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Economic analysis of BIPV systems as a building envelope material for building skins in Europe

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A B S T R A C T

The main purpose of this study is to evaluate the economic feasibility of the BIPV system as a building envelope material for the whole building skins. The paper is dealing with the lifecycle cost analysis (LCCA) of BIPV system in the capitals of all the European Union member states (EU) as well as the capitals of Norway and Switzerland.

The results revealed that by a discount rate of zero, BIPV system could refund all the investment even on the north facades while in terms of traditional building envelope materials as an alternative option for building skins, there would be rarely added benefits after investment. Furthermore, the societal and environmental benefits of a BIPV system in Europe have its greatest impact on the south façade. Moreover, for all the studied directions of building skins with a discount rate of five present in Europe except the north facade, just the quantified amount of societal and environmental advantages of BIPV systems could almost reimburse all the invested money.

The results illustrated that the BIPV system as a building envelope material for the whole building skins could reimburse not only all the investment costs but also become a source of income for the building.

1. Introduction

Although the average cost of direct current electricity (DC) generated by photovoltaic modules has dropped below 0.02 Euro (€) per kilowatt hour (kWh) in many places worldwide, the current issue with PV production is the significant additional cost component related to transporting the electricity from the solar PV module to where and when it is needed. This is part of the latest report of the European Union, PV status report 2019 [1], which calls for solutions to tackle the emerging issues in supplying the increasing power demand of the world.

One of the most reasonable solutions is the building integrated photovoltaic system (BIPV). BIPV system is photovoltaic cells that are capable of being integrated into the building skins such as roof or facade to generate clean energy from sunshine. Such a system plays two roles in the building. First, it functions as building skins. Therefore, the system must have the specification of conventional building envelope materials like weather and noise protection, heat insulation, structural strength, etc. Second, the system is a power generator for the building [2,3].

A BIPV system delivers the energy where the end-user needs it. Besides, with an energy storage system (ESS) or using the power grid as ESS, it can provide energy when the user needs it. This is also a response to the recent criticism, which has been raised regarding the consequences of solar farms on climate change and occupying the agricultural lands [4,5]. With the BIPV system, these concerns and worries are avoided because the system is located on buildings that use the energy, as building skins.

The PV systems can be developed and perform as photovoltaic thermal (PVT) systems with either active or passive ventilation to remove the heat and cool the PV module using air or water as a medium [6–8] and produce both electrical and thermal energy with a higher efficiency [9–11]. In a BIPV system with air ventilation, as an example, the photovoltaic system is typically installed in front of the façade or roof of the building. Fresh air can naturally ventilate the system at the back of the BIPV cooling it. If the system exploits this removed warm air for heating purposes, the system

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Nomenclature

€	Euro
BIPV	Building integrated photovoltaics
BIPVT	Building integrated photovoltaic thermal
$C_{EU,AV,Conv}$	The average price of conventional building envelope materials
C_I	Cash inflows
C_O	Cash outflows
C_{OM}	Operation and maintenance cost
C_{RC}	Inverter replacement cost
C_T	Carbon tax
DC	Direct current electricity
DPP	Discounted payback period
D_R	Discount rate
E_G	BIPV annual electricity generation
E_{Gn}	BIPV annual electricity generation for the n_{th} year
Eionet	European Environment Information and Observation Network
E_{kWh}	CO_2 emission per kWh
ESS	Energy storage system
E_T	Electricity tariff
EU	European Union
EU_{av}	The average of Europe
GaAs	Gallium Arsenide
GHG	Greenhouse gas
GHI	Global horizontal irradiance
HCT	Homogenous carbon tax
IEA	International Energy Agency
I_{EMC}	Equivalent envelope material cost
$I_{EMC,E}$	Equivalent envelope material cost of the east facade
$I_{EMC,N}$	Equivalent envelope material cost of the north facade
$I_{EMC,R}$	Equivalent envelope material cost of the roof
$I_{EMC,S}$	Equivalent envelope material cost of the south facade
IMF	International Monetary Fund
$I_{EMC,W}$	Equivalent envelope material cost of the west facade
I_{PIC}	Project investment cost
IRR	Internal rate of return
kWh	Kilowatt-hour
LCCA	Lifecycle cost analysis
n	Number of the year
N_{Cn}	Net cash flow of the year n
NOAA	National Oceanic and Atmospheric Administration
NPV	Net present value
P_{DC}	Power delivery saving ratio
P_{DR}	Degradation rate of BIPV panels
P_{TL}	Electric power transmission and distribution losses ratio
PV	Photovoltaics
PVGIS	Photovoltaic Geographical Information System
PVT	Photovoltaic thermal
Q	Initial investment of BIPV systems
S_{CT}	Saving from carbon tax
S_{PB}	Projected benefit
S_{PD}	Saving from power delivery cost
sq.m.	Square meter
S_{TL}	Saving from the electric power transmission and distribution losses
UK	United Kingdom
USA	United States of America
USD	United States Dollar
W_P	Watt peak
y	Expected life-time of BIPV (years)
Y_{PP}	Calculated payback time (years)
ZEB	Zero energy building

changes to become a new configuration called building integrated photovoltaic thermal system (BIPVT).

