture is ETFE/PET/ITO/Perovskite/Spiro-OMeTAD/silver/ETFE, shown in Fig. 2 (Chang et al., 2020). Notably, other PSC technologies could be considered, but given the study target of evaluating a reliable circularity strategy, this study focuses on this cell structure which is able to be recycled by existing technology.

2.2. Advantage of perovskite solar cell for vertical envelope

PSC panels weigh approximately 500 g/m^2, which is over 40 times lighter than silicon panels. PSC panels can be attached to the existing building envelopes and structures that would otherwise be oversized to bear the self-weight of conventional silicon solar panels. PSCs are also significantly thinner than silicon solar cells, resulting in material savings that are beneficial to the environment.

Colorful PSCs, which are regarded as an attractive energy-efficient technology, are being implemented in BIPV. By adjusting the thickness, porosity, and composition of perovskite layer, it is possible to adjust the color of PSCs, and hence the bandgap. Due to their aesthetic value-adding potential, this trait is particularly desirable for BIPVs.

PSCs generate higher PCE in low-intensity light environment as an attractive option for vertical envelopes. Vertical BIPV envelopes, although not inherently aligned with the sun, but rather installed vertically, benefit from PSCs exhibiting minimal angle dependence. The advantageous feature includes the ability to operate effectively in low-intensity light environments.

2.3. Circularity of perovskite solar cell

Applying CE principles to building components can make the built environment more circular. The PSC panels directly bonded to the vertical envelope promotes recycling because the substructure material required for silicon PV cells is no longer required, thereby reducing the different types of materials used in the multi-material composite. A low cost and environmentally friendly recycling process is provided by material group of TU Delft (TUD, 2023) consists of the following steps.

Step 1

The ETFE foil is peeled off mechanically.

Step 2

The silver front electrode is delaminated by ethyl acetate, then the silver can be separated through filtration. The substrate is extracted from the solution and dried under a stream of nitrogen.

Step 3

Perovskite material is reconverted into PbI_2 and MAI by a short immersion in double-distilled water, and the MAI is subsequently removed from the water. Then, the materials are dried under a nitrogen stream thereafter. The substrate is placed on a 100 °C hotplate for 10 min to evaporate any remaining water. PbI_2 is isolated from the substrate by briefly immersing the sample in DMF.

Step 4

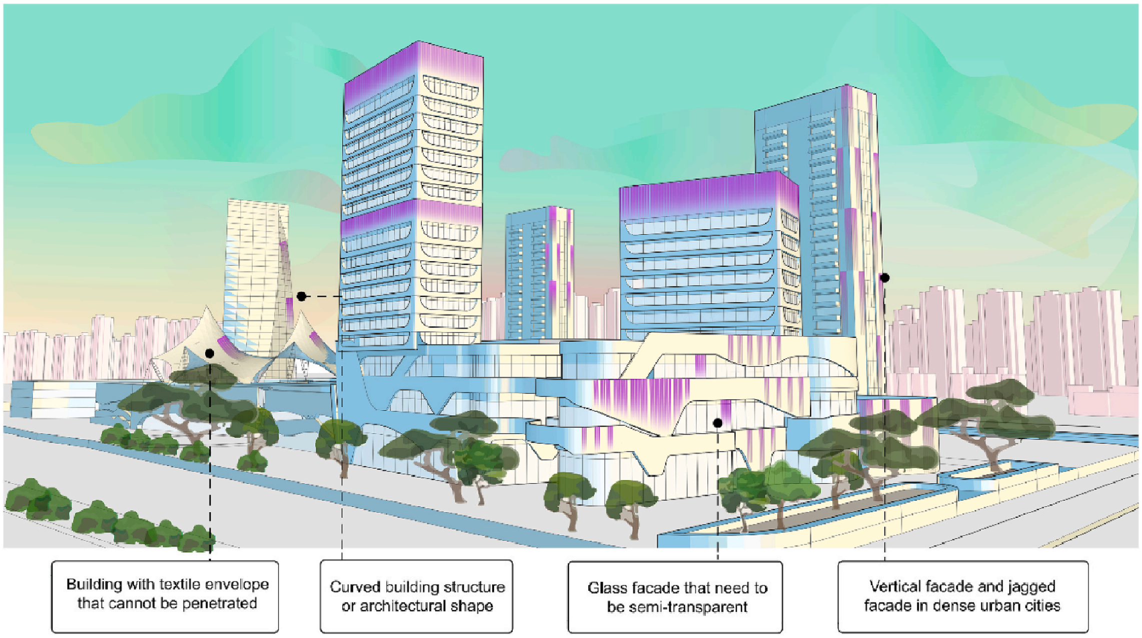

Fig. 1. Renderings of the PSC envelope.

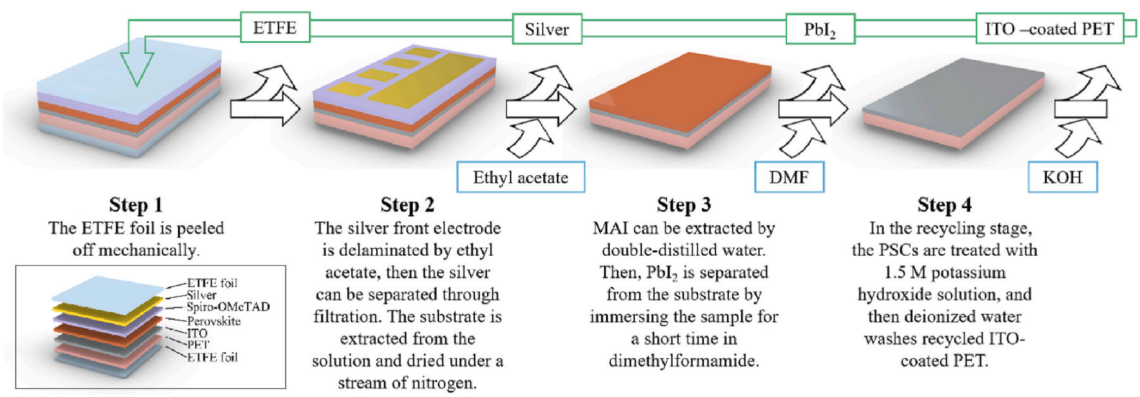

Fig. 2. Recycling process of perovskite solar cell.

The samples are treated with 1.5 M potassium hydroxide (KOH) solution, and then deionized water washes recycled ITO-coated PET.

3. Case study description

Solsmaragden Office is a seven-story office building situated in the pier district of the Norwegian city of Drammen (59.74° N, 10.19° E). The BIPV system was integrated into the building envelope as a result of enterprise and contractor collaboration. Collaboration between the owner, the design company and the PV supplier resulted in the module design and mounting mechanism. Enova, a government corporation tasked with promoting renewable energy generation, will provide a subsidy of 1,553,236 NOK for this BIPV system.

The current vertical BIPV system were custom-made. For the majority of the building envelopes in this project, they have been combined with glass cladding. The envelope modules are composed of three distinct layers. The first layer consists of 4 mm glass face sheet. The subsequent layer consists of conventional 6-inch monocrystalline silicon solar cells. The rear layer is a 4 mm thick glass sheet. The layers are bonded together with EVA in the lamination process. The choice of material and installation method conforms to safety criteria for glazing envelopes, ensuring that PV systems will not fall out. The BIPV envelope weight is 20.5 kg/m^2 and has a total surface area of 1146 m^2.

The BIPV modules have an efficiency of 16.6%. The entire (1146 m^2) BIPV envelope is comprised of 1011 panels with a maximum power output of 127.5 kWp. The BIPV modules required various shapes and sizes of PV panels ranging from 55 Wp to 170 Wp of varying wattages. Ten SMA inverters are connected by BIPV strings. The cost details of the BIPV project are shown in Table 1.

This study considers an alternative scenario where a vertical perovskite solar cell envelope is used instead of the current vertical envelope with rigid silicon PV system (Fig. 3). In laboratory-scale manufacturing, the PCE of flexible PSCs achieved a maximum of 25.7% (Kumar and

Table 1
Current BIPV envelope and PSC envelope estimated cost breakdown.

	Current monocrystalline silicon BIPV envelope (NOK)	PSC envelope (NOK)
BIPV envelope	2767590	1275164
Mounting system	435480	0
Mounting labor	665826	133165
Elect. job and equipment	461838	461838
Lift	184506	36901
Other costs	110554	110554

Fig. 3. Solsmaragden building skin with the PSC envelope.

