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Feasibility of textile envelope integrated flexible photovoltaic in Europe: Carbon footprint assessment and life cycle cost analysis

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ABSTRACT

Textile envelope integrated flexible photovoltaic (TE-FPV) systems gain more attentions in recent years because of their lightweight structure and innovative design. Three types of TE-FPV systems are designed as a sunshade for a teaching building in Politecnico di Milano to replace the current PV glazing sunshade. The environmental and economic feasibility of TE-FPV systems is investigated by applying life cycle assessment (LCA) and life cycle cost analysis (LCCA) in a cradle-to-cradle approach. LCA provides carbon footprint of systems to quantify the environmental performance. LCCA study considers the contribution of life cycle cost, building owner income, and social and environmental benefits. The results are compared with the PV glazing sunshade. From the results, all TE-FPV systems can achieve the economic benefits for the whole society while producing renewable and clean energy. Building owner can even earn benefits from the TE-FPV systems in Norway. The proved success of economically feasible TE-FPV systems in Bergen, Norway serves as compelling evidence for the broad applicability of such systems across the most areas within Europe.

1. Introduction

The European Union is so ambitious to achieve carbon neutrality by 2050, necessitating remarkable reductions in energy consumption in all sectors (Action, 2009). The building sector, including the largest energy consumer in the European Union and responsible for 40% of total energy consumption and 27% of greenhouse gas emissions, should play a key role in this endeavor (Walker et al., 2022). Architects widely acknowledge the potential of solar energy utilization as an important method to decrease energy demand in the building sector.

Photovoltaic (PV) presents a promising solution, which is able to realize the conversion of light into electricity (Gholami et al., 2019). Integrating photovoltaics with building structures, termed Building Integrated Photovoltaics (BIPV), entails replacing traditional building enclosure systems with fully functional PV modules (Zhou et al., 2023). Compared to non-integrated systems, BIPV offers advantages such as reduced land resource consumption and independence from separate photovoltaic installations, thereby positioning it as a highly favorable development prospect (Vassiliades et al., 2023). A specific BIPV style gaining traction in recent years is the PV glazing sunshade. However, scholars emphasize the need for such sunshades to align with functional, technological, aesthetic, and cost considerations, apart from their high degree of integration with construction practices (Li et al., 2020a). Special attention must be given to the fragility of the glass encapsulation during transport and construction, necessitating careful handling and additional workforce allocation to ensure site safety and orderliness (Shukla et al., 2018).

The development of emerging photovoltaic technologies has spurred innovation in BIPV, resulting in cost reductions and simpler processing techniques, as well as diverse photovoltaic structures, including flexibility and transparency (R.J.J.A.i.C. Yang, 2015). Consequently, the textile envelope integrated flexible photovoltaic (TE-FPV) system has garnered increased attention, because it upholds the required durability and meets aesthetic (Li and Zanelli, 2021). TE-FPV is a good choice to serve as a suitable replacement for traditional PV glazing sunshades. Moreover, the maturation of perovskite solar cell (PSC) technology provides a competitive option for TE-FPV systems (Li et al., 2022). Although some TE-FPV products for sunshade applications are available in the market, their environmental and economic feasibility is still uncovered, an important aspect influencing their diffusion and commercialization.

To facilitate comprehensive evaluation and decision-making concerning BIPV systems, the integration of Life Cycle Cost Analysis (LCCA) and Life Cycle Assessment (LCA) methods proves essential (Bahramian

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and Yetilmezsoy, 2020; Li et al., 2020b). LCCA enables economic analyses of BIPV systems, considering input parameters such as initial investments, thereby aiding in optimal technology selection (Sorgato et al., 2018).

Prior research has demonstrated the economic feasibility of BIPV systems compared to conventional facade materials (Gholami et al., 2020). On the other hand, LCA provides valuable insights into the environmental performance of building components throughout their life cycle. Notably, it has been applied to investigate the environmental impact of potential organic solar cell (OSC) applications in solar rooftop arrays (Tsang et al., 2016). Combining LCCA and LCA methodologies offers deep insights into the financial and environmental performance of BIPV systems, with the ultimate goal of minimizing costs, maximizing benefits, and reducing environmental burdens (Yang et al., 2021).

Based on the situations above, this study pays more attentions on the following contents. The concept of the TE-FPV system will be reinforced and diffused for the diffusion in the near future. The influence of social and environmental factors on TE-FPV systems will be involved, which is rarely considered in previous studies. The feasibility of PSC in the real projects will be the first time to be figured out. The technical improvement of PSCs will be considered to make the power generation more accurate.

In this study, three kinds of TE-FPV systems are considered, including PVC roof integrated CIGS, PVC roof integrated flexible mono-Si PV, and ETFE roof integrated PSC. It is simulated to replace the PV glazing sunshade in the campus of Politecnico di Milano by the TE-FPV systems. A cradle-to-cradle life cycle study is conducted to figure out the environmental and economic feasibility of TE-FPV systems. LCA is applied to identify the carbon footprint of systems. LCCA is used to investigate the profitability of systems with the consideration of life cycle cost, building owner income, and social and environmental benefits. Four economic indicators are considered to quantify the results, including net present value (NPV), levelized cost of energy (LCOE), internal rate of return (IRR), and discounted payback period (DPP). Furthermore, the results are also calculated based on the parameters of the Netherlands and Norway.

Herein, the paper is organized as follows: section 2 gives a brief introduction for the project and presents the specifications and prototypes of the PV glazing sunshade and alternative TE-FPV systems. In section 3, the methodology of LCA and LCCA is presented. The results are expressed in Section 4, with sensitivity analyses. Finally, in Section 5, the conclusions based on the investigation of TE-FPV systems in the project is presented.

2. Project description

The building 16A of Politecnico di Milano is a new one-floor laboratory building completed in 2021 (Fig. 1). It is located at 45.5°N, 9.2°E in Italy (Table 1). There are two sunshades constructed by mono-Si PV glass on the two side of the laboratory. In this study. we select one sunshade of the two as the study object to replace the PV glass roof into TE-FPV systems. The area of the PV glass canopy is 131.7 m^2. It is supported by steel structure. Notably, the structure is most basic level to meet the construction standards. It means that even though we applied lighter TE-FPV system, the structure can only be designed as current one but cannot be reduced the amount of the steel. In this case, the BIPV system is the on-grid type which means that the electricity generated by the system is directly transmitted to the network by a grid-connected inverter, thus, there is no storage system.

Table 1
Project 'building 16A of Politecnico di Milano' information.

Project Data	
City	Milan, Italy
Location	45.5°N, 9.2°E
Building function	Teaching laboratory
BIPV installation position	Sunshade
BIPV system size	131.7 m^2

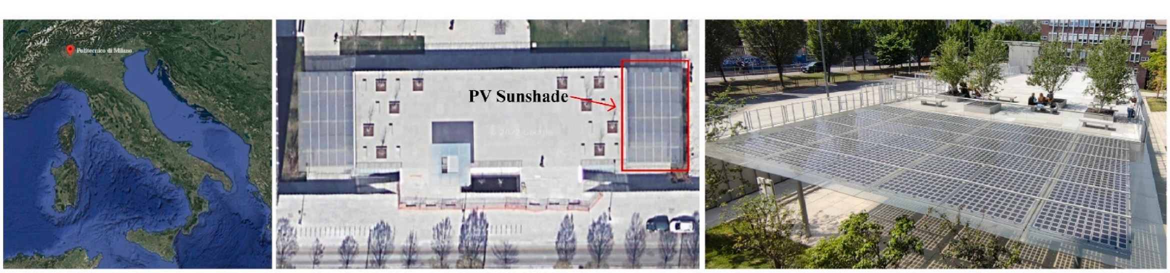
Three kinds of TE-FPV systems are selected for the project, including PVC roof integrated flexible mono-Si PV, PVC roof integrated CIGS, and ETFE roof integrated PSC. The flexible mono-Si PV is the first-generation PV panel. CIGS is the most used second-generation solar cell. PSC is the most promising third-generation solar cell. PVC is easy to integrate flexible mono-Si PV panels and CIGS. ETFE is more suitable to integrate PSCs.

2.1. Mono-Si PV glazing sunshade

The type of mono-Si PV glazing sunshade is EGM77ST purchased from Energyglass company (ENERGYGLASS) (Table 2). The prototype of mono-Si PV glazing sunshade is shown in Fig. 2(a). The canopy consists of 36 PV modules and one PV module power is 375 ± 5% W. Therefore, the total power of the canopy is 13500 W. The dimensions of one module 1376 mm by 2376 mm. Its thickness is 21.5 mm and its weight is 170 kg. The PV glass price is 1.34 €/W. The information about the mono-Si PV glazing sunshade mentioned above is provided by energy commission of Politecnico di Milano (Commissione Energia).

Table 2
Specifications of mono-Si PV glazing.