Different methods have been proposed to classify the BIPV systems. It can be classified based on the solar cell composition (crystalline Silicon cells, single-junction Gallium Arsenide (GaAs), thin-film technology, multi-junction cells, and emerging PV), application (roof and façade integration), market (foils, tiles, modules, and solar cell glazing) and connection type to the grid (stand-alone, grid-connected, or hybrid) [12,13]. In addition, the BIPV system application is not just limited to the building. It can also be employed in other applications, like ships and contributes to the optimal performance of ships in terms of energy consumption of the ships [14].

The expected lifetime of the BIPV system is defined as the period that the panels will produce at least 80% of its rated power. Although according to the manufacturers, the current BIPV systems are guaranteed for up to 30 years [15], new studies show that the service life of the BIPV system can be up to 50 years [16,17]. This means the system can deliver at least 80% of its original (as new) electricity production. More than 80% of the implemented BIPV systems in the world are currently rooftop-mounted and the rest are the façade-mounted systems [18]. The BIPV products for facades are less widespread [19] and previous studies have reported that BIPV facades are still a challenging alternative to employ compared to BIPV roofs because of issues involved with this application [18]. Urban obstacles, shading issues, openings and other architectural elements are some of the drawbacks which can significantly affect the public acceptance of façade integrated BIPV [20].

One of the key advantages of renovating the façades of existing buildings with BIPV systems is the possibility to achieve zero energy building (ZEB) or even plus energy building goals [21,22]. Using different facades of a building with various orientations to spread energy production throughout a day [23,24], the contribution of the system to enhance the energy performance of the envelopes [25], the participation of BIPV facades in the retrofit intervention of the building are some other advantages of such a system.

1.1. State of the art

Lifecycle cost assessment (LCCA) is a lifecycle approach that provides a framework for specifying the estimated total incremental cost of developing, producing, using, and retiring a particular item [26]. It applies to the direct monetary costs from a product or service from production through transport, use, and end of life.

A holistic LCCA is an approach that allows the customers to choose the source of energy for their building, considering all consequences of their decision. This type of analysis is expected to evaluate and examine various available options such as different BIPV systems considering their environmental and societal advantages, as well as their role in building material offset, because of their dual service as building skins and PV functionality [2].

Sorgato et al. [21], in 2018, examined the economic and technical feasibility of the BIPV system with thin-film Cadmium telluride (CdTe) materials for a building in six Brazilian cities (six different climates). The results showed that the annual energy demand of the investigated building could be supplied by using the building's roof and façade for the BIPV application. The research also illustrated that climate plays an essential role in energy production by the BIPV systems as well as the net annual energy consumption of the building.

Aste et al., in 2016 [27], investigated a BIPV system performance (the first Italian BIPV project) to elaborate its technical and economic performances after thirteen years of continuous operation. The other aim of the investigation was to predict its lifetime performance. The degradation rate of the BIPV system after thirteen years of operation was equal to 0.37% per year, which was meaningfully less than the general degradation rate of the multi-crystalline silicon system (approximately 0.5% per year) [28]. Moreover, visual inspection and infrared spectroscopy showed that no BIPV module was damaged.

Wang et al. [29] also accomplished a study for environmental and economic assessments of a BIPV system by calculating the net present values (NPV) and the payback period (DPP) of the BIPV system of a building in Shanghai, China over its expected lifetime. The DPP of the system was obtained in 6.52 years, considering the feed-in tariff (FiT) program for renewable energy resources in China.

Naser W. Alnaserin [30] examined the performance of an 8.6 kW BIPV system with polycrystalline PV cells. The building was located at Awali Town, Kingdom of Bahrain, which is in an arid zone with high annual solar radiation. Because of the low cost of the electricity in Bahrain (8 cent for consumption up to 3000 kWh per month, worth mentioning that the electricity tariffs in Bahrain is subsidized while it is mainly produced by cheap oil) and lack of feed-in tariff (FiT) program, the payback time of the BIPV system was more than 600 years. The study concluded that if the FiT were set to 1 USD per kWh of solar electricity, the payback time would be equal five years. Furthermore, the study found out that by assuming the emission of one kg CO_2 per one kWh of electricity in Bahrain, system saving from GHG emission would be nine tons, annually.