Naidu, 2021). In this study, the PCE of PSCs is set 15%. And the effective area of the solar cell is 0.7. Additionally, the lifespan is uncertain because the product has not yet been tested in real-world scenarios. So, the lifespan is set to 5 years, 10 years, and 15 years to establish the influence of lifespan on the economic feasibility. Since there are currently no commercial PSC panels on the market, the cost of PSCs is based on the selling price forecast from literature (NREL, 2022). Existing research (Mathews et al., 2020) shows that a small-scale factory (1–10 MW/year) is required to maintain a minimum Average Selling Price of 1.5–3 dollars per watt ($/W) for their products. Larger factories are mandated to sell at a minimum rate of 1 $/W, and the most substantial model (1 GW/year) is expected to sell for no less than 0.72 $/W. Therefore, for the purposes of this study, the PSC is assumed to be produced in large-scale factory locally and purchasing price is set as 1 $/W (10.6 NOK, the exchange rate is 1 dollar equal to 10.6 NOK). Through its integrated backside adhesive, the PSC films can easily be glued to vertical envelope surfaces. This study assumes that a suitable adhesive could be potentially found through adequate testing including accelerated ageing tests. Therefore, the mounting system cost can be saved. Also, Heliatek company reported that the labor-hour for mounting solar films by adhesive is only one fifth of that for traditional rigid PV panels (Heliatek). So, the labor cost is set as one fifth of the current silicon BIPV project. Moreover, the lift cost of two projects has a big difference. The PSCs are really lightweight, which is able to greatly reduce a workload of lift. For the electricity job and equipment and other costs, it is assumed that the two projects have the same spence. The estimated cost is collected and shown in Table 1.

4. Methodology

This section describes the LCCA methodology used in this study. The assessment is performed considering 30-year lifespan of the BIPV system. The LCCA indicators includes net present value (NPV), Levelized Cost of Energy (LCOE), discounted payback period (DPP), and internal rate of return (IRR). The methodology is depicted in Fig. 4 for clarity.

4.1. Input parameters

This input parameters involved in this LCCA study, are described below.

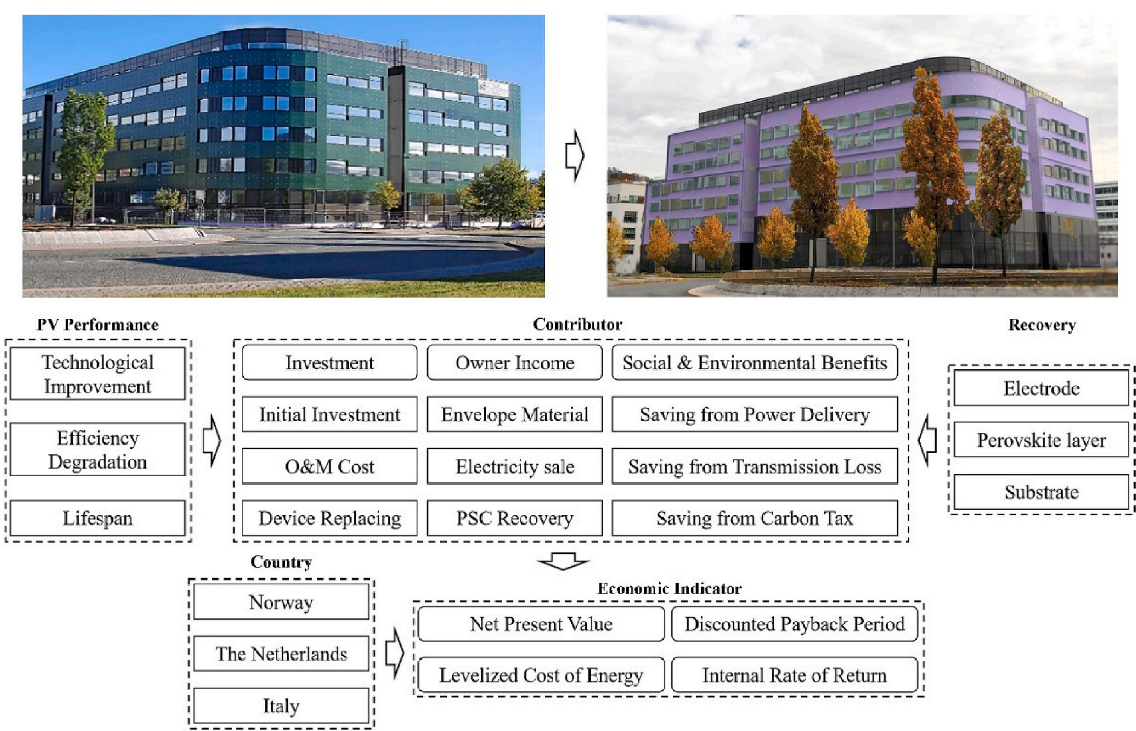

Fig. 4. The methodology for LCCA of the PSC envelope.

4.1.1. Initial investment

Initial investments consist of the costs of the BIPV project. The cost of PV panels and inverters are considered. The installation, labor, administrative, transportation, and purchasing expenses are also considered.

4.1.2. Operation and maintenance (O&M) costs

O&M expenses are incurred during the operational phase of a project's lifecycle. The expected annual O&M expense is 0.5% of the initial investment (D'Adamo et al., 2020).

4.1.3. Inverter replacement cost

Throughout the course of a project, replacing inverter is a substantial spence. The study set 10% of the initial cost for replacing inverters. Furthermore it is assumed that that the cost of the inverters remained constant for successive replacements, and inverters were replaced every 15 years (Han et al., 2022; Jean et al., 2019). Therefore throughout the lifecycle, a single inverter was replaced.

4.1.4. Solar cell replacement cost

The lifespan of PSCs cannot cover the whole period of the BIPV project. This study considers different lifespans (5 years, 10 years, and 15 years) (Jean et al., 2019). So, the PSC panels need to be replaced 5 times, twice, and once, respectively.

4.1.5. Solar cell degradation

Regardless of the specific external environmental conditions solar cells naturally degrade over time. The PV degradation rate varies according to the materials used in the solar cell: 0.5% per year is used for the silicon solar cells (Lindroos et al., 2016); 1.0% per year is used for the PSCs (Dunfield et al., 2020).

$$PCE_m = PCE * (1 - \alpha)^{m-1} \tag{1}$$

where α stands for the degradation rate of the solar cell. m stands for the number of years the solar cell has been in use.

4.1.6. PCE improvement

The PCE of PSC technology rapidly improved from 3.8% to 25.7% in the recent ten years. In this study it is assumed that the year-on-year improvements will continue at a rate of 1.5% per year. Therefore with a starting PCE of 15% assumed in this study, the PCE is expected to increase to 23.4% after 30 years.

4.1.7. Building envelope material cost

In this study, the BIPV system is an alternative for an envelope with an average price of 1855 NOK (181.9 €) (1 € equal to 10.2 NOK in 04/11/2022) per square meter (Gholami, H. et al., 2020). This amount will therefore be subtracted from the overall BIPV investment.

4.1.8. Transmission line lost power

For a BIPV project, the power generation is used to support the energy demand of the building itself, thereby eliminating transmission line losses. From World Bank data, the transmission loss of electrical power in Norway is 6% (World-Bank, 2018).

4.1.9. Power delivery cost

A BIPV system can significantly decrease the capital expenditures necessary to maintain the electricity distribution infrastructure. The electricity delivery cost includes expenditures for device that distributes power at lower voltages and transmission fees among other things. In contrast to BIPV systems, the electricity grid may need the expansion of network infrastructure. The power generation from a BIPV project reduces distribution costs by approximately 20% of the entire power price (Gholami et al., 2019).

4.1.10. Social cost of carbon

The social cost of carbon (SCC) is the overall amount of damage resulting from GHG emissions. Norway has begun to increase taxes on carbon emissions, which is known as carbon tax. The carbon tax in Norway is 500 NOK per tonne of CO_2 (48.9 €) (this cost will most likely increase over time) (World-Bank, 2019). A growth rate of 3.5% has been established for the present carbon tax (IMF, 2009).

4.1.11. GHG emission

The emission of GHG from the generation of electricity is related to the energy source. In this analysis, the average GHG emission rate of 134 g/kWh with a drop rate of 4.2% in 2016 is modified and utilized (NVE, Norwegian Water Resources and Energy Directorate, 2019).

4.1.12. Electricity tariff and its growth rate

The electricity tariff is set as 1.533 NOK (0.150 €) and the annual growth rate of electricity is 3.5% (Gholami, H. et al., 2020).

4.1.13. Discount rate

The discount rate means the interest rate a bank charges on its loans. The discount rate applied to this study is 3%, which is an average value calculated from the discount rates over 20 years (Gotzens et al., 2018).

4.1.14. Recycling benefit

Cost analyses for the various types of solar cells show that the ITO-PET is a primary factor on the module cost. In this study, the cost estimation (Table 2) also presents the ITO-PET is the largest contributor for perovskite solar cells. Spiro-OMeTAD is also an important cost factor, however, recent research shows that several low-cost materials have the potential to replace the current Spiro-OMeTAD. Therefore, recycling Spiro-OMeTAD is less critical. The perovskite layer containing PbI_2 and MAI contributes only a small part to the whole cost of the PSC. So, the recycling of the perovskite layer is more important for environmental rather than economic reasons due to the toxicity of PbI_2 but the economic benefits are negligible. The recycled efficiency is set as 70% (Le Khac et al., 2024). Furthermore, the contribution of silver electrodes is also small because of the low amount of silver per square meter. The cost of input materials for the recycling is shown in Table 3.

According to the indicators described above, the input parameters for the LCCA study are shown in Table 4.

4.2. Economic indicators

Four main economic indicators of LCCA are introduced to evaluate the feasibility of the PSC envelope, namely: NPV, LCOE, IRR, and DPP. Their calculation methods are shown in this section.