BIPV System Data	
Company	Energyglass
Solar model	EGM77ST
Solar technology	Mono silicon
Module size	2376 x 1376 mm^2
Number of modules	36
Tilt	0°
Power conversion efficiency	18%
System power	13500 Wp
Module cost	1.3 €/Wp
Module Lifespan	30 years



(a) (b) (c)

Fig. 1. (a) Location of the PV sunshade. (b)(c) PV sunshade in Politecnico di Milano.

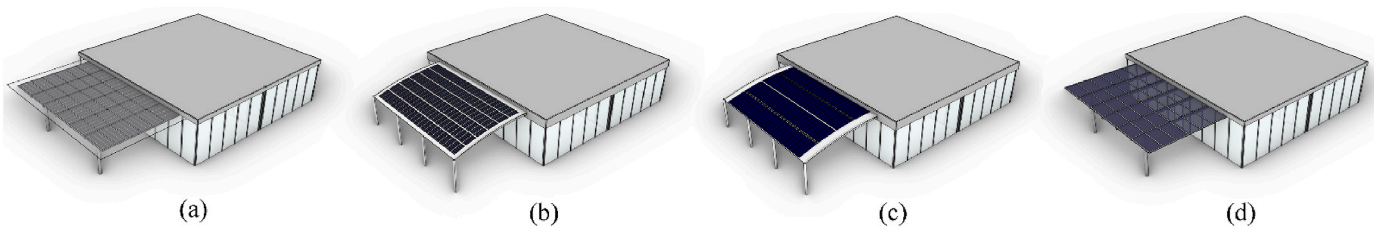


Fig. 2. Sunshade prototypes. (a) Mono-Si PV glazing. (b) PVC roof integrated flexible mono-Si PV. (c) PVC roof integrated CIGS. (d) ETFE roof integrated PSC.

2.2. PVC roof integrated CIGS/flexible mono-Si PV

Polyvinyl chloride (PVC) coated polyester fabric is a well-used material for the covering of tensile fabric buildings. The main materials include a woven base fabric and a PVC coating applied on both sides. This kind of fabric is flexible, durable and waterproof. It is always used for the tensile roof structure for the stadium, the shopping mall, the airport terminal and the sunshade. PVC-coated polyester woven textile has attempted to integrate FPV in diverse pilot projects. Volvo car applied solar-powered PVC mesh membranes for a Pure Tension Pavilion (Li and Zanelli, 2021). In this study, we applied CIGS and flexible mono-Si PV panels on the PVC sunshade to replace the PV glass sunshade in the building 16A.

The area of the tensile PVC sunshade is also 131.7 m^2. Mono-Si PV modules were purchased from XINPUGUANG company (Fig. 3). The module dimension is 1170*540 mm. 132 modules are well distributed on the roof. The power of each module is 100 W. So, the whole system power is 13200 W. The PEC of mono-Si PV module is 16%. The price of the mono-Si PV module is 0.89 €/W. The information of CIGS PV modules are from Honsun company. The price of the CIGS PV module is 1.125 €/W. The PEC of the CIGS PV module is 13.5% and the designed power for the system is 12960 W. Specifications of PVC roof integrated CIGS and PVC roof integrated flexible mono-Si PV are shown in Table 3.

Table 3
Specifications of PVC roof integrated CIGS/flexible mono-Si PV.

TE-FPV System Data	
Tensioned PVC textile	
Textile area	131.7 m^2
Textile cost	80 €/m^2
Textile company	Canobbio Textile Architecture
Flexible mono-Si PV	
Company	XINPUGUANG
Tilt	0°
Power conversion efficiency	16%
System power	13200 Wp
Solar cell cost	0.89 €/Wp
Module Lifespan	30 years
CIGS	
Company	Honsun
Tilt	0°
Power conversion efficiency	13.5%
System power	12960 Wp
Solar cell cost	1.125 €/Wp
Module Lifespan	30 years

2.3. ETFE roof integrated PSC

Single layer ETFE roof is suitable for small-scale roof application. Because single-layer ETFE foils are not pretensioned, frames are indispensable in the ETFE roof system to maintain the shape of ETFE foils. ETFE foil is a perfect substrate to integrate PSC, which can be directly sticked on the foil surface. The price of single-layer ETFE roof is 110 €/m^2 (formTL. https). Specifications of ETFE roof integrated PSC are shown in Table 4.

Table 4
Specifications of ETFE roof integrated PSC.

TE-FPV System Data	
Single layer ETFE foil	
Textile area	131.7 m^2
Textile cost	110 €/m^2
Textile company	Canobbio Textile Architecture
Perovskite solar cell	
Tilt	0°
Power conversion efficiency	15%
System power	13832 Wp
Solar cell cost	105 €/m^2
Module Lifespan	10 years/15 years
Degradation rate	

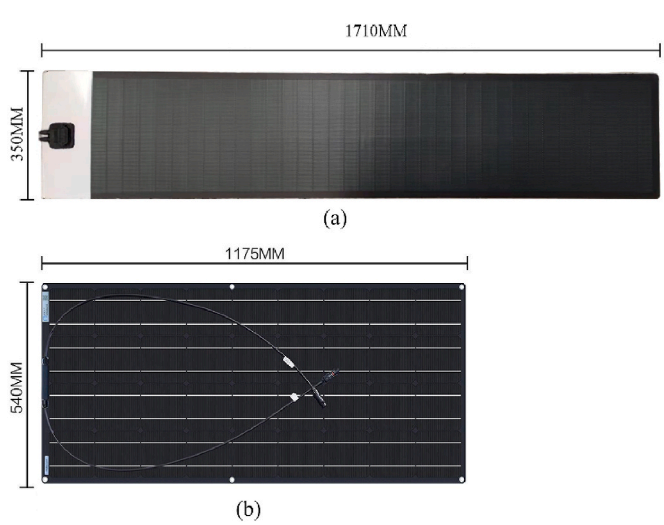


Fig. 3. FPV panels. (a) CIGS panel. (b) Flexible mono-Si PV panel.

3. Methodology

3.1. Goal and scope definition

The goal of this study is to figure out the carbon footprint of TE-FPV systems in average European production by LCA method with 1 m^2 TE-FPV system in the 30-year life cycles as the functional unit. Based on the carbon footprint results, the economic performance of TE-FPV systems as a sunshade is investigated by LCCA method from the perspective of building owner and whole society, and compared with the current PV glazing sunshade.

The life cycle phases considered are shown in Fig. 4 according to EN 15978:2011, including A1-Raw material supply, A3-Manufacture, A4-Transport, A5-Construction&Installation, B1-Use, B2-Manufacture, B4-Replacement, B6-Operational energy use, C1-Demolition, C2-Transport, C3-Waste processing, C4-Disposal and D-Reuse/Recovery/Recycling.

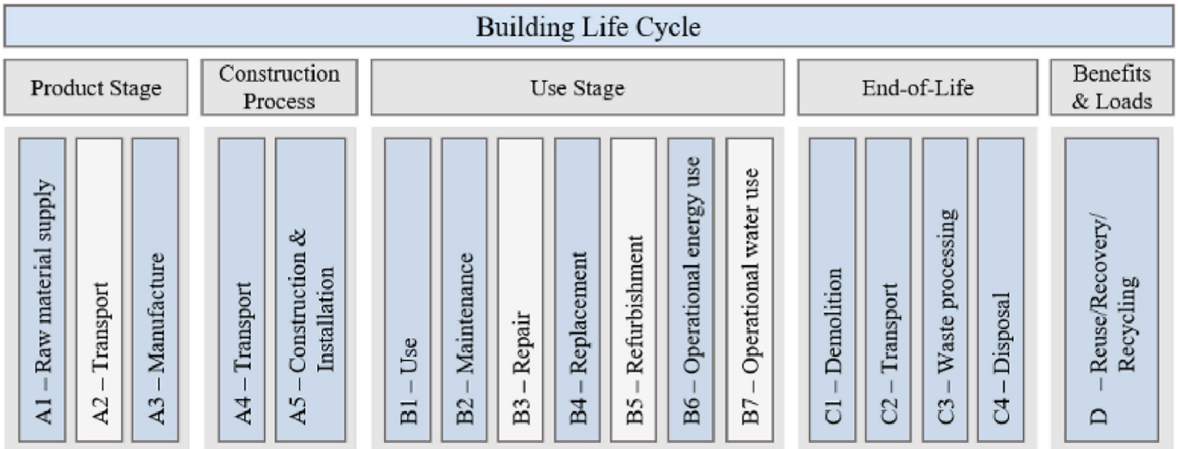


Fig. 4. The different Life Cycle information phases involved in this study.