Moreover, in recent years a number of researchers have sought to determine the economic feasibility of BIPV systems on the facades with north-facing or even west and east-facing orientation, considering the amount of radiation there. It is perceived that there seems to have been an assumption that these orientations and, more specifically, northern façades are unfeasible economically because the radiation there is low [3,12,15,19,21,27,29–37].

1.2. Problem statement

All the mentioned studies, however, did not evaluate the societal and environmental effects of the BIPV system on the economic analysis or LCCA. Furthermore, the total cost introduced to the economic analysis was the sum of both functions of the system (building skins and PV functionality).

The hypothesis of this study is that in the economic analysis of a roof-mounted or façade-mounted BIPV system as a substitute for the conventional building envelope materials (while an architect rarely does so for the traditional alternatives), what should be inserted into the calculations is the extra charges that BIPV system causes and not the overall cost. This amount is usually not a big part considering the total cost of a building's construction. In other words, the cost of a BIPV has two parts [38]. The first part represents the share of the costs that is avoided because no conventional building material (passive element) has to be used. The second part represents the actual additional costs that the owner needs to spend in order to apply a PV functionality (which is energy production) in its building skin. The total cost results from the sum of two contributions (building skins and PV functionality). In this study, the economic analysis related to the total cost as well as the second part has been accomplished.

Furthermore, the BIPV system would become more feasible economically (even for untraditional orientations) if the analysis takes the environmental and societal benefits of the BIPV system into consideration. Some of the most crucial environmental and societal advantages of BIPV systems are saving in transmission line lost power, saving in power delivery cost, saving form carbon tax and saving in building envelope material cost [2].

So far, the research to date has tended to focus on the technical and economic feasibility as well as aesthetic aspects of the BIPV system as a building envelope material for one specific direction of buildings or some directions of building skins with high irradiation potentials, rather than analysing the BIPV system as a building envelope material for the whole skins of building.

1.3. The aim of the study

The aim of this research project has therefore been to determine whether the BIPV system as an alternative for the building envelope materials is economically feasible for the whole skin of the buildings in Europe or not. The other objective of this study is also to evaluate a holistic lifecycle cost analysis (LCCA) of the BIPV systems on different façade orientations and flat roofs for the capitals of all the European Union member states (EU) as well as the capitals of Norway and Switzerland by taking the quantified environmental and societal benefits of the BIPV systems into consideration.

This paper is structured as follows. In section two, the methodology, input parameters, formulation and constraint is discussed. In section three, the results are demonstrated in detail. In section four, sensitivity analysis is done and finally, in section five, the conclusion is presented.

2. Methodology

From the literature review [39–43], it can be seen that different solar potential definitions and diverse approaches to calculate and classify the solar potential make it complicated to compare the output of studies. Therefore in the following section, the term "BIPV potential" is defined and classified first and then methodologies for BIPV potential assessment is presented.

There are four basic approaches currently available to evaluate the solar energy potential in an area [43] which are theoretical, geographical, technical and economic potential. The theoretical potential is defined as all the available irradiation in an area without any limitations (geographical or technical). The geographical potential is the fraction of the theoretical potential that is utilizable (because the land or area is available and suitable). The technical potential is defined as the fraction of the geographical potential that is technically useable (taking into account the efficiency of photovoltaic modules). Finally, the economic potential is the portion of the technical potential that is economically feasible. The feasibility could be based on an investors' or macroeconomic point of view.

In terms of the BIPV systems, these approaches are redefined and the methodologies, as well as required parameters and calculations, are explained in detail in later sections.

a. Theoretical potential

The theoretical potential of a region is all the solar radiation received by the region disregarding any technical or geometrical constraint. For instance, solar irradiation maps are placed in this category. Fig. 1 shows the theoretical potential of solar radiation in Europe and more specifically, global horizontal irradiance (GHI). GHI is the total amount of radiation received from above by a