4.2.1. Net present value

NPV is a basic economic measure used to calculate the net economic benefits of a project over its lifetime. It is determined as the discrepancy between the present value of the project's benefits and its costs. To compare numerous projects, this study computes NPV of the systems. The proposed calculation is shown in Equation:

$$NPV = \sum_{1}^{n} (C_I - C_O)(1 + D_R)^n \tag{2}$$

Table 2
The benefits of materials recycled from the PSC.

	Price (NOK/m^2)	Source
ITO-coated PET	293.6	Mianyang Prochema Commercial Co., Ltd.
Perovskite	10.6	Binek et al. (2016)
Ag electrodes	5.7	Machui et al. (2014)
ETFE foil	179.1	Machui et al. (2014)

Table 3
Cost of input materials for the recycling.

	Price for 10 MW	Amount ($/m^2$)	Price (NOK/ m^2)	Source
Ethyl acetate	160.2 NOK/L	0.02 L	2.6	Sigma-Aldrich
DMF	106 NOK/kg	2.9 g	0.3	Sigma-Aldrich
1.5M KOH	36.1 NOK/L	0.03 L	1.3	Sigma-Aldrich

Table 4
Parameters of the BIPV project for economic analysis.

Parameter	Value	Unit	Geometric standard deviation
Site	Norway		
PSC price	10.6	NOK/W	1.15
PCE	15%		1.15
O&M cost	0.5%		1.05
Equivalent envelope cost	1855	NOK/m^2	1.05
Equivalent envelope area	1146	m^2	
Inverter replacement cost	10%		1.05
Transmission line lost power	6%		1.05
Power delivery cost	20%		1.05
Carbon tax	500	NOK/t	1.05
growth rate of the carbon tax	3.5%		1.1
average carbon intensity of electricity generation	134	g CO_2/ kWh	1.05
carbon intensity reduction rate	4.2%		1.1
Electricity tariff	1.533	NOK/ kWh	1.15
Electricity tariff inflation rate	3.5%		1.2
Discount rate	3%		1.1
Solar insolation	911	kWh/m^2/ year	32.3

where C_I and C_O represent cash inflows and cash outflows. D_R and n stand for discount rate and BIPV lifespan.

A positive NPV indicates an economically advantageous project because the complete cost may be paid back within the project's lifetime. Negative NPV is financially infeasible since the investment cannot be recouped from the revenue earned throughout the lifetime.

Two types of NPV are applied: Standard NPV, which accounts for the investment and benefits to stakeholders, reflecting the profits for building owners derived from the BIPV system; and Integrated NPV, which considers benefits from a holistic societal perspective. The two kinds of NPV apply same parameters (discount rate, PSC price, replacement, etc.) for the calculation. But the integrated NPV also involves the transmission line lost power, power delivery cost, and social cost of carbon. Therefore, the cash inflow of the standard NPV is defined as

$$C_{I-S} = I_1 + I_2 + I_3 \tag{3}$$

where I_1 represents envelope material; I_2 represents electricity sale; I_3 represents PSC recovery. For the integrated NPV, the cash inflow is defined as:

$$C_{I-I} = I_1 + I_2 + I_3 + S_1 + S_2 + S_3 \tag{4}$$

where S_1 represents saving from power delivery; S_2 represents saving from transmission loss; S_3 represents saving from carbon tax. For the two kinds of NPV, the calculation of cash outflow is same, as follows:

$$C_O = O_1 + O_2 + O_3 \tag{5}$$

where O_1 represents initial investments; O_2 represents O&M expense; O_3 represents device replacement.

The latter metric provides insights into the benefits of BIPV from the standpoint of a broader administrative area, such as a city, region, or nation. Notably, for one project, it is plausible for its standard NPV to be negative while its integrated NPV is positive. This implies that although the building owner may not experience economic gain, the project is advantageous for the broader society. In such instances, the BIPV system could potentially benefit from subsidies provided by the local or national government.

4.2.2. Levelized cost of energy

LCOE is a financial indicator connected with lifecycle costs and is a basic economic evaluation approach for renewable energy applications. LCOE is the ratio of the cost per unit of energy produced across the whole lifecycle of energy production (kWh). Equation for LCOE calculation is shown as follows:

$$LCOE = \frac{Lifecycle\ cost}{E_g} \tag{6}$$

where E_g represents all the power generation. LCOE is typically compared to the national price of electricity. A LCOE that is less than the price of electricity indicates that the cost of energy generation in the BIPV system is below the national average, which is favorable.

4.2.3. Discounted payback period

DPP denotes the duration necessary to recoup an investment. This calculation involves deducting the initial investment from the annual savings, with consideration for the time value of money. Short payback periods are preferred by investors. The DPP (Q) is calculated from:

$$Q_{DPP} = \sum\nolimits_I^n (C_{Ii} - C_{Oi})(1 + D_R)^{-n} \tag{7}$$

where C_{Ii} and C_{Oi} represent the cash inflow and the cash outflow in the i year.

4.2.4. Internal rate of return

IRR is a metric utilized in financial analysis to assess the profitability of potential investments. IRR represents the discount rate that, in a discounted cash flow analysis, results in the NPV of all cash flows being equal to zero.

$$Q_{IRR} = \sum\nolimits_I^n (C_{Ii} - C_{Oi})(1 + IRR)^{-n} \tag{8}$$

4.3. Uncertainty analysis and sensitivity analysis

In order to assess the feasibility of PSC envelope in different European regions, this study investigates and compares the economic performance of PSC envelopes in the same BIPV project in Norway, the Netherlands, and Italy. They represent northern Europe, western Europe, and southern Europe, respectively. The cities Oslo, Amsterdam, and Milan were selected as the study areas, representing three of the different climatic zones in Europe: Warm-summer humid continental climate; Temperate oceanic climate and; Humid subtropical climate, respectively. The geographic coordinates of these cities are listed in Table 5. To a certain extent, the economic performance of the PSC envelope in the three countries is able to extend to the whole European countries. The system boundary for this evaluation was the geographical boundaries of each city under this study. Therefore, all the PSC

Table 5
locations of three case cities (Zhang et al., 2021).

	Oslo, Norway	Amsterdam, the Netherlands	Milan, Italy
Location in Europe	Northern Europe	Western Europe	Southern Europe
Coordinates	59.91° N, 10.75° E	52.36° N, 4.90° E	45.46° N, 9.19° E

manufacture activities are assumed to be performed within each country. In this study, it was not possible to calculate differences in the solar cell costs in Italy, Netherlands, and Norway, and thus the same cost is assumed for all locations (Martinopoulos, 2020). In order to simulate the most likely implementation PSC technology in the near future, it is assumed that PSC factories will extend to the largest manufacturing scale, making the price of PCS 0.73 €, and the lifespan is set 5 years. All labor costs, other than solar cell price, need to be calculated according to the local labor cost. Here, we consider Norway as the baseline and we apply the relevant labor cost index for Italy and the Netherlands. Moreover, the price level index from the Organization for Economic Co-operation and Development is also applied to calculate the equivalent envelope material price. Their parameters for the LCCA study are shown in Table 6.

There are several sources of inherent uncertainty which are considered in this study, Firstly, the accuracy of economic assessment is entirely dependent on the input parameters, yet their reliability is unknown. Secondly, solar cell technologies are not sufficiently established and have not yet achieved industrial manufacture, there must be fluctuations in terms of electricity output (Gong et al., 2015). Thirdly, it is extremely difficult to obtain precise data for the predicted lifespans and PCE of PSCs based on past research. Fourthly, the solar insolation, power rates, discount rates, etc. are also subject to future uncertainty. Consequently, this study applies the probability distribution to the parameters based on the findings of prior research (Long et al., 2023; Yuan et al., 2023a, 2023b). In addition, Oracle Crystal Ball is used to calculate the extent to which these uncertain parameters can impact economic outcomes. Except for insolation which follows a normal distribution., all other parameter distributions follow the lognormal distribution. This study establishes 500000 trials. In addition, sensitivity analyses are performed on the simulation data to determine the influence of input factors on the LCCA outcomes.

5. Results and discussion

This section shows the economic performance of the PSC envelope to establish its economic feasibility. The results are also compared to the economic performance of the current silicon PV envelope. This is followed by an assessment of the economic feasibility in different European countries.

5.1. Electricity generation

The power production results of PSC envelope and current BIPV envelope are shown in Fig. 5. The power generation is calculated by the following equation:

$$P = G * PCE * A * \eta * \omega \tag{9}$$

where P is annual power generation of the BIPV system. G is annual received solar radiation in unit area. A is the area of the PV modules. η is rate of effective area. ω is operation efficiency of the BIPV system.

PSC envelopes with 5-year, 10-year, and 15-year lifespan are compared here. This analysis shows the yield potential of PSCs on vertical envelope. From the results, it can be seen that with up to 1615.3 MWh, the PSC5 envelope has the highest power production among the four BIPV systems. Next is the PSC10 envelope with 1517.1 MWh electricity generation, followed by the PSC15 envelope with 1424.5 MWh. The current monocrystalline silicon BIPV system produces the lowest electricity amount among 4 systems. Therefore, results show that the PSC envelope presents a favorable performance in energy production compared to the traditional BIPV system. In addition, as expected, a step-change in annual power production is seen after solar cell replacement. Therefore, the results show that the more frequent PSC panels are replaced, the more electricity can be produced. This is due to the technology improvement of PSC in the intervening periods. It can be seen that replacement.