3.1.1. *Product stage*

The textile envelope, PV modules, inverters and cables are the major items. As for the structure, although the weight of TE-FPV sunshade is lighter than that of PV glass sunshade, their steel structures are similar because the structure needs to meet the requirement of basic load combination in the regulation. So, the structure is not considered in the study. The PV modules applied in this study include mono-Si PV glazing, flexible mono-Si PV, CIGS solar cell and PSC. The textile materials include ETFE and PVC.

3.1.2. *Construction process*

The products need to be transported to the site. But the transportation distances are not same. Actually, the factories that are capable of manufacturing products mentioned above can all be found around Milan. In this study, the assumption is made that the transportation distance of all products is 20 km by 32 metric-ton lorry powered by diesel. Next, the construction & installation stage needs mounting components. Energy consumptions during the installation are considered. The amounts of mounting material and labor force cost are provided by Canobbio company.

3.1.3. *Use stage*

In the use stage, there are three main parts, including replacement of inverters and solar cells, maintenance and electricity generation. The building real estate spends operation and maintenance (O&M) fee to ensure the continuous high output of systems. As for the replacement, the lifespan of inverters is 15 years based on information provided by the manufacturing company. The lifespans of multi-Si PV glass, flexible mono-Si PV module and CIGS solar cell are 30 years. PSC is one of the third-generation solar cells, which is limited by their relatively shorter lifespan and performance degradation. Meanwhile, it is reported that periodic replacement of solar cells can eliminate the influence of degradation and keep a high power conversion efficiency (PCE) to generate more electricity due to the fast technical advancement of PSC. So, the lifespan of PSC is set as 10 years and 15 years, which means solar cells are replaced twice or once, to figure out the environmental impacts and economic performance of periodic replacement.

In terms of electricity generation, the output is affected by location (received irradiation) and PCE. The PCE will gradually degrade in the following years because of the aging and exposure under UV and pollution. The periodic replacement can realize the PCE of PSCs back to a high level. For the degradation, the degradation rate of multi-Si PV and mono-Si PV is set as 0.5% per year and within 10% (JordanS.R.J.P.i.p.R. Kurtz, 2013). Moreover, the degradation rate of CIGS solar cells is set as 1% within 10% (Theelen, 2015). Based on the Celik's research (Celik et al., 2016), the degradation rate of PSCs is reasonable to be set as 1% (BisquertE.J.J.T.j.o.p.c.l. Juarez-Perez, 2019). With respect to PCE improvement of PSCs, it is projected to achieve an 1.5% improvement per year.

3.1.4. *End-of-life*

In the EOL scenario, the BIPV systems are demolished totally. Landfilling is considered as the disposal process for all solid waste in the EOL scenario. The environmental impacts depend on the mass of each solid waste. It is assumed that the demolition process is considered to require no further energy, materials, and cost any more. Assumptions are made that the waste transport distance is set as 50 km.

3.1.5. *Reuse/recovery/recycling*

The wastes that can be easily collected and classified are recovered to realize the sustainability and profits. The wastes that are potentially recovered are identified, including ETFE foil, PVC textile, aluminum alloy components, steel components, and glass. The recovery percentage of these waste materials are learned from literature (Gholami et al., 2020). The recovery prices of these waste materials are based on the average price in EU. The data are shown in Table 5.

3.2. *Assumptions*

In this study, some assumptions are made and summarized here.

1. the lifespan is assumed as 30 years (Gholami et al., 2020). The lifespan of PSC is assumed as 10 years and 15 years.
2. The prices of envelopes and service are set based on the average price of Europe but not the price in different countries.
3. The electricity price is forecasted based on the data of last 20 years.
4. The spence of the systems in the life cycle only considers initial investment, O&M cost, and replacement cost, which are main spence for the projects (Gholami et al., 2020).
5. The power delivery cost is assumed to account for 20% of the electricity price (Gholami et al., 2020).

Table 5
Materials recovered in the systems.

Material	Recovery yields	Recovery price
Plastic	90%	244.7 €/ton
Aluminum	86%	2820 €/ton
Steel	90%	500 €/ton
Glass	98%	55.1 €/ton

3.3. Life cycle assessment

3.3.1. Life cycle inventory

In the life cycle inventory (LCI) phase, input and output data are listed for each unit process, including all relevant involved energy and mass. The amounts of all the materials in one system are collected firstly, and then converted into the LCI in the scale of functional unit. The calculation is conducted in the software Simapro and the data are from Ecoinvent. The LCIs of systems are shown in Table 6. The inventories of PVC textile and ETFE foil are provided by Serge Ferrari company. As for the PV modules, the inventories of multi-Si PV and mono-Si PV are from the Ecoinvent. Inventory of CIGS solar cell is learned from the research of Stamford (StamfordA.J.S.o.t.T.E. Azapagic, 2019). Inventory of PSC is based on the literature (Gong et al., 2015). Manufacture of PV modules, textiles and other components is concentrated in several main companies in Europe. Therefore, data of materials are all used "RER" which means the average European production. And the European average electricity is used in the energy inventory.

Now, there is no data for PSC in the Ecoinvent database. So, this study develops the LCI of PSC for the calculation. The inventories of PSC are based on the research (Gong et al., 2015). The manufacturing technology of third-generation solar cells makes a great improvement. So, the material amount and energy consumption have been modified based on the recent literature. The structure of the PSC is shown in Fig. 5. The material inventory and energy inventory of PSC are shown in Table 7 and Table 8.

3.3.2. Life cycle impact assessment

In the life cycle impact assessment (LCIA) phase, environmental impacts are quantified and weighted to provide an environmental profile that can show contributions to several impact categories. This study focuses on carbon footprint that is a prevalent impact indicator among various impact categories. Calculation methodology of Intergovernmental Panel on Climate Change (IPCC) 2013 GWP 100a is applied to quantify the total greenhouse impact of one material in accordance with the global warming potential of GHGs. The carbon footprint of one TE-FPV system is contributed by raw materials, energy consumption and direct emission during manufacturing, landfilling and beneficial by the recovery.

Table 6
Life cycle inventories of the five systems.

	Amount					Unit
	PV Glazing	PC	PM	EP10	EP15	
ETFE				0.45	0.45	kg
PVC		0.5	0.5			kg
Flexible mono-Si PV	1		1			m^2
CIGS		1				m^2
PSC				1[a]3	1[a]2	m^2
Mono-Si PV cell	0.7					kg
Flat glass	45					kg
Tempered glass	45					kg
Solar glass	70					kg
Ethylene vinyl acetate copolymer	0.365					kg
Cable	0.24	0.24	0.24	0.24	0.24	kg
Inverter, 2.5 kW	0.0128	0.096	0.16	0.12	0.12	P
Aluminum alloy	0	0.2	0.2	1.4	1.3	kg
Steel	2	0.3	0.3			kg
PV roof mounting	1	1	1	1	1	m^2
Transport, freight, 32-ton lorry	1.59	0.4	0.38	0.24	0.24	tkm

[a] PM stands for PVC roof integrated flexible mono-Si PV. PC stands for PVC roof integrated CIGS. EP10 stands for ETFE roof integrated PSC in 10 years of lifespan. EP15 stands for ETFE roof integrated PSC in 15 years of lifespan.

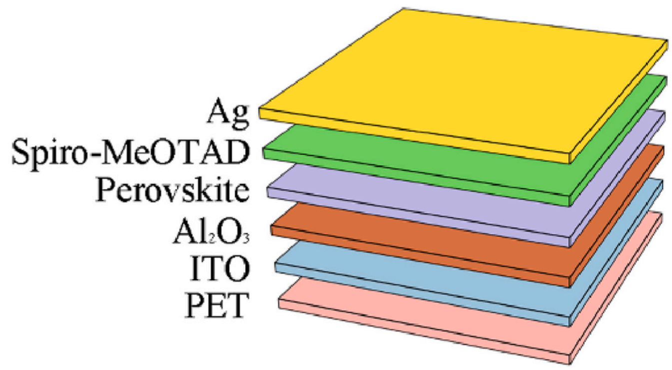


Fig. 5. The structure of PSC.

Table 7
Material inventory of 1 m^2 printed PSC with a 70.0% active area.

	Amount	Unit
Substrate		
PET	1	m^2
Front electrode		
ITO	1	layer
Water	0.327	kg
Hole transport layer		
ZnO ink	45.9	g
Active layer		
PbI_2	0.41	g
CH3NH3I	0.14	g
5-AVAI	0.01	g
Electron transport layer		
Spiro-OMeTAD	0.85	g
Chlorobenzene	11.8	g
Back electrode		
Ag	1.19	g
Encapsulation		
PET	61.70	g
3 M 467 MPF	20.02	g

Table 8
Energy inventory of 1 m^2 printed PSC with a 70.0% active area (Gong et al., 2015; Espinosa et al., 2011).