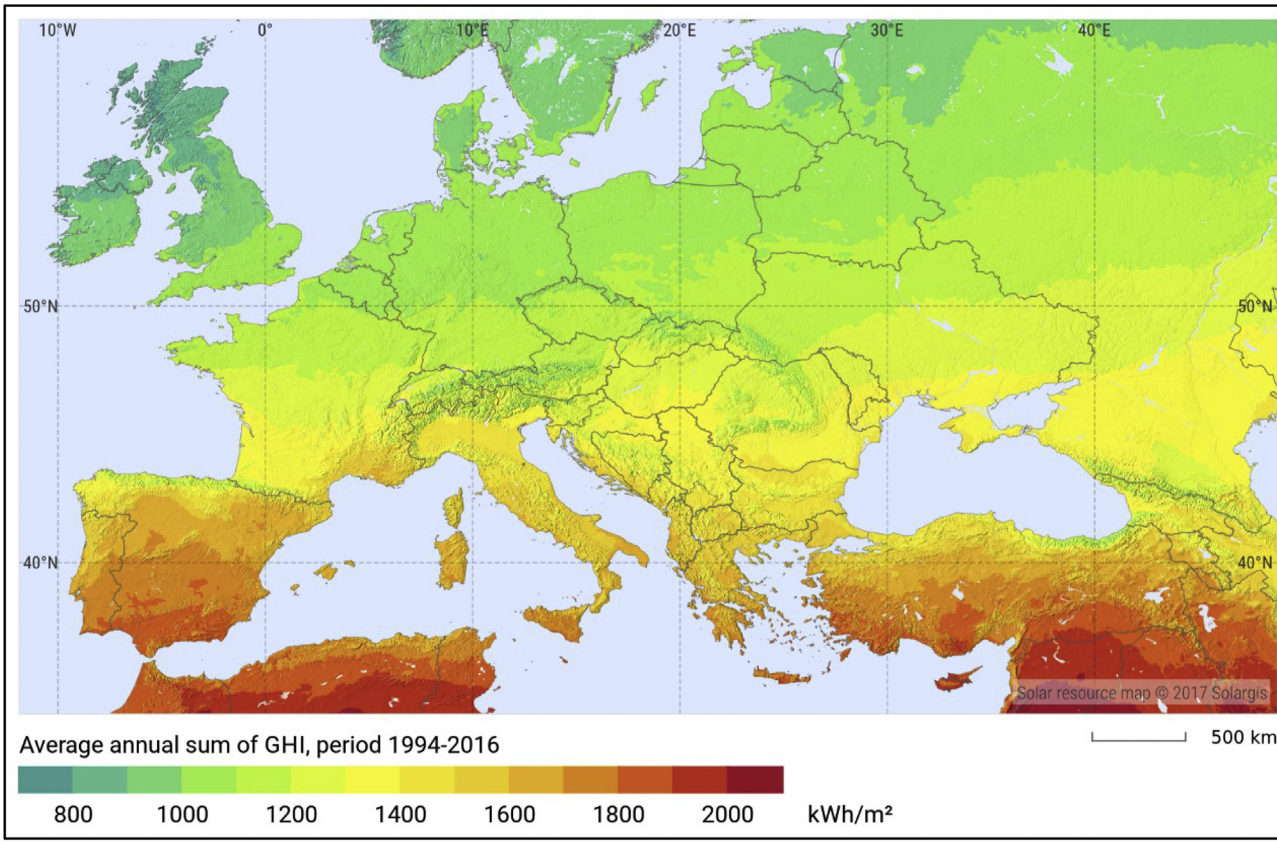


Fig. 1. The theoretical potential map of solar irradiance in Europe [44].

horizontal surface in the ground. GHI includes both direct irradiance and diffuse irradiance and is of particular interest to PV and BIPV installations.

b. Geographical potential

The geographical potential is the utilizable amount of theoretical potential. In other words, it is that fraction of the theoretical potential, which is suitable for solar energy systems. For example, if the case study is about solar radiation potential of BIPV in a city, the geographical potential is the aggregate of solar radiation on all available surfaces in city buildings.

Table 1 presents the average annual geographical irradiation potential on building skins in the capitals of all the European Union member states (EU) together with the capitals of Norway and Switzerland. The analysis and calculated amounts are based on the hourly incident radiation data between 2005 and 2016 from the Photovoltaic Geographical Information System (PVGIS) [45].

The technical potential is the produced power from the BIPV system in the region considering the technology and efficiency. From the geographical potential, the technical potential could be calculated. To be able to calculate the technical potential, the technology and efficiency of the BIPV module need to be specified.

The average overall efficiency of a BIPV system is varied depending on the technology, configuration, climate of the site, ventilation and etc. Based on the experimental projects done so far, it is between 10% and 22% [18,26]. Therefore, by taking the average efficiency of 18% for the BIPV panels -which is the average efficiency of commercialized BIPV panels in the market and not the system-, the technical potential can be simply calculated by multiplying the 18% (efficiency of the BIPV system) by the geographical potential. Based on this efficiency and the data in Table 1, the technical potential of BIPV systems for Europe is presented in Table 2. It is worth mentioning that the emerging PV materials and advances in technology promise more efficiencies for solar PV modules in the near future.

The portion of the BIPV technical potential which is economically feasible is called economic potential. The economic potential of the BIPV system usually needs more study because of various parameters involved with this subject such as technology, market price, energy tariffs, annual production, system degradation rate, possible subsidies, etc. The purpose of this study is to calculate the economic potential of building skins for the BIPV application.

The adopted life cycle cost analysis (LCCA) to this study as well as the input parameters in order to focus on the economic potential of BIPV systems on building skins of urban areas, is presented in the next sections.