5.2. Life cycle cost analysis

The standard NPV results are shown in Fig. 6. The NPV of property owner only considers the investment and stakeholder income. The results indicate that the NPVs of PSC envelopes are positive. This is because the equivalent building envelope material cost covers the initial investment of the PSC envelope. In addition, only the PSC15 envelope and the PSC10 envelope can achieve positive NPVs, which means the property owner is able to gain profits from the BIPV project. The NPV of the PSC15 envelope reaches 1.25M NOK and the NPV of the PSC10 envelope is 0.56M NOK. Additionally, the NPV of the PSC5 envelope (−1.81M NOK) is slightly higher than that of current BIPV system.

The integrated NPV results of 4 BIPV systems are shown in Fig. 7. The integrated NPV accounts for initial investment, stakeholder's income, and social and environmental benefits. The subsidies are not considered here. The trend of integrated NPV results is similar with standard NPV results. The results show that, at up to 1.89M NOK, the PSC15 envelope has the highest NPV among the 4 systems. Then, NPV of PSC10 envelope is also positive, with the total value of 1.25M NOK. This indicates that these two PSC envelopes could reimburse the whole investment from the whole society perspective without any subsidies. In contrast, the PSC5 envelope and current BIPV system do not yield positive NPVs. The cumulative NPV of PSC5 envelope and current BIPV systems are both around 1.07M NOK. As expected the NPVs fall significantly after solar cell replacement, due to high cost of PSC panels. The negative NPV of the PSC5 envelope is due to the five replacements required over the 30-year horizon. The electricity generation of the PSC5 is in fact the highest among four BIPV systems, but the additional electricity produced from this option is insufficient to payback the investment of replacement. So, without the subsidies from government, PSC5 does not generate the profits, either from stakeholder perspective or society perspective.

Fig. 8 shows the cash flow of BIPV projects in the 30-year horizon. The results show that the cash flow of the BIPV projects increases for the whole 30-year horizon except the year when replacing solar cells and inverters happened. The cash flow of PSC envelope is always higher than the current BIPV systems. After replacing of solar cells, the cash flow increases as expected, because the PCE of solar cells is improved leading to the increase of electricity generation.

The recycling of the PSC envelope is investigated in view of the need for circular BIPV components. The NPV results of the PSC envelope without recycling benefits and with recycling benefits are therefore compared and shown in Fig. 9. It is evident that the recycling of PSC materials will improve the economic benefits for the property owner. And it can be seen that the NPV benefits increase with the frequency of PSC module replacement. Notably, integrated NPV of PSC5 considered recycling benefits becomes positive, from −1070885 NOK to 295951 NOK. This means that for circular PSC envelopes it is feasible for the government to provide subsidies for PSC envelopes, even if the lifespan

Table 6
Parameters of the BIPV projects in different countries (Gholami and Rostvik, 2020).

Parameter	NO	NLD	IT	Unit
PSC price	0.73	0.73	0.73	€
Labor cost index	152.89	115.9	108.8	
O&M cost	0.5%	0.5%	0.5%	
Price level index	130	105	89	
Inverter replacement cost	10%	10%	10%	
Transmission line lost power	6%	5%	7%	
Power delivery cost	20%	20%	20%	
Carbon tax	48.9	0	0	€/t
Electricity tariff	0.150	0.171	0.216	€/kWh
Electricity tariff inflation rate	3.5%	3.8%	4.3%	
Discount rate	3.0%	2.5%	3.0%	
Solar insolation	911	1065	1127	kWh/m^2/year

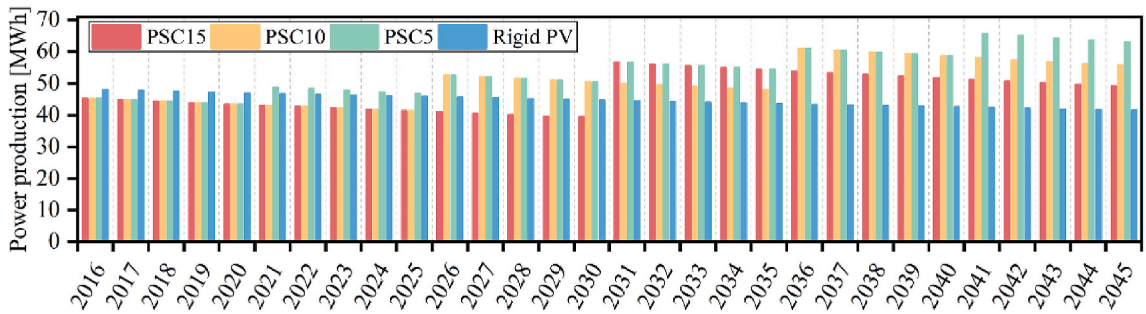

Fig. 5. Power production of four BIPV systems. PSC15 stands for BIPV envelope with 15-year lifespan PSC; PSC10 stands for BIPV envelope with 10-year lifespan PSC; PSC5 stands for BIPV envelope with 5-year lifespan PSC; Rigid PV stands for the traditional monocrystalline silicon BIPV with 30-year lifespan.

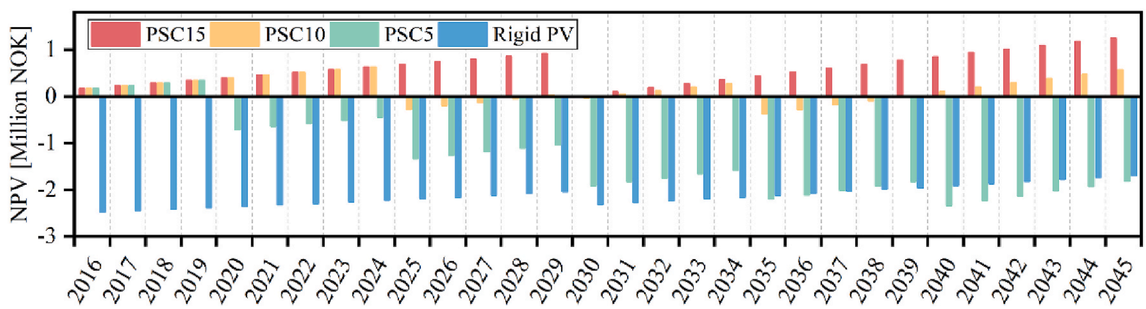

Fig. 6. Standard NPV of property's owner, contributed by investment and stakeholder's income, without social and environmental benefits, subsidies, and recycling benefits.

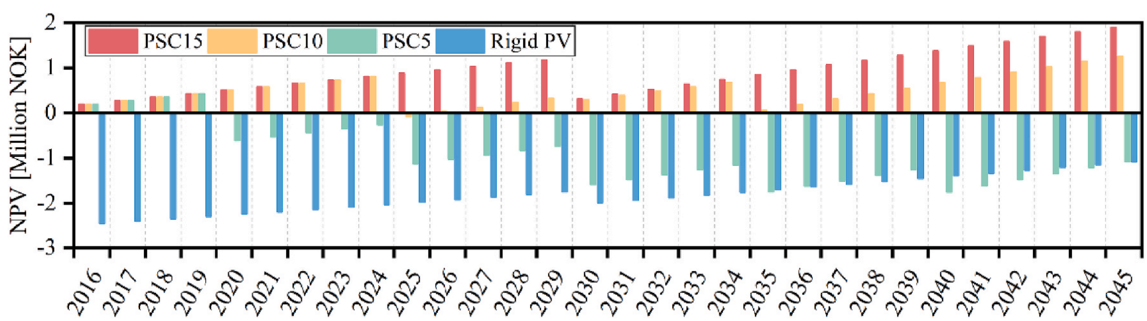

Fig. 7. Integrated NPV, contributed by investment, stakeholder's income, and social and environmental benefits, without subsidies and recycling benefits.

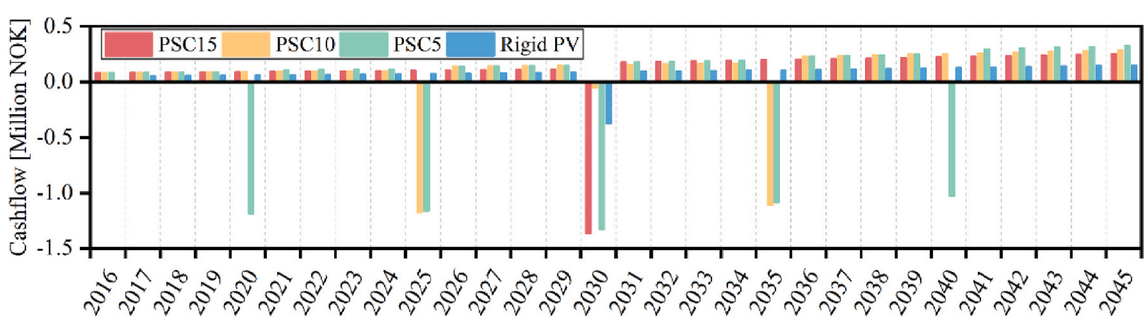

Fig. 8. The cash flow of BIPV systems.

of PSC is relatively short (5 years). For the PSC10 and PSC15, all NPVs are positive and recycling will generate additional economic gains.