	Amount	Unit
Electrode processing		
Graphene transfer	0.08	Wh
Hole transport deposition		
ZnO slot-die coating	99.92	Wh
Drying	459.02	Wh
Active layer deposition		
PbI_2 slot-die coating	499.58	Wh
Drying	355	Wh
Electron transport deposition		
Spiro-OMeTAD coating	99.92	Wh
Drying	459.02	Wh
Back electrode deposition		
Slot-die coating	10.93	Wh
Drying	245.9	Wh
Sheeting		
Laser scribing	0.94	Wh
Lamination		
Encapsulation	4.10	Wh

3.4. Life cycle cost analysis

LCCA is a method to assess the economic performance of the target system. LCCA is mainly applied to identify the feasibility of new systems. This study uses an improved LCCA method that includes three parts: life cycle cost, building owner income, and social and environmental benefits. Costs in different stages can be compared to those of the traditional system that has similar function. In this study, the starting year for LCCA is 2021 and the end year is 2050.

3.4.1. Economic indicators

For the LCCA study, LCOE, NPV, IRR and DPP are four main economic indicators and are applied to show the profitability of various TE-FPV systems.

Levelized Cost of Energy is an essential economic indicator for renewable energy technology. Specifically, it is the ratio of lifecycle costs to lifecycle energy production, namely the cost per unit of energy. Generally, LCOE is compared to the electricity price in the market. The following equation shows the formulation:

$$LCOE = \frac{Lifecycle\ cost}{Eg} \tag{1}$$

where E_g stands for the energy generation in the lifecycle. The lifecycle cost is calculated as follows:

$$Lifecycle\ cost = QI + CO \tag{2}$$

where Q_I is the initial investment and C_O is the cash outflows. Q_I is calculated as follows:

$$QI = IPIC - IEMC \tag{3}$$

I_{PIC} stands for the project initial investment cost and I_{EMC} stands for equivalent building envelope material cost.

where C_O of the system in year i can be calculated by following Equation:

$$COi = COMi + CRi\ (If\ i = 10 or 15) \tag{4}$$

where C_{OMi} means the operation and maintenance (O&M) costs and C_{Ri} indicates the investment for equipment replacement in the *i* year.

Net Present Value is a typical economic factor that shows net financial benefits of the system in the lifecycle. It is the difference of the present value of benefits and total costs of the system in the entire life. The Equation is shown as follows:

$$NPV = \sum_{1}^{n}(CI - CO)(1 + DR)^{n} \tag{5}$$

where C_I represents cash inflows. D_R, n stand for discount rate and BIPV lifespan. The discount rate is the rate of interest that is charged by a bank for its loans, which is primary factor influencing the NPV calculation. In this study, the real discount rate is considered to be 4%.

This study considers two kinds of NPV. One is standard NPV, which considers the investment and stakeholder's benefits. It represents the profits of property's owners from the BIPV project. The other one is integrated NPV, considering the benefits from the whole society perspective, including the investment, stakeholder' income, and social and environmental benefits. This indicator is to support decision-maker to understand the benefits of BIPV from the whole picture of the country. Notably, there is a special situation that the standard NPV is negative, but the integrated NPV is positive. It means the property's owner cannot obtain the profits but the project is beneficial for the society or an administrative area. In this situation, the BIPV project can be encouraged and promoted by the subsidies released from the government.

Discounted payback period is a standard parameter that investigate the required time over which the system can recover the entire investment. It is a measurement of the year that the net cash flow is equal to the initial investment. The Equation is as follows:

$$\sum_{i}^{n}(CIi - COi)(1 + DR)^{-n} = Q \tag{6}$$

where C_{Ii} and C_{Oi} stand for the cash inflow and the cash outflow in the *i* year.

Internal rate of return is a standard indicator to assess the profitability of potential investments. It is a discount rate making the NPV equal to zero. The calculation relies on the Equation as follows:

$$\sum_{i}^{n}(CIi - COi)(1 + IRR)^{-n} = Q \tag{7}$$

3.4.2. Life cycle cost

Initial investment consists of material cost and personnel cost. The cost of the PV glass modules, inverters, and other components are collected from the procurement list of energy commission in Politecnico di Milano. In terms of the textile materials, their costs are provided by Canobbio company. As for the CIGS solar cell and mono-Si PV module, our lab (Textile Architecture Network) purchased them directly from manufacturers and consulted the unit price for sunshade roof scale. The PSCs have not commercialized until now, therefore, there is no accurate price for PSCs. Some literature reports their forecasts of the price of PSCs that can maintain the sustainable manufacture. This study sets105 €/m^2 as the price of PSCs from the recent literature in which a techno-economic model is established for the assessment. With respect to personnel cost, the data comes from the BIPV projects in Politecnico di Milano considering the inflation. In Milan, Italy, the personnel cost is set as 1.05 €/Wp. The prices of materials mentioned above are listed in the Table 9.

O&M cost is spent to maintain the normal operation of TE-FPV systems. Based on BIPV projects in Politecnico di Milano, the O&M expense for one year is around 0.05% of the initial cost, which is also set as the O&M cost in the LCCA study.

Replacement cost includes the replacement of inverter and the replacement of PSCs. The price for replacement is assumed to be same as the price to purchase them in the first year. While calculating NPV, the discount rate is considered.

3.4.3. Building owner income

Equivalent building envelope material cost means the cost for the common concrete roof slab as the sunshade that TE-FPV systems replace in this study. It is taken into consideration and subtracted from the TE-FPV investment. The average price of the concrete slab is 45 €/m^2 in Europe.

Table 9
Parameters for the LCCA and prices of components involved in this study.

Parameter	Amount	Unit	Geometric Standard Deviation
Normal distribution			
Global irradiation	1127.4	kWh/m^2	58.9
Lognormal distribution			
Electricity tariff	0.236	€/kWh	1.15
Growth rate of electricity tariff	4.6%		1.2
Discount rate	3%		1.1
O&M cost	0.05%		
Equivalent building envelope cost	45	€/m^2	1.05
Equivalent building envelope area	131.7	m^2	1.1
Transmission line lost power	7%		1.05
Power delivery cost	20%		1.05
Average carbon intensity of electricity generation	444	g CO_2/kWh	1.05
Carbon intensity reduction rate	4%		1.2
PSC PCE	15%		1.15
Material			
Single ETFE foil	110	€/m^2	1.05
PVC	80	€/m^2	
Perovskite solar cell	105	€/m^2	1.15
CIGS	1.125	€/Wp	
Flexible mono-Si PV	0.89	€/Wp	
Inverter 20 kW	4167	€/p	
Inverter 5 kW	1359	€/p	
Personnel cost	1.05	€/Wp	

Electricity sale income is one of the most significant contributions. It is affected by electricity production and local electricity price in the market. The electricity price (including taxes) for household consumers in Italy is 0.236 €/kWh in the first half 2021, based on the statistic of Eurostat. The report also shows the increase of the electricity price is 4.3% compared to that last year. Therefore, we set 4.3% as the growth rate of the electricity price.

Salvage value means that the book value of TE-FPV systems in the EOF has been fully expensed in this study. The recovery price of materials has shown in the Table 5.

3.4.4. Social and environmental benefits

Transmission line lost power means the power losses during the long-distance transmission from the grid to house. But for TE-FPV systems, this problem is solved because the produced electricity can be directly consumed by the building daily operation. According to the World Bank Data, the electricity transmission loss in Italy is 7% (World-Bank, 2018).

Power delivery cost means the expense of the infrastructure for transmission of electricity and distribution. However, the TE-FPV system just needs to spends the installation cost on the house, which achieves a significant decrease compared to the large-scale infrastructure construction. Generally, the power delivery cost accounts for 20% of the electricity price.

Social cost of carbon (SCC) is the whole negative impacts that additional CO_2 emissions cause. The carbon tax can directly express the SCC. But not all the countries have released the policy of carbon tax. Italy government has not started to charge the carbon tax. Carbons emitted by producing electricity are different among countries due to the different energy mix (e.g., coal, gas or oil). The average carbon intensity of electricity production is 444 g CO_2/kWh in Italy. Italy government has released policies to decrease the average carbon intensity. This study applies 4% decline per year for the carbon intensity of the power sector in these two countries based on the literature.

3.5. Uncertainty analysis and sensitivity analysis

This paper also investigates the economic performance of TE-FPV systems in the Netherlands and Norway to understand their feasibility in Western Europe and Northern Europe. Amsterdam, and Bergen are selected as the study areas. The locations of the cities are shown in Table 10.

The parameters for the LCCA and prices of components in the Netherlands and Norway are provided in the Table S1 and Table S2. Notably, Norway has implemented the carbon tax and the price of carbon tax is 53.7 €/t CO_2 (543 NOK/t, exchange rate is 0.99 in May 2020). The growth rate of the carbon tax is also taken into consideration and set as 3.5%. In Netherlands, the carbon tax has also been implemented and its price is 30 €/t CO_2. Moreover, Netherlands government plans to increase the carbon tax price to 125 €/t CO_2 in 2030 (Akerboom et al., 2021). So, the growth rate of the carbon tax is 15.4% in Netherlands.