2.1. Input parameters

Table 3 represents electricity tariffs, greenhouse gas emissions (GHG) and electric power transmission and distribution losses of the European countries. The electricity tariffs are for household consumers with annual electricity consumption of 2500–5000 kWh, including taxes based in 2018 figures. The average electricity tariff inflation rate for Europe is 2% [45]. The greenhouse gas emission (GHG) of each country depends on the resources used to produce electricity. For example, thanks to the substantial hydropower potential in Norway -practically all electricity produced is from hydropower-, the country has the lowest GHG emission rate from electricity production in Europe [46]. Switzerland is in a similar situation. The average electric power

Table 1
The average annual geographical irradiation potential on building skins of the capitals of the European Union member states (EU) with Norway and Switzerland.
c. Technical potential

No	Country	Capital	Average annual radiation (kWh/sq.m.)				
			Roof	South	East	West	North
1	Austria	Vienna	1225	1004	702	736	294
2	Belgium	Brussels	1073	902	649	656	295
3	Bulgaria	Sofia	1352	1042	797	743	332
4	Croatia	Zagreb	1312	1031	734	773	301
5	Cyprus	Nikosia	1928	1330	1044	1040	348
6	Czechia	Prague	1132	935	672	680	293
7	Denmark	Copenhagen	1051	926	634	664	271
8	Estonia	Tallinn	932	830	571	601	252
9	Finland	Helsinki	926	836	552	600	240
10	France	Paris	1174	975	712	667	302
11	Germany	Berlin	1079	922	661	652	288
12	Greece	Athens	1819	1286	990	997	338
13	Hungary	Budapest	1309	1069	756	762	302
14	Ireland	Dublin	975	862	613	597	291
15	Italy	Rome	1640	1262	937	846	309
16	Latvia	Riga	980	858	601	616	265
17	Lithuania	Vilnius	986	829	598	596	270
18	Luxembourg	Luxemburg	1121	900	677	681	300
19	Malta	Valleta	1875	1281	986	1056	341
20	Netherlands	Amsterdam	1065	902	636	675	291
21	Poland	Warsaw	1087	912	658	654	281
22	Portugal	Lisbon	1751	1277	953	1029	339
23	Romania	Bucharest	1406	1071	761	805	305
24	Slovakia	Bratislava	1253	1018	720	735	291
25	Slovenia	Ljubljana	1249	958	613	752	292
26	Spain	Madrid	1788	1401	1035	1015	321
27	Sweden	Stockholm	961	886	608	632	263
28	UK	London	1046	900	645	639	300
29	Norway	Oslo	911	865	568	594	245
30	Switzerland	Bern	1252	1045	754	735	302

Table 2
The average annual technical potential of the BIPV system for Europe.
d. Economic potential

No	Country	Capital	Average annual technical potential (kWh/sq.m.)				
			Roof	South	East	West	North
1	Austria	Vienna	220.5	180.72	126.36	132.48	52.92
2	Belgium	Brussels	193.14	162.36	116.82	118.08	53.1
3	Bulgaria	Sofia	243.36	187.56	143.46	133.74	59.76
4	Croatia	Zagreb	236.16	185.58	132.12	139.14	54.18
5	Cyprus	Nikosia	347.04	239.4	187.92	187.2	62.64
6	Czechia	Prague	203.76	168.3	120.96	122.4	52.74
7	Denmark	Copenhagen	189.18	166.68	114.12	119.52	48.78
8	Estonia	Tallinn	167.76	149.4	102.78	108.18	45.36
9	Finland	Helsinki	166.68	150.48	99.36	108	43.2
10	France	Paris	211.32	175.5	128.16	120.06	54.36
11	Germany	Berlin	194.22	165.96	118.98	117.36	51.84
12	Greece	Athens	327.42	231.48	178.2	179.46	60.84
13	Hungary	Budapest	235.62	192.42	136.08	137.16	54.36
14	Ireland	Dublin	175.5	155.16	110.34	107.46	52.38
15	Italy	Rome	295.2	227.16	168.66	152.28	55.62
16	Latvia	Riga	176.4	154.44	108.18	110.88	47.7
17	Lithuania	Vilnius	177.48	149.22	107.64	107.28	48.6
18	Luxembourg	Luxemburg	201.78	162	121.86	122.58	54
19	Malta	Valleta	337.5	230.58	177.48	190.08	61.38
20	Netherlands	Amsterdam	191.7	162.36	114.48	121.5	52.38
21	Poland	Warsaw	195.66	164.16	118.44	117.72	50.58
22	Portugal	Lisbon	315.18	229.86	171.54	185.22	61.02
23	Romania	Bucharest	253.08	192.78	136.98	144.9	54.9
24	Slovakia	Bratislava	225.54	183.24	129.6	132.3	52.38
25	Slovenia	Ljubljana	224.82	172.44	110.34	135.36	52.56
26	Spain	Madrid	321.84	252.18	186.3	182.7	57.78
27	Sweden	Stockholm	172.98	159.48	109.44	113.76	47.34
28	UK	London	188.28	162	116.1	115.02	54
29	Norway	Oslo	163.98	155.7	102.24	106.92	44.1
30	Switzerland	Bern	225.36	188.1	135.72	132.3	54.36

Table 3
Electricity tariffs, GHG and electric power transmission and distribution losses of the European countries.