The absolute NPV of different contributors is shown in the Fig. 10. The results show that the electricity sale income the is the largest contributor to the NPV consequently governing the earnings from the project. For the social and environmental benefits, the saving in power delivery cost and transmission loss show the same proportional relationship between BIPV systems as the electricity sale income because they are calculated based on the electricity generation. Furthermore, the saving in carbon taxing is so low compared to other items, that it can be neglected. For the investment, it can be seen the initial investment of current BIPV system is remarkably higher than that of PSC envelope. The

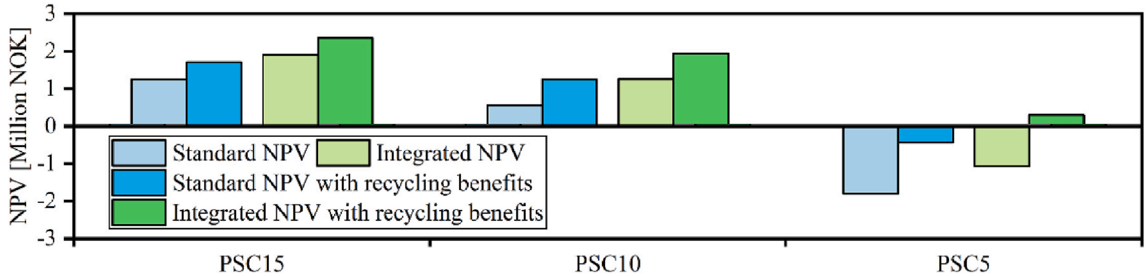

Fig. 9. Comparison of NPV without recycling benefits and with recycling benefits.

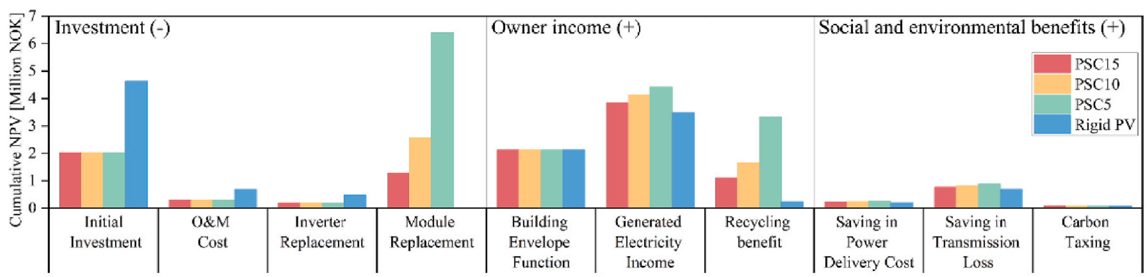

Fig. 10. The absolute cumulative NPV of different items in each BIPV project.

initial investment of current BIPV system is 4.63M NOK, which is more than twice that of PSC envelopes (2.02M NOK). The reason for the low initial cost of PSC envelope is the low cost of PSC panels, the saving in mounting system, and the saving in mounting labor. It can be concluded that PSC envelope has a significant cost advantage over the current BIPV system at the initial stage, thereby easing the funding pressure, which is attractive for property owners with limited initial funding. A high capital up-front investment is in fact one of the principal barriers for the uptake of BIPV systems (Arnold et al., 2022). For the cost of solar cell replacement, the current BIPV system does incur costs of solar cell replacement because the lifespan of silicon solar cell exceeds the period of the project horizon. In contrast, the PSC panels require replacement during the project horizon due to their short lifespans. The costs of PSC5 panels, PSC10 panels, and PSC15 panels in the BIPV project account for 88%, 80%, and 74% of the whole investment, respectively. They are significantly higher than the share of rigid Monocrystalline silicon PV panels in the entire investment (60%). As for recycling benefits, it is obvious that the potential recycling value of the PSC envelope is far higher than that of the current BIPV system. The recycling benefit of the current BIPV system is only 0.24M NOK, which is significantly lower than that of PSC envelopes. The recycling benefits of PSC15, PSC10, and PSC5 are 1.11M NOK. 1.66M NOK, and 3.32M NOK, respectively, which remarkably shows a large potential for developing PSC BIPV components for the circular economy. In addition, O&M and inverter replacement costs are both calculated by initial investment. Therefore, they show the same proportional relationship between each BIPV system.

With respect to the entire investment, PSC10 envelope (3.67M NOK) and PSC15 envelope (2.84M NOK) invest less than the current BIPV system (4.63M NOK), as shown in Table 7. But the whole investment of PSC5 envelope reaches 6.20M NOK, which is far higher than the other BIPV systems. As for the LCOE, PSC10 envelope and PSC15 envelope present 1.99 NOK/kWh and 2.42 NOK/kWh, respectively. They are both lower than the LCOE of current BIPV system (2.45 NOK/kWh) and the average electricity tariff (2.64 NOK/kWh). For DPP, PSC10 and PSC15 invest less than the normal building envelope, therefore, their DPP is 0. In contrast, the PSC5 envelope cannot pay back the investment.

Table 7
Economic results of the PSC envelope in Norway.

	Total investment (NOK)	LCOE (NOK/kWh)	DPP (year)	IRR
PSC15	2836101	1.99	0	0%
PSC10	3672491	2.42	0	0%
PSC5	6199963	3.84	NA	34.9%
Rigid PV	4625794	2.45	NA	0%

5.3. Economic feasibility in different countries

The standard NPV results of three European countries are calculated in the context that the price of PSCs is 0.73 € and the lifespan is 5 years. The results (Fig. 11), show that the PSC envelope applied in Italy and the Netherlands can achieve positive NPV results. The standard NPV of PSC envelope in Italy reaches 177k €, which is almost three times as much as that in the Netherlands (59k €). Notably in Italy, the revenue from the systems in the first 20 years is able to pay the cost of the fourth PSC replacement. This means that the property owner needs not input additional money into the project, and the system becomes self-sufficient in revenue. However, results show that PSC envelope in Norway cannot achieve profitability (standard NPV is −21k €). At the initial stage, the NPVs of three countries are all positive and Norway's figure leads the way. It means that the initial investment of PSC envelope system is lower than that of equivalent building envelope material, thereby lowering the investment threshold.

The integrated NPV results in three European countries are shown in Fig. 12. For the integrated NPV, PSC envelopes can all realize the profitability from the perspective of whole society. The integrated NPV of PSC envelope in Italy is still the highest among three countries, up to 308k €. Subsequently, PSC envelope in the Netherlands show a 152k € integrated NPV. Particularly, the integrated NPV result in Norway (51k €) turns positive from a negative standard NPV result. This means that it is economically beneficial for the government is to support PSC envelopes by releasing subsidies in order to meet profitability requirements of property owners.

The absolute cumulative NPV results of different items in the three countries are compared in the Fig. 13. The results show that the investment is highest in Norway. Next is the PSC envelope in the Netherlands, followed by Italy which shows the lowest investment. This ranking reflects the labor costs, which are highest in Norway and lowest in Italy. In addition, the revenue from electricity sale in Italy is the

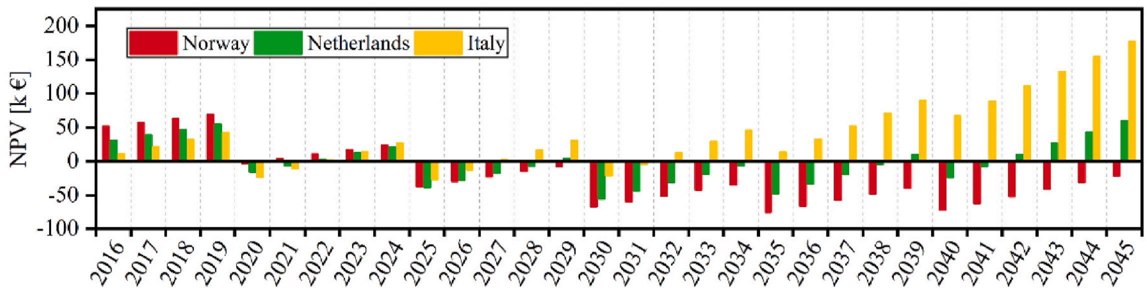

Fig. 11. Standard NPV in three European countries, contributed by investment and stakeholder's income, without social and environmental benefits, subsidies and recycling benefits. The PSC5 is used.