Carbons emitted by producing electricity are different among countries due to the different energy mix (e.g., coal, gas or oil). The average carbon intensity of electricity production is 582 g CO_2/kWh and 19 g CO_2/kWh in Netherlands and Norway, respectively. The average carbon intensity of electricity production in Norway has been in a considerably low level. So, this study does not consider its decline rate. But for Italy and Netherlands, they have released policies to decrease the average carbon intensity. This study applies 4% decline per year for the carbon intensity of the power sector in these two countries based on the literature (Gholami and Rostvik, 2020).

Uncertainty analysis and sensitivity analysis are conducted for the results in the software Oracle Crystal Ball. The trial is 500000 times for each simulation. The parameters involved, their distribution, and their geometric standard deviation are shown in the Table 9. The geometric standard deviations are set based on (Gong et al., 2015).

Table 10
The locations of these cities.

	Milan, Italy	Amsterdam, Netherlands	Bergen, Norway
Location in Europe	Southern Europe	Western Europe	Northern Europe
Coordinates	45.46°N, 9.19°E	52.22°N, 4.54°E	60.39°N, 5.32°E

4. Results and discussion

In this section, the results of LCA and LCCA are shown and discussed.

4.1. Electricity production

Electricity productions of TE-FPV systems are shown in Fig. 6. It is obvious that PSCs take advantages in the electricity production. Especially, the replacement of PSCs shows a significant effect on the improvement of the electricity production. Therefore, results show that the EP10 system produces most electricity among TE-FPV systems, reaching 418392 kWh. Next is EP15 system, whose production is still more than the original PV glass system, at 392856 kWh. As for the PM system and PC system, their yields are 311119 kWh and 289996 kWh, respectively. They are a little less than the energy yield of PV glass system, at 316386 kWh.

4.2. Carbon footprint assessment

The carbon footprint results of TE-FPV systems are provided in the Fig. 7 (b) and compared to the current PV glass system. From the results, it can be found that EP15 system shows the lowest GHG emission among the TE-FPV systems, at 174.1 kg $CO_{2\text{-eq}}$. PC system and EP10 system emit 190.9 kg $CO_{2\text{-eq}}$ and 193.3 kg $CO_{2\text{-eq}}$, respectively. Their emissions to the environment are lower than that of PV glass system. PM system shows the most unfavorable environmental performance in terms of carbon footprint, reaching 312.1 kg $CO_{2\text{-eq}}$. Compared to the results of the BIPV system in Italy in 2005 (463 kg $CO_{2\text{-eq}}$), the results in this study show a reasonable decrease in terms of GHG emission because of the improvement of the manufacturing technology (Battisti and Corrado, 2005). Results of GHG emission factor present same trend with GHG emission results. GHG emission factor is also calculated and shown in Fig. 7 (c). From the results, EP10 and EP15 present an even greater advantage than PV glazing sunshade. GHG emission factor of EP10 and EP15 is only 58.4 g CO_2-eq/kWh and 60.9 g CO_2-eq/kWh.

4.3. Life cycle cost analysis

The economy analysis was calculated. Firstly, Fig. 8 shows the investment, building owner income, and social and environmental benefits from all contributors mentioned in the Section 3.3. The five systems described in Section 2 are all analyzed and their contributions have been quantified. As for the investment, they are negative contributors. The initial investment, including the cost of textile, PV modules, components, and personnel, accounts for the biggest share. EP10 system and EP15 system show the same initial investment that is highest among the five systems, reaching 46055 €. The initial investment of PV glass system is the lowest, at 35471 €. Next is the contribution of PV module replacement in EP10 system and EP15 system. O&M cost and inverter also contribute to the investment but far lower than the other two. In terms of building owner income, it is obvious that the dominant contribution is from the sale of electricity produced by the TE-FPV systems. It has positive correlation with the electricity production. Yields of EP15 system and EP10 system are more comfortably ahead of the rest of systems because of the periodic replacement of solar cells. So,

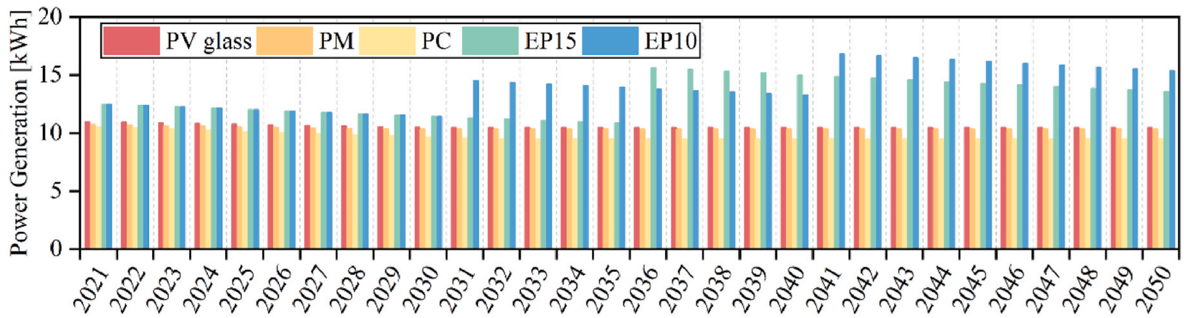


Fig. 6. Electricity generation of five systems.

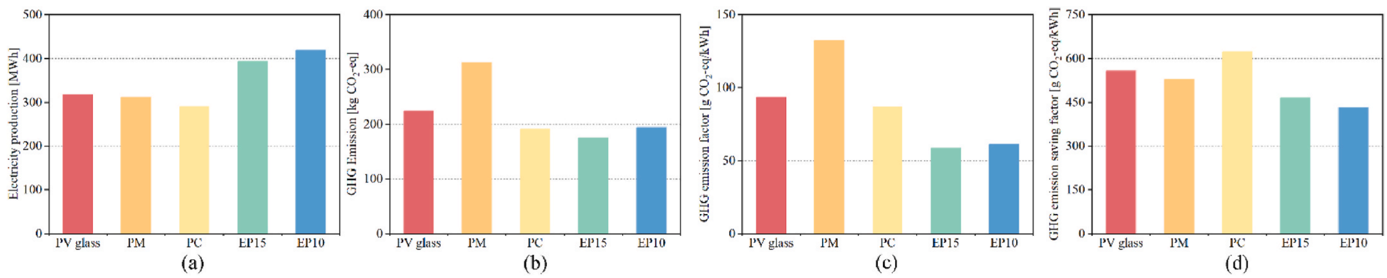


Fig. 7. (a) Electricity generation. (b) GHG emissions. (c) GHG emission factor. (d) GHG emission saving factor.

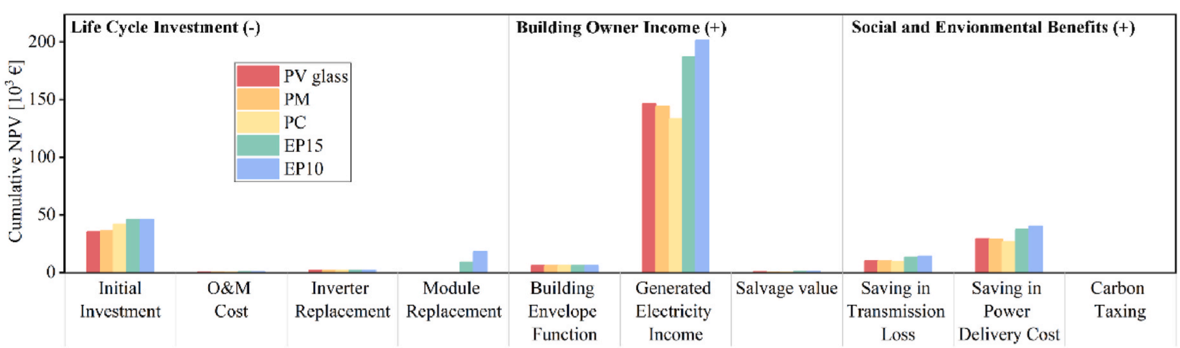


Fig. 8. Contributions (including negative and positive) from the investment, building owner income, and social and environmental benefits.

their income from electricity sale are far more than other systems. The salvage values of the systems can be neglected because they only account for a small share of the whole income. As for the social and environmental benefits, carbon tax saving in Italy is 0 because the policy about carbon tax has not been released. The saving in transmission loss and power delivery cost is also positively associated with the electricity production. Therefore, their distributions are also similar with the distributions of electricity production.