LCCANo	Country	E_T (€) [45]	CO2 emission (g/kWh) [46]	Electric power transmission and distribution losses (%) [47]
1	Austria	0.201	156	5
2	Belgium	0.294	233	5
3	Bulgaria	0.101	585	9
4	Croatia	0.132	282	13
5	Cyprus	0.218	773	4
6	Czechia	0.159	587	5
7	Denmark	0.312	386	6
8	Estonia	0.142	1152	7
9	Finland	0.170	209	6
10	France	0.180	92	4
11	Germany	0.300	567	4
12	Greece	0.165	755	8
13	Hungary	0.112	368	12
14	Ireland	0.254	555	8
15	Italy	0.216	444	7
16	Latvia	0.151	185	9
17	Lithuania	0.110	262	22
18	Luxembourg	0.169	283	6
19	Malta	0.131	868	5
20	Netherlands	0.171	582	5
21	Poland	0.140	929	6
22	Portugal	0.229	355	10
23	Romania	0.132	413	11
24	Slovakia	0.146	211	2
25	Slovenia	0.164	351	5
26	Spain	0.248	305	10
27	Sweden	0.199	25	5
28	UK	0.202	584	8
29	Norway	0.191	19	6
30	Switzerland	0.166	37	7

transmission and distribution losses for the European Union is currently 6% [47].

According to the International Energy Agency (IEA), the world electricity demand increased by 4% in 2018. This growth rate is notably higher than the total increase in energy demand [48]. One reasonable solution to manage this growth rate is to produce electrical energy closer to the end-users. BIPV technology could be an excellent response for this purpose [2]. As per the IEA report of September 2017 [49], electricity prices reflect rising delivery costs while the electricity generation cost is declining. In terms of the USA, delivery costs are responsible for 36% of the total price of electricity for the end-user and for some countries this contribution reaches even 50%. Some components of delivery cost are transmission costs, distribution equipment expenses, charges for installing, operating, maintaining meters and sensors. Considering a depreciated estimate, generated electricity by a BIPV system can decrease the delivery cost of around 20% of the electricity [50].

The discount rate is the rate of interest that bank charges on its loans and can be defined based on two approaches of social discount rate and the financial (or individual) discount rate [51–53]. Although it changes from country to country, a discount rate of 5% has been applied to this study [51].

When it comes to the evaluation of BIPV economic feasibility, as mentioned earlier, that part of the investment which is caused by the system's application as an energy generator should be placed into the calculation. In other words, the real investment cost for a wall-mounted or roof-mounted BIPV system is the capital expenditure of the system minus the cost of the equivalent regular building material the PV is replacing as a building skin over the implemented area. Table 4 depicts the average cost of conventional façades and roofs in European countries [38] and the adopted prices for this analysis.

Table 4
End-user costs of conventional façades and roof materials in Europe (including VAT) [38].

Category	Material	Price Range €/sq.m.	Average Price €/sq.m	Adopted prices for this study
Facade	Wooden	80–380	230	230
	Stone	170–900	535	
	Metal	120–580	350	
	Brick ceramic	100–380	240	
	Fibrocement	90–220	155	
Roof	Thatch roofing	110–150	130	130
	Slates	90–170	130	
	Metal roofing	40–100	70	
	Ceramic tiles	40–90	65	
	Concrete tiles	30–60	45	

Table 5 represents the price range of a complete BIPV system in Europe (including structure, equipment and BOS) based on market research accomplished by Swiss BIPV Competence Centre at the University of Applied Sciences and Arts of Italian Switzerland [38,54] and the adopted values for this study. BIPV roof products cost averagely about 200 €/sq.m more expensive than conventional roof products (extra-cost) [38]. Moreover, the cost of BIPV facade products varies from 100 to 150 €/m^2 for a thin film BIPV façade (with a simple sub-structures and a low-efficiency PV technology) to 500–700 €/sq.m. for a high-efficiency BIPV crystalline module. The wide range of prices is mainly because of various products available in the market, including custom made components) [38].