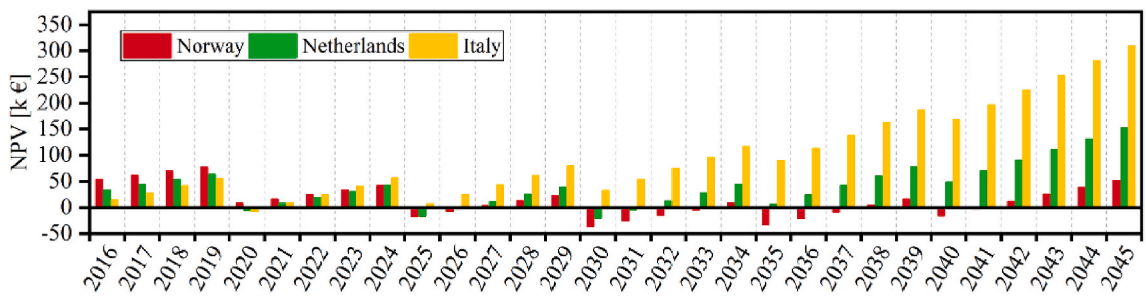

Fig. 12. Integrated NPV in three European countries, contributed by investment, stakeholder's income, and social and environmental benefits, without subsidies and recycling benefits. The PSC5 is used.

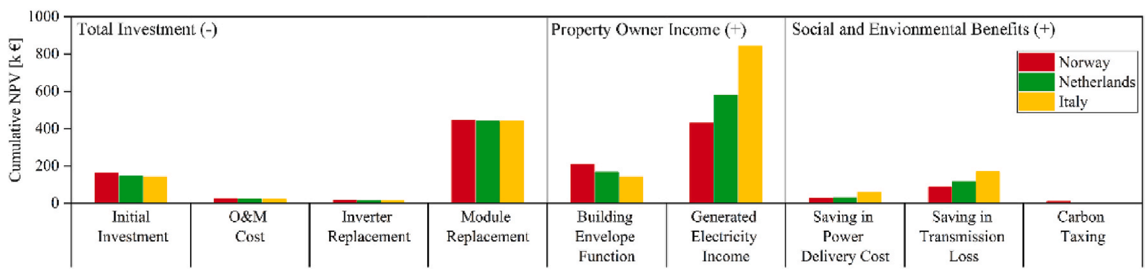

Fig. 13. The absolute cumulative NPV of different items in three European countries.

highest because of the high irradiation, and the equivalent building material cost in Italy is the lowest due to the low price level index. The carbon tax saving is only implemented in Norway. Furthermore, the PSC envelope in Italy saves most in power delivery cost and transmission loss because of the highest electricity generation.

The LCCA indicators in three countries are shown in Table 8. In Norway, the LCOE is the highest, up to 0.282 €/kWh. It is higher than the average electricity tariff in the 30 years (0.258 €/kWh). The investment in Norway has a payback period of 27 years. For the Netherlands, the LCOE is 0.250 €/kWh, far lower than the local electricity tariff (0.309 €/kWh). And its investment is lower than that of the normal building skin. Also, the LCOE in Italy is 0.226 €/kWh, which is far lower than the average electricity tariff in the 30 years (0.425 €/kWh).

Table 8
Economic results of the PSC envelope in Norway, the Netherlands, and Italy.

	Total investment (k€)	LCOE (€/kWh)	DPP (year)
Norway	648	0.282	27
the Netherlands	619	0.250	0
Italy	615	0.226	NA

5.4. Uncertainty analysis and sensitivity analysis

Fig. 14 shows the probability distributions of the two projections for LCOE and NPV of the PSC15 envelope. Both distributions exhibit a broad range, with the highest values signifying the highest probabilities. Due to the nonlinear relationship between input parameters and economic indicators, both distributions exhibit an asymmetric character.

Table 9 summarizes the outcomes of the simulation. It is evident that NPVs are quite robust when crucial factors are uncertain. The low NPVs across all regions with a confidence level of 95% indicate that PSC15 is already a highly competitive power generator. In addition, both Fig. 11 and Table 7 indicate that the LCOEs are stable in the presence of parameter uncertainties, with the lowest value being close to the current electricity tariff in Norway. From the perspective of a 30-year application, however, the LCOE of PSC envelope is significantly lower than the average 30-year power rate. Therefore, the next step toward PSC envelope could involve implementing simple, scalable manufacturing techniques with a high PCE and a low cost.

The NPVs and LCOE of the PSC15 envelope in Norway are then subjected to sensitivity analysis. The departure of NPVs from their nominal value is mostly attributable to fluctuations in the electricity tariff, PSC price, PSC PEC, and solar insolation. The negative indication indicates that increasing these parameters decreases the EPBT. The electricity tariff has the greatest impact, accounting for 41.0% of the

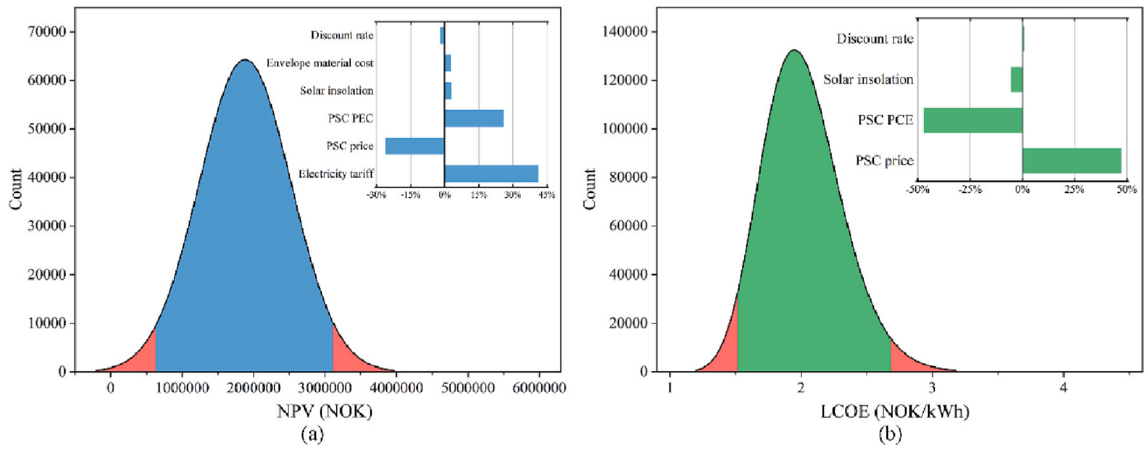

Fig. 14. Probability distributions for NPV and LCOE of PSC15 envelope in Norway.

Table 9
Simulation results for NPV and LCOE of PSC15 envelope in Norway.

	NPV (NOK)	LCOE (NOK/kWh)
Mean	1894646	1.991
Standard deviation	642739	0.308
95% confidence region	(587224, 3129286)	(1.501, 2.704)

variance, while the PSC price accounts for −25.9% of the difference. In the LCOE sensitivity analysis, the PSC price is the largest contributor (47.1%). It is important to note that the PSC PCE has a considerable impact on the LCOE (−46.9%).

6. Discussion

6.1. Implications

Based on the results in the section 4, the PSC envelope shows a more favorable economic performance than the current rigid silicon BIPV system. Since there is little overshadowing in the current BIPV project, it can also be concluded that the PSC envelope is likely to achieve an even better comparative economic performance in dense urban areas, because shadowing has a significant adverse effect on silicon BIPV envelopes, but a much smaller influence on PSC panels.

The economic feasibility of PSC envelope is influenced by several factors (Fan et al., 2023; Li et al., 2020, 2022, 2023, 2024a, 2024b; Li and Zanelli, 2021). In fact, the PSC's lifespan is currently the largest barrier for its diffusion and marketization. Although this study simulates that PSC is 5-year lifespan with the lowest sustainable sale price, it is also a significant challenge (standard NPV is negative) to apply it on the vertical envelope as BIPV systems without subsidies in Norway because of the high replacement cost of PSC panels. But even in the worst situation of PSC properties considered in this study (5-year lifespan and middle manufacture scale), the PSC envelope can still present a similar NPV level with the current rigid BIPV system. On the other hand, the frequent replacement of solar cells obviously boosts the energy production. In this context building owners face a difficult trade-off between environment responsibility and benefits. However, the results of integrated NPV are positive, whereby the Norwegian government would make a profit, from the whole society perspective, by releasing subsidies that promote the PSC envelope. In addition, it is a notable that the standard NPV of PSC envelope is positive in Italy and the Netherlands. The positive standard NPV in the Netherlands indicates that the PSC envelope could achieve profitability in a big portion of European nations because the electricity tariff is relatively low and the climatic conditions are representative of some of the most densely populated parts of Europe.

6.2. Limitations

For several of the input parameters, it was not possible to identify a defined uncertainty distribution in the literature. Therefore, the authors made necessary assumptions on some factors. For instance, the lifespan of PSCs was deemed an external feature, which the designer cannot influence. The alternative, that correct design and planned maintenance can extend the PSC lifespan was not considered as a design parameter in this study.

The objective of this research was to incorporate as many parameters as feasible into the LCCA models using the most recent calculation methods (Li et al., 2024c; Li and Li, 2024). Nevertheless, the standard calculation methods are a simplification of reality. For example, certain phenomena such as climate change scenarios and shadow circumstances, are not currently considered in calculations. Other phenomena are considered, but are currently modeled using the normative methods (degradation of solar cells, electricity tariff inflation, etc.). Future research should explore ways of improving the fidelity of existing calculating methods and parameters.