Fig. 9 presents the simulation results for the integrated NPV of the five systems. From the results, it can be seen that all systems can pay back the total investment in their lives according to the LCCA method used in this study. The results prove the profitability of all TE-FPV systems that they can all gain positive NPV results. The NPV of PV glass sunshade is only 80143 €. Compared to the current PV glass sunshade, EP10 system and EP15 system show a more favorable NPV performance, up to 95602 € and 92102 €, respectively. Notably, although EP10 pays more on the replacement of solar cells, EP10 achieve more NPV finally. It proves that the periodic replacement of solar cells in the ET-FPV systems can achieve more profits because the PCE of solar cells can stay in a high level. With respect to PM system and PC system, the NPVs are 77459 € and 64070 €, which are less than that of PV glass sunshade. Moreover, it can be seen that the final NPV results show the same trend

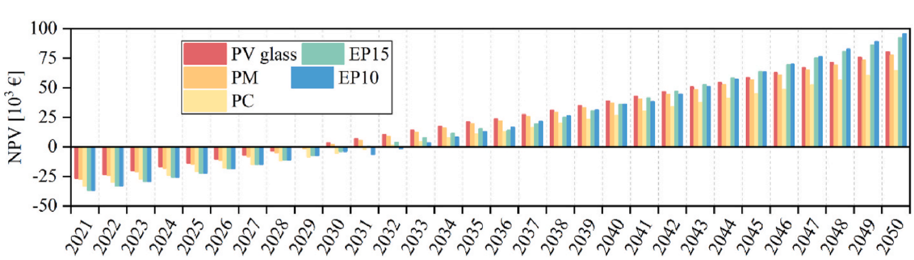


Fig. 9. Integrated NPV of five systems.

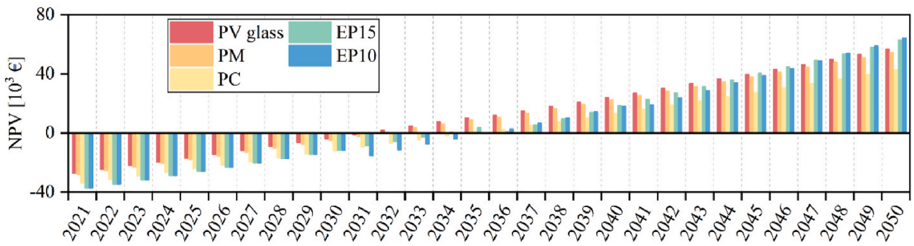


Fig. 10. Standard NPV of five systems.

with the electricity production. Based on the results analyzed above, TE-FPV system can all achieve the economic benefits for the whole society while producing renewable and clean energy.

The standard NPV without considering the social and environmental benefits is presented in the Fig. 10, which can show the benefits or loss of solo building owner without the influence of the society and environment. Results show that all TE-FPV systems can also realize the profitability for the building owner. Because of the heavy investment at the beginning, EP10 system and EP15 system fall behind other systems in terms of NPV. After using 25 years, the NPVs of EP10 system and EP15 system catch up. Finally, EP10 system and EP15 system achieve a better economic performance. Therefore, EP10 system and EP15 system show an advanced performance among the system although they pay more on the replacement of solar cells. Moreover, the TE-FPV systems can gain profits and be diffused without any support or subsidies from the government.

Fig. 11 presents the cash flow of TE-FPV systems in their whole life. Because the growth rate of electricity price is higher than discount rate, the cash flow of systems gradually increases year by year although the power output decreases. In 2036, the cash flow shows a sudden drop in all systems. The reason of this is the replacement expense of the inverters. Results show that the cash flows of EP10 and EP15 are more than that of others in the most of period without year 10, year 15, and year 20 due to the replacement of the solar cells. It means that EP10 and EP15 gain more profits among the systems in most of time of the entire life. Moreover, after replacing the solar cells, it is apparent that the cash flow of the system shows a considerable leap because of more income from the sale of electricity. Finally, their cash flows reach 16226 € and 14398 € in one year, respectively. As for the PM and PC, their cash flow trend is similar with that of current PV glass sunshade, at 10613 € and 9753 € most in one year.

Total investment, LCOE, DPP, and IRR of the TE-FPV systems are illustrated in Fig. 12. The results show that the total investment of EP10 is the highest, reaching 70652 €, which is 1.87 times than the current PV glass sunshade. But EP10 can earn more money for building owner and produce value for society. With respect to LCOE, EP10 and EP15 show higher LCOEs than other TE-FPV systems and current PV glass sunshade, up to 0.14 €/kWh and 0.15 €/kWh, respectively. But their LCOEs are also less than the electricity price in Italy. As for the DPP, TE-FPV systems show higher DPPs than current PV glass sunshade. EP10 and EP15 can payback the entire investment at year 13 and year 11. DPP of PM is 10 years and DPP of PV is 12 years. Furthermore, the TE-FPV systems present lower IRRs than PV glass sunshade. The IRR of PC is the lowest among the TE-FPV systems, at 11.4%. Based on the results analyzed above, it can be seen that the current PV glass sunshade still has its superiority in economic performance compared to TE-FPV systems. However, the TE-FPV systems also show more favorable economic performances than the grid electricity. It proves the feasibility of TE-FPV systems in terms of economic performance.

4.4. *Feasibility in different European regions*

The economic performances of TE-FPV systems in the Netherlands and Norway are also investigated to identity the feasibility in western Europe and Northern Europe in this study.

Figs. 13 and 14 present the simulation results for integrated NPV of the five systems in the Netherlands and Norway, respectively. From the results, it can be seen that all systems in the two countries can pay back the total investment even without considering social and environmental benefits. It means that the TE-FPV systems can be profitable even in Northern Europe. But in Norway, the standard NPVs of TE-FPV systems are lower than that of PV glazing sunshade (32756 €). In the Netherlands, the benefits of PM and PC system are unfavorable compared to the PV glazing. Moreover, EP10 performs best among the five systems, up to 51574 €.

Figs. 15 and 16 show the standard NPV of the five systems in the two countries. From the results, it can be seen that the PV glazing sunshade shows the high NPVs among five systems (9564 € in the Netherlands and 19048 € in Norway). It means that although the TE-FPV systems can achieve profitability in the whole lifespan, PV glazing is more investment friendly for the building owner if the government has no subsidies. What is amazing is that the integrated NPV of TE-FPV systems in Norway is higher than that in the Netherlands although the irradiation in Norway is lower. The reason for this is the far higher electricity tariff in Norway.

When comparing the results in Italy, the Netherlands, and Norway, it can be found that of TE-FPV systems in Italy show the most favorable economic performance. The key reason is because the irradiation in Italy is far higher than that in the Netherlands and Norway, which can generate more power by PVs. The proved success of economically feasible TE-FPV systems in Norway serves as compelling evidence for the broad applicability of such systems across the most areas within Europe.

4.5. *Uncertainty analysis and sensitive analysis*

The probability distributions of NPV and LCOE forecasts for EP10 are

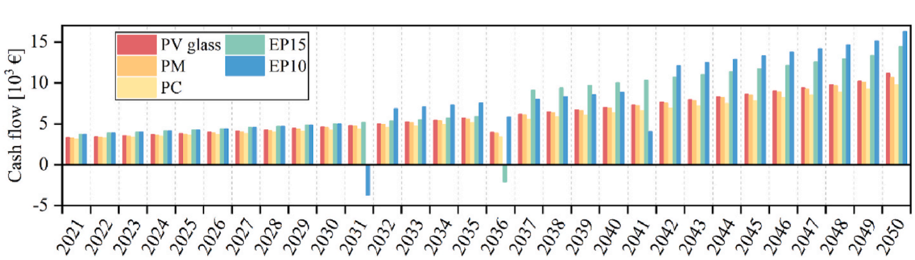


Fig. 11. BIPV cash flow without investment.

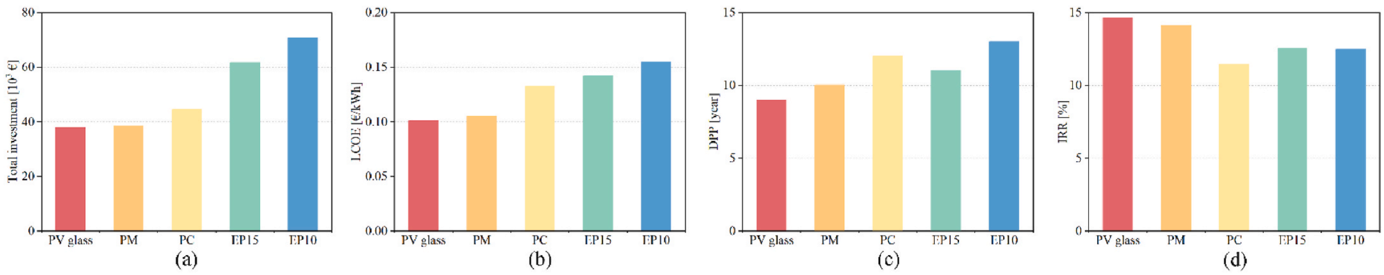


Fig. 12. Economic performance of five systems. (a) Total investment. (b) Levelized cost of energy. (c) Discounted payback period. (d) Internal rate of return.