According to the National Oceanic and Atmospheric Administration (NOAA) [55], the average surface temperatures on Earth rose 0.95° Celsius just between 1880 and 2016, and that growth has accelerated in recent years. In 2017, 159 countries signed the Paris Agreement to commit halting global warming at 1.5° Celsius above the Earth's average temperature before the industrial age (1870–2100). A recent study by the International Monetary Fund (IMF) [56] concluded that halting global warming to 2° Celsius or less requires immediate policy measures on a demanding scale, like planning to raise the carbon tax to 75 USD per ton by 2030. Although some countries have already started to align with this goal, there is still no carbon tax in some other countries like China, the United States, India, and Russia, even though those countries are responsible for half of the world's carbon emission until 2019. According to the World Bank data [57], currently (2019) there are just 25 countries in the world, out of the world's 195 nations, that have implemented carbon tax explicitly. The figures for 2019 is presented in Table 6.

A homogenous carbon tax (HCT) in Europe for the fossil fuel-based power resources and simultaneously, granting a subsidy or incentive equal to the mitigated amount of carbon by renewable energy resources, would be a considerable asset to shorten the reimbursement time of renewable energy investments more. This incentive will have a significant impact on the economic feasibility of BIPV systems considering their dual functionality.

Therefore, an HCT in European countries should happen as soon as possible. The HCT should start at a lower rate (in order to not lead to a shock to the economy of those of European countries, which have not even started to prepare such a fundamental change) and with a reasonable growth rate in order to meet the 2 °C goal. The evaluated plan in this study is that the HCT starts with the amount of 50 € per ton for 2020 and then, with the growth rate of 4%, the amount of HCT in 2030 will reach 74 € per ton. At the same time, according to the historical data of the European Environment Information and Observation Network (Eionet) the GHG emission from electricity production is experiencing a reduction rate of 2.1% per year [58]. Table 7 presents the estimated HCT as well as GHG emission of Europe from 2020 to 2050. In order to see the effect of an HCT on the economic feasibility of BIPV systems in each of European countries, the GHG emission of each country has been applied to this analysis with a decline rate of 2.1%.

Table 6
Carbon Tax of countries which already implemented [57].

Rank	Country	USD carbon Tax per ton [57]
1	Sweden	121.29
2	Liechtenstein	96.57
3	Switzerland	96.57
4	Finland	68.43
5	Norway	57.14
6	France	49.23
7	Iceland	31.30
8	Denmark	25.91
9	Ireland	22.07
10	UK	21.79
11	Slovenia	19.09
12	Spain	16.56
13	Canada	15.13
14	Portugal	14.06
15	South Africa	8.29
16	Argentina	6.24
17	Chile	5.00
18	Colombia	4.99
19	Latvia	4.97
20	Singapore	3.63
21	Mexico	3.00
22	Japan	2.65
23	Estonia	2.21
24	Ukraine	0.38
25	Poland	0.08

2.2. LCCA formulation

The basis of the lifecycle cost analysis (LCCA) in this study is three financial tools, which are net present value (NPV), discounted payback period (DPP) and internal rate of return (IRR). Net present value is a tool to presents the net difference between the profits and costs of the system in the present which is calculated by the difference between the present value of profits and the present value of costs. The discounted payback period is the minimum time it takes to refund the investment costs of the system. Internal rate of return is the interest rate at which the NPV of all the cash flows (both cash inflows and cash outflows) from a project or investment equals zero [2,59,60]. IRR is used to evaluate the economic feasibility of investment. If the IRR of the investment exceeds the required interest rate, that project is suitable. If IRR falls below the

Table 5
End-user costs of conventional façades and roof materials in Europe [38,54].

Category	Price Range €/sq.m.	BIPV Power W_P/sq.m	Average Price €/sq.m	Adopted values for this study	
				BIPV Power W_P/sq.m	BIPV Price €/sq.m
Facade	100–700	50–150	450	120	450
Roof	300–400	80–160	350	150	350

Table 7
The estimated HCT and GHG emission of Europe according to the historical data.

Year	Adopted HCT (€)	GHG (g/kWh) [58]
2020	50.00	271.72
2021	52.00	266.02
2022	54.08	260.43
2023	56.24	254.96
2024	58.49	249.61
2025	60.83	244.37
2026	63.27	239.24
2027	65.80	234.21
2028	68.43	229.29
2029	71.17	224.48
2030	74.01	219.76
2031	76.97	215.15
2032	80.05	210.63
2033	83.25	206.21
2034	86.58	201.88
2035	90.05	197.64
2036	93.65	193.49
2037	97.40	189.42
2038	101.29	185.45
2039	105.34	181.55
2040	109.56	177.74
2041	113.94	174.01
2042	118.50	170.35
2043	123.24	166.77
2044	128.17	163.27
2045	133.29	159.84
2046	138.62	156.49
2047	144.17	153.20
2048	149.94	149.98
2049	155.93	146.83
2050	162.17	143.75

required interest rate, the project should be rejected. In other words, IRR is the discount rate when the NPV of particular cash flows is equal to zero. Therefore, the higher the IRR, the more potential a project has.