The result obtained in this research are very sensitive to the uncertainty of the input values. Utilizing particular parameter ranges, specifically the parameters of solar cells, enabled the authors to perform the assessment for the case study using our methodology. Some of the scenarios are less likely than other, e.g. the 15-year lifespan PSCs is unlikely to be achieved in the near future. The objective of this was to prevent an underestimating of some parameters in the absence of further details. It shows that even when considering a big uncertainty of certain factors, the influence of these factors does not appear significant. Therefore, the PCE of solar cells, lifespan, PSC price, electricity tariff are indeed the main parameters to consider in BIPV LCCA studies. Also, the durability of the adhesive for the integration of PSCs on the external envelope has yet to be proven through further development and testing and is therefore an uncertainty.

7. Conclusions

This paper focused on the economic feasibility of the PSC envelope including within a circular economy. An LCCA study was conducted based on a BIPV case in Norway. The performance of the current monocrystalline silicon PV envelope was compared to an alternative PSC envelope with the same surface area. The economic performance of PSC envelope was calculated taking recycling of PSCs into account. The whole recycling process of various PSC layers was developed and the recycling benefits were quantified. The results were also compared to the current monocrystalline silicon BIPV system. Furthermore, this study also assessed the economic performance of vertical BIPV envelope by applying PSC panels with 5-, 10-, 15- year lifespan and lowest sustainable price of production in Norway, the Netherlands, and Italy. Uncertainty analyses for NPV and LCOE were conducted to assess the fluctuation range and sensitivity analyses were performed to identify the governing parameters. The main conclusions are as follows.

1. The majority of the PSC materials can be recycled to achieve quasi-circular BIPV components. The recycling benefit of PSC envelope is up to 482.5 NOK/m^2, which is 43.4% of the new PSC cost. Its potential for circularity is significantly higher than that of current silicon BIPV system.
2. PSC5 envelope, PSC10 envelope, and PSC15 envelope are all able to produce more energy than the current silicon BIPV system. But only the PSC10 envelope and the PSC15 envelope achieve profitability for the property owner without subsidies. The PSC10 and PSC15 show a more favorable economic performance than the current BIPV system. But the economic performance of the PSC5 is worse than the current BIPV system.
3. The PSC envelope requires less up-front capital investment than the silicon BIPV system, which can ease the initial funding pressure and is attractive for the individual investor or property owner with limited initial funding. Frequent replacement of PSC panels is able to improve the energy production, but also increases the capital load. The cash input for the PSC panels in the PSC5 envelope accounts for 88% of the whole investment.
4. In the scenario that the PSC panel achieves 5-year lifespan and the largest manufacture scale, it is economically feasible for the Norwegian government to support PSC envelopes through subsidies, because of the positive net economic outcomes for the broader society. Additionally, the PSC envelope is capable of generating benefits without subsidies in Italy and the Netherlands. The standard NPV of PSC envelope in Italy reaches 177k €. The positive standard NPV in the Netherlands indicates that the PSC envelope can achieve profitability in the highly populated latitudes of Europe and because the Netherlands has an electricity tariff that is relatively low when compared to other European nations.
5. The deviation of NPVs from their nominal value is mostly attributable to fluctuations in the electricity tariff, PSC price, PSC PEC, and solar insolation. In the LCOE sensitivity analysis, the PSC price and the PSC PCE are two most influential factors.

CRediT authorship contribution statement

Qingxiang Li: Writing – original draft, Methodology, Investigation, Conceptualization. **Ziyue Chen:** Writing – review & editing, Investigation. **Xinwei Li:** Investigation. **Stijn Brancart:** Supervision. **Mauro Overend:** Writing – review & editing, Supervision.

Declaration of competing interest

I confirm that we have mentioned all organizations that funded our research in the Acknowledgements section of my submission, including grant numbers where appropriate. We declare that we have no commercial or associative interest that represents a conflict of interest with other people or organizations that can inappropriately influence our work entitled, "Vertical Perovskite Solar Cell Envelope for the Circular Economy: A Case Study using Life Cycle Cost Analysis in Europe".

Data availability

The authors are unable or have chosen not to specify which data has been used.

Acknowledgement

This work was sponsored by China Scholarship Council and IDEA league. Authors highly appreciate the help of Mr. Haoxu Wang in the recycling process.

References

Arnold, F., Jeddi, S., Sitzmann, A.J.E.E., 2022. How Prices Guide Investment Decisions under Net Purchasing—An Empirical Analysis on the Impact of Network Tariffs on Residential PV, 112, 106177.
Aste, N., Del Pero, C., Leonforte, F.J.S.E., 2016. The First Italian BIPV Project: Case Study and Long-Term Performance Analysis, 134, pp. 340–352.
Balakumar, P., Vinopraba, T., Chandrasekaran, K.J.S.C., 2022. Machine Learning Based Demand Response Scheme for IoT Enabled PV Integrated Smart Building. Society, 104260.
Binek, A., Petrus, M.L., Huber, N., Bristow, H., Hu, Y., Bein, T., Docampo, P.J.A.a.m., interfaces, 2016. Recycling perovskite solar cells to avoid lead waste, 8 (20), 12881–12886.
Bing, J., Caro, L.G., Talathi, H.P., Chang, N.L., Mckenzie, D.R., Ho-Baillie, A.W.J.J., 2022. Perovskite Solar Cells for Building Integrated Photovoltaics—Glazing Applications.
Biyik, E., Araz, M., Hepbasli, A., Shahrestani, M., Yao, R., Shao, L., Essah, E., Oliveira, A. C., Del Cano, T., Rico, E.J.E.s., technology, a.i.j., 2017. A key review of building integrated photovoltaic (BIPV) systems, 20 (3), 833–858.
Chang, R., Yan, Y., Zhang, J., Zhu, Z., Gu, J.J.T.S.F., 2020. Large-grain and Smooth Cesium Doped CH3NH3PbI3 Perovskite Films by Cesium Iodide Post-treatment for Improved Solar Cells, 712, 138279.
Chen, H.-C., Zheng, Y.-J., Guo, S.-W.J., Cells, S., 2021. Solution Process of Selective Color-Gamut Perovskite Solar Cell Modulated with Organic Fabry-Perot Electrode for Building-Integrated Photovoltaic, 230, 111192.
Chen, Z., Yu, B., Li, Y., Wu, Q., Wu, B., Huang, Y., Wu, S., Yu, S., Mao, W., Zhao, F.J.S.C., Society, 2022. Assessing the Potential and Utilization of Solar Energy at the Building-Scale in Shanghai, 82, 103917.
D'Adamo, I., Falcone, P.M., Gastaldi, M., Morone, P.J.E., 2020. The Economic Viability of Photovoltaic Systems in Public Buildings: Evidence from Italy, 207, 118316.
Dunfield, S.P., Bliss, L., Zhang, F., Luther, J.M., Zhu, K., van Hest, M.F., Reese, M.O., Berry, J.J., 2020. From defects to degradation: a mechanistic understanding of degradation in perovskite solar cell devices and modules, 10 (26), 1904054.
Economidou, M., Todeschi, V., Bertoldi, P., D'Agostino, D., Zangheri, P., Castellazzi, L.J. E., 2020. Review of 50 Years of EU Energy Efficiency Policies for Buildings, 225. Buildings, 110322.
Fan, Z., Zanelli, A., Monticelli, C., Li, Q., 2023. Flexible photovoltaic solar design. In: Zanelli, A., Monticelli, C., Jakica, N., Fan, Z. (Eds.), Lightweight Energy, Research for Development. Springer International Publishing, Cham, pp. 93–149. https://doi.org/10.1007/978-3-031-08154-5_4.
Fuller, S.J.N., 2010. An authoritative source of innovative solutions for the built environment. Life-cycle Cost Analysis (LCCA), p. 1090.
Gholami, H., Rostvik, H.N., 2020. Economic analysis of BIPV systems as a building envelope material for building skins in Europe. Energy 204.
Gholami, H., Rostvik, H.N., Kumar, N.M., Chopra, S.S., 2020a. Lifecycle cost analysis (LCCA) of tailor-made building integrated photovoltaics (BIPV) facade: Solsmaragden case study in Norway. Sol. Energy 211, 488–502.
Gholami, H., Røstvik, H.N., Kumar, N.M., Chopra, S.S.J.S.E., 2020b. Lifecycle Cost Analysis (LCCA) of Tailor-Made Building Integrated Photovoltaics (BIPV) Façade: Solsmaragden Case Study in Norway, 211, pp. 488–502.
Gholami, H., Røstvik, H.N., Müller-Eie, D.J.E., Buildings, 2019. Holistic Economic Analysis of Building Integrated Photovoltaics (BIPV) System: Case Studies Evaluation, 203, 109461.
Giuliano, G., Bonasera, A., Arrabito, G., Pignataro, B.J.S.R., 2021. Semitransparent perovskite solar cells for building integration and tandem photovoltaics: design strategies and challenges, 5 (12), 2100702.
Gong, J., Darling, S.B., You, F.Q., 2015. Perovskite photovoltaics: life-cycle assessment of energy and environmental impacts. Energy Environ. Sci. 8 (7), 1953–1968.
Gotzens, F., Heinrichs, H., Hake, J.-F., Allelein, H.-J.J., 2018. The Influence of Continued Reductions in Renewable Energy Cost on the European Electricity System, 21, pp. 71–81.
Han, X., Garrison, J., Hug, G.J.R., Reviews, S.E., 2022. Techno-economic Analysis of PV-Battery Systems in Switzerland, 158, 112028.
Hartwell, R., Macmillan, S., Overend, M.J.R., 2021. Conservation, recycling. In: Circular Economy of Façades: Real-World Challenges and Opportunities, 175, 105827.
Heliatek, https://www.heliatek.com/en/.
IMF, 2009. Fiscal Monitor: How to Mitigate Climate Change. Washington.
Jansen, B.W., van Stijn, A., Gruis, V., van Bortel, G.J.R., 2020. Conservation, recycling. In: A Circular Economy Life Cycle Costing Model (CE-LCC) for Building Components, 161, 104857.
Jean, J., Woodhouse, M., Bulovic, V., 2019. Accelerating photovoltaic market entry with module replacement. Joule 3 (11), 2824–2841.
Kumar, N.S., Naidu, K.C.B., 2021. A review on perovskite solar cells (PSCs), materials and applications, 7 (5), 940–956.
Le Khac, D., Chowdhury, S., Najm, A.S., Luengchavanon, M., mebdir Holi, A., Jamal, M. S., Chia, C.H., Techato, K., Selvanathan, V.J.S.E., 2024. Efficient Laboratory Perovskite Solar Cell Recycling with a One-step Chemical Treatment and Recovery of ITO-Coated Glass Substrates, 267, 112214.