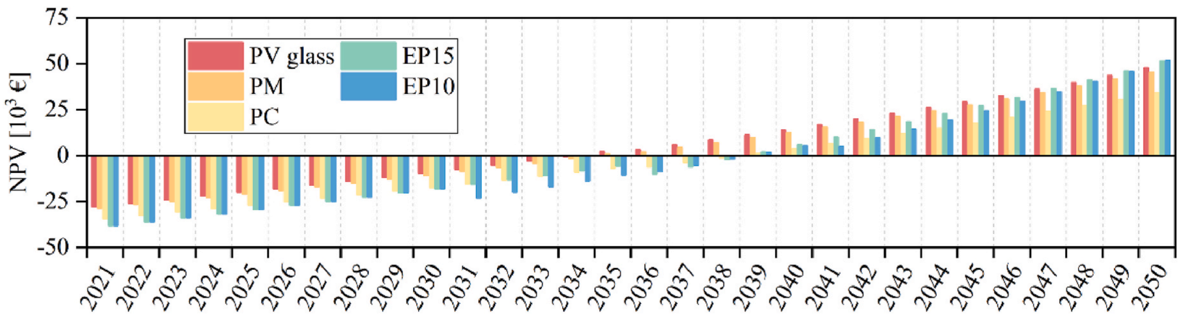


Fig. 13. Integrated NPV of five systems in the Netherlands.

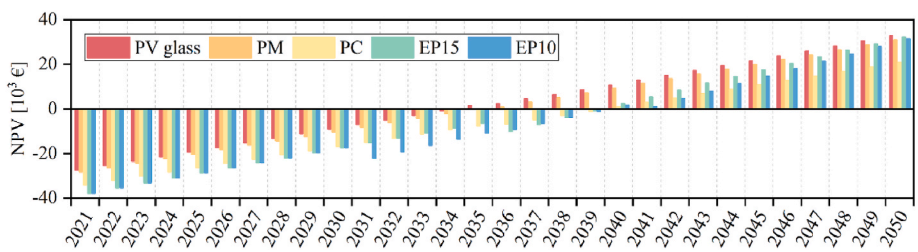


Fig. 14. Integrated NPV of five systems in Norway.

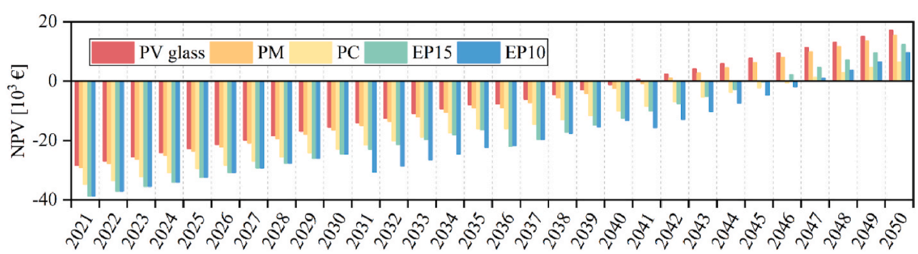


Fig. 15. Standard NPV of five systems in the Netherlands.

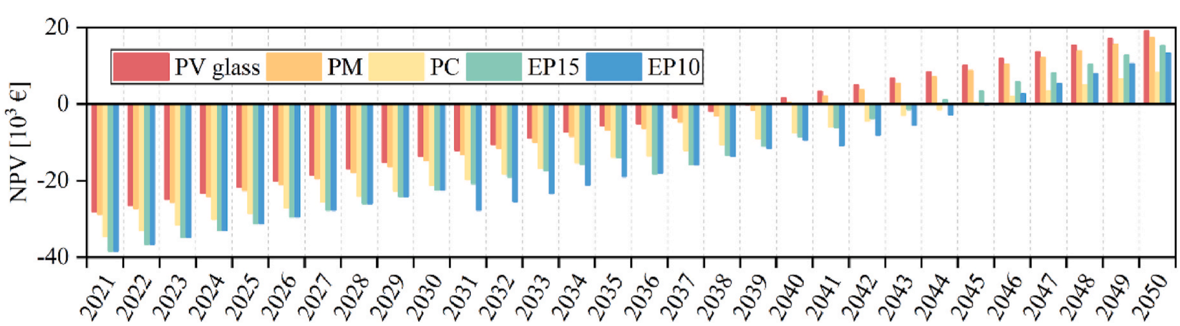


Fig. 16. Standard NPV of five systems in Norway.

presented in Fig. 17. The highest bars mean the values of the highest probabilities. The distribution results are in asymmetric profile because of the nonlinear relationship between different specifications.

For the NPV simulation, both the NPV and LCOE of EP10 system are stable enough when the input parameters suffer from uncertainty. The lowest NPV value of EP10 in the 95% confident regions is 40657 €. It means that EP10 system is capable of making a profit even in the worst condition. In the best condition, the system can earn 191340 €. With respect to LCOE, the 95% confident region of EP10 is from 0.13 €/kWh to 0.16 €/kWh, which are all lower than the current electricity tariff. It will boost the confidence in the marketability of EP10 system.

Sensitivity analyses for NPV and LCOE with respect to EP10 are also conducted. The uncertainties of 13 input parameters have been taken into consideration in this study. In Fig. 17, it only shows the parameters that contribute more than 1% of the variance. It can be seen that electricity tariff presents the most significant influence on the NPV of EP10. Moreover, the growth rate of electricity tariff accounts for 17.9% of the variance of EP10. These all show the dramatic influence of electricity tariff on the variance of NPV. The fluctuations in the discount rate, global irradiation, and envelope area are also responsible for the deviation of NPVs from their nominal value. In terms of LCOE, the PEC of PSC is the major contributor (−63.2%) to the uncertainty of LCOE. Additionally, PSC price, global irradiation, ETFE price, and envelope area also contribute to the uncertainty of the LCOE.

5. Limitations

The LCCA research heavily relies on the accuracy of data. But it is not easy to obtain all data from the three countries. Especially, the parameters are unpredictable in some period because of the development of new technologies and the international situation (Gholami et al., 2020). So, the uncertainty analysis of these factors is conducted in this study to quantify the influence of the factors' fluctuation. Furthermore, the regions selected in this study are all developed countries. For developing countries, the trend of parameters always experiences heavy fluctuation, which is more influenced by their domestic situations (Ebohon, 1996). In the next step, the feasibility of TE-FPV systems in developing countries will be investigated. Moreover, the project is only a small project with TE-FPV systems in Italy. Exactly, it cannot show the whole picture of the feasibility of TE-FPV systems in Italy. But on the one hand, if the project scale is enlarged, the unit cost of the products will decrease. If the case in our study could be economically feasible, most of projects is able to achieve profits from the TE-FPV system. On the other hand, Milan is in the north of Italy. Most of cities are in the south of Milan. It means that in the most regions of Italy, more radiations can be received and TE-FPV systems can generate more electricity. So, if the TE-FPV system is feasible in Milan. The system should be feasible for the most regions of Italy. Lastly, this study only selects three types of TE-FPV systems as representative prototypes. Actually, novel TE-FPV systems are being developed. In our future research, more TE-FPV types will be created and investigated.

6. Conclusions

In this study, TE-FPV systems were provided and investigated for the promotion and diffusion of cleaner energy in the urban city. 3 types of TE-FPV systems were applied as a sunshade for a teaching building in Politecnico di Milano to replace the current PV glazing sunshade. The environmental and economic feasibility of TE-FPV systems were investigated by applying LCA and LCCA in a cradle-to-cradle approach. LCA provided GHG emissions, GHG emission factor, and GHG emission saving factor to quantify the environmental performance. The consideration in the LCCA study includes the contribution of life cycle cost, building owner income, and social and environmental benefits to show the economic viability and evaluate their financial performance. The results were compared with the current PV glazing sunshade.

From the results, PC, EP10, and EP15 emit lower CO_2 than PV glazing sunshade. GHG emission factor of EP10 and EP15 is only 58.4 g CO_2-eq/kWh and 60.9 g CO_2-eq/kWh. In Italy, for the economic performance, the initial investment accounts for the biggest share of the costs. EP10 system and EP15 system show the same initial investment that is highest among the five systems, reaching 46055 €. All TE-FPV systems can achieve the economic benefits for the whole society while producing renewable and clean energy. EP10 system and EP15 system show a more favorable NPV performance, up to 95602 € and 92102 €, which are higher than PV glass sunshade. But NPV of PM system and PC system is lower than that of PV glass sunshade.