Li, Q., Li, T., Kutlu, A., Zanelli, A., 2024a. Life cycle cost analysis and life cycle assessment of ETFE cushion integrated transparent organic/perovskite solar cells: Comparison with PV glazing skylight. J. Build. Eng. 87, 109140 https://doi.org/10.1016/j.jobe.2024.109140.

Li, Q., Monticelli, C., Kutlu, A., Zanelli, A., 2024b. Environmental performance analysis of textile envelope integrated flexible photovoltaic using life cycle assessment approach. J. Build. Eng. 89, 109348 https://doi.org/10.1016/j.jobe.2024.109348.

Li, Q., Monticelli, C., Kutlu, A., Zanelli, A., 2023. Feasibility of textile envelope integrated flexible photovoltaic in Europe: carbon footprint assessment and life cycle cost analysis. J. Clean. Prod. 430, 139716 https://doi.org/10.1016/j.jclepro.2023.139716.

Li, Q., Monticelli, C., Zanelli, A., 2022. Life cycle assessment of organic solar cells and perovskite solar cells with graphene transparent electrodes. Renew. Energy 195, 906–917. https://doi.org/10.1016/j.renene.2022.06.075.

Li, Q., Yang, G., Gao, C., Huang, Y., Zhang, J., Huang, D., Zhao, B., Chen, X., Chen, B.M., 2024c. Single drone-based 3D reconstruction approach to improve public engagement in conservation of heritage buildings: a case of Hakka Tulou. J. Build. Eng. 87, 108954 https://doi.org/10.1016/j.jobe.2024.108954.

Li, Q., Zanelli, A., 2021. A review on fabrication and applications of textile envelope integrated flexible photovoltaic systems. Renew. Sustain. Energy Rev. 139, 110678 https://doi.org/10.1016/j.rser.2020.110678.

Li, Q., Zhu, L., Sun, Y., Lu, L., Yang, Y., 2020. Performance prediction of Building Integrated Photovoltaics under no-shading, shading and masking conditions using a multi-physics model. Energy 213, 118795. https://doi.org/10.1016/j.energy.2020.118795.

Li, T., Li, Q., 2024. Virtual reality in historic urban district renovation for enhancing social and environmental sustainability: a case of tangzixiang in anhui. Sustainability 16, 2665. https://doi.org/10.3390/su16072665.

Lindroos, J., Savin, H.J.S.E.M., Cells, S., 2016. Review of Light-Induced Degradation in Crystalline Silicon Solar Cells, 147, pp. 115–126.

Long, L., Li, Q., Gan, Z., Mu, J., Overend, M., Zhang, D., 2023. Life cycle assessment of stone buildings in the Taihang mountains of Hebei province: evolution towards cleaner production and operation. J. Clean. Prod. 399, 136625 https://doi.org/10.1016/j.jclepro.2023.136625.

Machui, F., Hösel, M., Li, N., Spyropoulos, G.D., Ameri, T., Søndergaard, R.R., Jørgensen, M., Scheel, A., Gaiser, D., Kreul, K.J.E., Science, E., 2014. Cost analysis of roll-to-roll fabricated ITO free single and tandem organic solar modules based on data from manufacture, 7 (9), 2792–2802.

Martinopoulos, G.J.A.E., 2020. Are Rooftop Photovoltaic Systems a Sustainable Solution for Europe? A Life Cycle Impact Assessment and Cost Analysis, 257, 114035.

Mathews, I., Sofia, S., Ma, E., Jean, J., Laine, H.S., Siah, S.C., Buonassisi, T., Peters, I.M., 2020. Economically sustainable growth of perovskite photovoltaics manufacturing. Joule 4 (4), 822–839.

Mathur, N., Singh, S., Sutherland, J.J.R., 2020. Conservation, recycling. In: Promoting a Circular Economy in the Solar Photovoltaic Industry Using Life Cycle Symbiosis, 155, 104649.

NREL, 2022. https://www.nrel.gov/pv/cell-efficiency.html.

NVE, Norwegian Water Resources and Energy Directorate, 2019. Electricity Disclosure 2018.

Osorio-Aravena, J.C., de la Casa, J., Töfflinger, J.A., Muñoz-Cerón, E.J.S.C., 2021. Identifying Barriers and Opportunities in the Deployment of the Residential Photovoltaic Prosumer Segment in Chile, 69. Society, 102824.

REN21, 2019. Renewables in Cities 2019 Global Status Report.

Shukla, A.K., Sudhakar, K., Baredar, P., Mamat, R.J.R., Reviews, S.E., 2018. Solar PV and BIPV System: Barrier, Challenges and Policy Recommendation in India, 82, pp. 3314–3322.

TUD, 2023. Photovoltaic Materials and Devices Group. TU Delft. https://www.tudelft.nl/en/ewi/over-de-faculteit/afdelingen/electrical-sustainable-energy/photovoltaic-materials-and-devices.

Van Stijn, A., Eberhardt, L.M., Jansen, B.W., Meijer, A.J.R., 2021. Conservation, recycling. In: A Circular Economy Life Cycle Assessment (CE-LCA) Model for Building Components, 174, 105683.

Verberne, G., Bonomo, P., Frontini, F., Van Den Donker, M., Chatzipanagi, A., Sinapis, K., Folkerts, W., 2014. BIPV products for facades and roofs: a market analysis. 29th European Photovoltaic Solar Energy Conference and Exhibition, pp. 3630–3636.

Weerasinghe, R., Yang, R., Wakefield, R., Too, E., Le, T., Corkish, R., Chen, S., Wang, C.J.R., Reviews, S.E., 2021. Economic viability of building integrated photovoltaics: a review of forty-five (45) non-domestic buildings in twelve (12) western countries, 137, 110622.

World-Bank, 2018. Electric Power Transmission and Distribution Losses. ZS. https://data.worldbank.org/indicator/EG.ELC.LOSS.

World-Bank, 2019. Carbon Pricing Dashboard. https://carbonpricingdashboard.worldbank.org/map_data.

Yuan, K., Li, Q., Ni, W., Lü, X., Della Vecchia, G., Wang, H., Nie, Y., 2023a. Analysis of the structural and environmental impacts of hydrophilic ZSM-5 molecular sieve on loess. Construct. Build. Mater. 366, 130248 https://doi.org/10.1016/j.conbuildmat.2022.130248.

Yuan, K., Li, Q., Ni, W., Zhao, L., Wang, H., 2023b. Graphene stabilized loess: mechanical properties, microstructural evolution and life cycle assessment. J. Clean. Prod. 389, 136081 https://doi.org/10.1016/j.jclepro.2023.136081.

Zhang, C., Hu, M., Laclau, B., Garnesson, T., Yang, X., Tukker, A.J.R., Reviews, S.E., 2021. Energy-carbon-investment payback analysis of prefabricated envelope-cladding system for building energy renovation. Cases in Spain, the Netherlands, and Sweden 145, 111077.

Zhu, L., Li, Q., Chen, M., Cao, K., Sun, Y., 2019. A simplified mathematical model for power output predicting of Building Integrated Photovoltaic under partial shading conditions. Energy Convers. Manag. 180, 831–843. https://doi.org/10.1016/j.enconman.2018.11.036.

Zhu, L., Zhang, J., Li, Q., Shao, Z., Chen, M., Yang, Y., Sun, Y., 2020. Comprehensive analysis of heat transfer of double-skin facades integrated high concentration photovoltaic (CPV-DSF). Renew. Energy 161, 635–649. https://doi.org/10.1016/j.renene.2020.07.045.

Zhu, S., Li, Y.J.S.-S.E., 2020. Performances of Perovskite Solar Cells at Low-Intensity Light Irradiation, 173, 107903.