To understand the feasibility of TE-FPV systems in Europe, the economic performance in the Netherlands and Norway is also investigated. TE-FPV systems in Milan, Italy show the most favorable economic performance. Building owner can still earn benefits from the TE-FPV systems in Bergen, Norway. The proved success of economically feasible TE-FPV systems in Bergen, Norway serves as compelling evidence for the broad applicability of such systems across the most areas within Europe.

This work contributes significantly to promoting the application of TE-FPV systems to generate cleaner energy in the urban city. TE-FPV systems have the potential to help professions in exploring more BIPV design solutions during the initial planning and design stage. The study can serve as a valuable guideline for the design of BIPV projects in Europe, promoting the development of cost-effective renewable energy solutions in the modern urban city. This, in turn, has the potential to facilitate the adoption of TE-FPV systems in the building sector to realize cleaner production.

In future work, an optimization framework of TE-FPV layouts will be developed based on a new plane segmentation method. Energy production, sustainability and profitability are considered in the optimization process. The framework can further help the architects design the

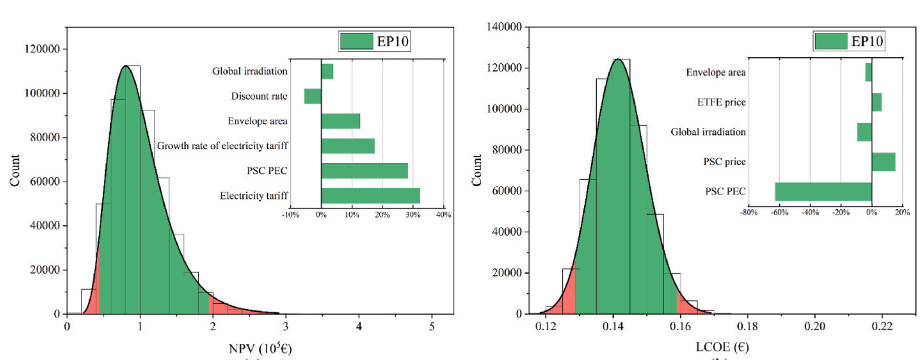


Fig. 17. Uncertainty analysis and sensitivity analysis of NPV and LCOE for EP10. The green regions are in the 95% confidence region. The red region is out of the 95% confidence region. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

TE-FPV systems in an easy way, in order to widespread the utility of clean energy in the building sector.

CRediT authorship contribution statement

Qingxiang Li: Conceptualization, Methodology, Investigation, Simulation, Writing – original draft. **Carol Monticelli:** Supervision, Writing – review & editing. **Alara Kutlu:** Illustration. **Alessandra Zanelli:** Supervision, Writing – review & editing.

Declaration of competing interest

Dear Editor, 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, "Feasibility of textile envelope integrated flexible photovoltaic in Europe: carbon footprint assessment and life cycle cost analysis".

Data availability

No data was used for the research described in the article.

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Abbreviations

Building Integrated Photovoltaics BIPV
Discounted payback period DPP
ETFE integrated Perovskite solar cell with 10-year lifespan EP10
ETFE integrated Perovskite solar cell with 15-year lifespan EP15
Ethylene Tetrafluoroethylene ETFE
Intergovernmental Panel on Climate Change IPCC
Internal rate of return IRR
Levelized cost of energy LCOE
Life cycle assessment LCA
Life cycle cost analysis LCCA
Life cycle inventory LCI
Life cycle impact assessment LCIA
Net present value NPV
Operation and maintenance O&M
Organic solar cell OSC
Perovskite solar cell PSC
Photovoltaic PV
Polyvinyl chloride PVC
PVC integrated CIGS PC
PVC integrated Mono-Si PV PM
Social cost of carbon SCC
Textile envelope integrated flexible photovoltaic TE-FPV

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.139716.

References

Action, E.C.C., 2009. The 2020 Climate and Energy Package. http://ec.europa.eu/clima/policies/package/index_en.htm.
Akerboom, S., Waldmann, S., Mukherjee, A., Agaton, C., Sanders, M., G.J.J.F.i.E.R. Kramer, 2021. Different this time? The prospects of CCS in the Netherlands in the 2020s 9, 644796.
Bahramian, M., Yetilmezsoy, K., 2020. Life cycle assessment of the building industry: an overview of two decades of research (1995-2018). Energy Build. 219.
Battisti, R., Corrado, A.J.E., 2005. Evaluation of technical improvements of photovoltaic systems through life cycle assessment methodology 30 (7), 952–967.
Bisquert, J., E.J.J.T.j.o.p.c.l. Juarez-Perez, 2019. The Causes of Degradation of Perovskite Solar Cells. ACS Publications, pp. 5889–5891.
Celik, I., Song, Z.N., Cimaroli, A.J., Yan, Y.F., Heben, M.J., Apul, D., 2016. Life Cycle Assessment (LCA) of perovskite PV cells projected from lab to fab. Sol. Energy Mater. Sol. Cell. 156, 157–169.
Commissione Energia. https://www.commissionenergia.polimi.it/.
Ebohon, O.J.J.E.p., 1996. Energy, economic growth and causality in developing countries: a case study of Tanzania and Nigeria 24 (5), 447–453.
ENERGYGLASS. https://energyglass.gruppostg.com/it/.
Espinosa, N., Garcia-Valverde, R., Urbina, A., Krebs, F.C., 2011. A life cycle analysis of polymer solar cell modules prepared using roll-to-roll methods under ambient conditions. Sol. Energy Mater. Sol. Cell. 95 (5), 1293–1302.
formTL. https://www.form-tl.de/?L=1.
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., Muller-Eie, D., 2019. Holistic economic analysis of building integrated photovoltaics (BIPV) system: case studies evaluation. Energy Build. 203.
Gholami, H., Rostvik, H.N., Kumar, N.M., Chopra, S.S., 2020. Lifecycle cost analysis (LCCA) of tailor-made building integrated photovoltaics (BIPV) facade: solsmaragden case study in Norway. Sol. Energy 211, 488–502.
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.
Jordan, D.C., S.R.J.P.i.p.R. Kurtz, 2013. Applications. Photovoltaic degradation rates—an analytical review 21 (1), 12–29.
Li, Q.X., Zanelli, A., 2021. A review on fabrication and applications of textile envelope integrated flexible photovoltaic systems. Renew. Sustain. Energy Rev. 139.
Li, Q.X., Zhu, L., Sun, Y., Lu, L., Yang, Y., 2020a. Performance prediction of Building Integrated Photovoltaics under no-shading, shading and masking conditions using a multi-physics model. Energy 213.
Li, S.P., Lu, Y.J., Kua, H.W., Chang, R.D., 2020b. The economics of green buildings: a life cycle cost analysis of non-residential buildings in tropic climates. J. Clean. Prod. 252.
Li, Q., Monticelli, C., Zanelli, A.J.R.E., 2022. Life cycle assessment of organic solar cells and perovskite solar cells with graphene transparent electrodes. Renew. Energy 195, 906–917.
R.J.J.A.i.C. Yang, 2015. Overcoming technical barriers and risks in the application of building integrated photovoltaics (BIPV). hardware and software strategies 51, 92–102.
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, 3314–3322.
Sorgato, M.J., Schneider, K., Ruther, R., 2018. Technical and economic evaluation of thin-film CdTe building-integrated photovoltaics (BIPV) replacing fa ade and rooftop materials in office buildings in a warm and sunny climate. Renew. Energy 118, 84–98.
Stamford, L., A.J.S.o.t.T.E. Azapagic, 2019. Environmental impacts of copper-indium-gallium-selenide (CIGS) photovoltaics and the elimination of cadmium through atomic layer deposition, 688, 1092–1101.
Theelen, M., 2015. Degradation of CIGS Solar Cells. TU Delft.
Tsang, M.P., Sonnemann, G.W., Bassani, D.M., 2016. Life-cycle assessment of cradle-to-grave opportunities and environmental impacts of organic photovoltaic solar panels compared to conventional technologies. Sol. Energy Mater. Sol. Cell. 156, 37–48.
Vassiliades, C., Lau, K., Moiseos, R., Buonomano, A., Savvides, A., Rizzo, A., 2023. A climate sensitive design approach to BIPV: investigating the nexus between solar energy and thermal comfort in cities in Sweden and Cyprus. Build. Environ., 110681
Walker, L., Hischier, I., Schlueter, A.J.B., 2022. Environment, Does context matter? Robust building retrofit decision-making for decarbonization across Europe 226, 109666.
World-Bank, 2018. Electric Power Transmission and Distribution Losses. https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS.
Yang, Y., Chen, S., Chang, T.X., Ma, J.R., Sun, Y., 2021. Uncertainty and global sensitivity analysis on thermal performances of pipe-embedded building envelope in the heating season. Energy Convers. Manag. 244.
Zhou, Z., Yuan, Z., Yin, Z., Xue, Q., Li, N., Huang, F.J.G.E., 2023. Environment, Progress of Semitransparent Emerging Photovoltaics for Building Integrated Applications.