NPV can be expressed as follows [2,29]:

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

C_I, C_O, D_R, y, and n are cash inflows, cash outflows, discount rate, the expected lifetime of BIPV (years) and the number of the year, respectively.

C_I is the money gained from the BIPV system. Sold electricity to the network and saving from the societal and environmental advantages are some examples of cash inflows for a BIPV system. C_O is the money that is spent on the system. The initial investment, O&M cost and inverter replacement cost are some examples of cash outflows for a BIPV system. A BIPV system is considered healthy or feasible economically if the total C_I becomes greater than the total C_O.

The initial investment of BIPV systems, Q, is calculated by (3):

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

I_{PIC} and I_{EMC} stand for project investment cost and equivalent envelope material cost, respectively.

C_I of the BIPV system in year n can be presented as (4):

$$C_I = E_T \times E_G + S_{PB} \tag{3}$$

E_T, E_G and S_{PB} represent electricity tariff, BIPV annual electricity generation and the projected benefit, respectively. E_G of each year can be calculated by the following equation:

$$E_{Gn} = E_{G1} \times (1 - P_{DR})^n \tag{4}$$

The P_{DR} represents the degradation rate of BIPV panels. P_{DR} is a term used to describe the decline in output power of the BIPV system over time. A study led by Jordan and Kurtz [28] gathered nearly 2000 degradation rates, measured on individual modules or entire systems from the literature and found that the median degradation rate is 0.5% per year. The other study, in this regard, is the study done by Niccolò Aste et al. [27]. The study dealt with a BIPV syatem after 13 years of operation and the results obtained showed that the analysed BIPV degradation rate is equal to 0.37%/year. Therefore, the degradation rate of 0.5% per year has been adopted in this study.

The projected benefit, S_{PB}, can be calculated as follows:

$$S_{PB} = S_{TL} + S_{PD} + S_{CT} \tag{5}$$

S_{TL}, S_{PD}, and S_{CT} are the saving from the electric power transmission and distribution losses, saving from power delivery cost, and saving from carbon tax and can be calculated as below:

$$S_{TL} = \mathrm{P}_{TL} \times E_T \times E_G \tag{6}$$

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

$$S_{CT} = \mathrm{C}_T \times E_{kWh} \times E_G \tag{8}$$

P_{TL}, P_{DC}, C_T, and E_{kWh} represent the electric power transmission and distribution losses ratio (in percent), the saving percentage from power delivery cost, carbon tax, and the average CO_2 emission per kWh, respectively.

C_O of the BIPV in year n can be shown as (6):

$$C_O = C_{OM} + C_{RC}(if\ n = 10, 20) \tag{9}$$

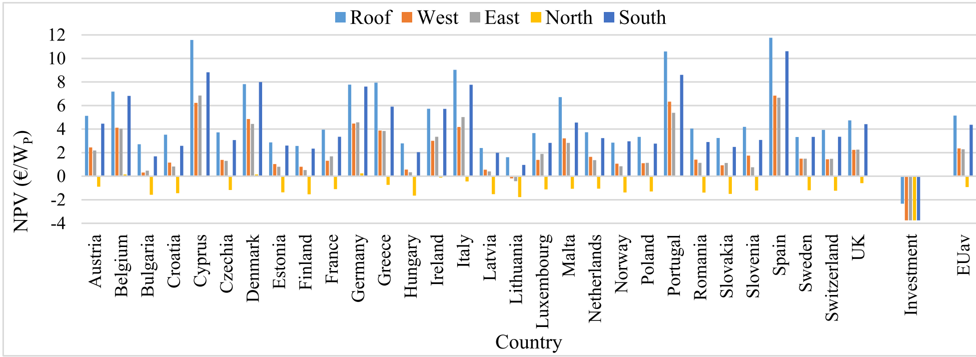
C_{OM} and C_{RC} stand for the cost of operation and maintenance and the cost of inverter replacement, respectively. The cost due to the replacement of BIPV inverters (equipment and labor costs) is averagely 17% of the whole BIPV system's initial cost and the BIPV inverters' expected lifetime is usually 10 years [2,21]. Therefore, an inverter replacement cost equal to 17% of the initial cost of the BIPV system for every 10th year of operation was inserted into the LCCA. The BIPV system has low maintenance and servicing requirements. Annual operation and maintenance (O&M) costs of a BIPV system is assumed to be 1% of the initial cost of BIPV system for this study [2].

The net cash flow of the year n, N_{Cn}, which refers to the difference between the BIPV system's cash inflows and outflows in the given period, can be expressed as:

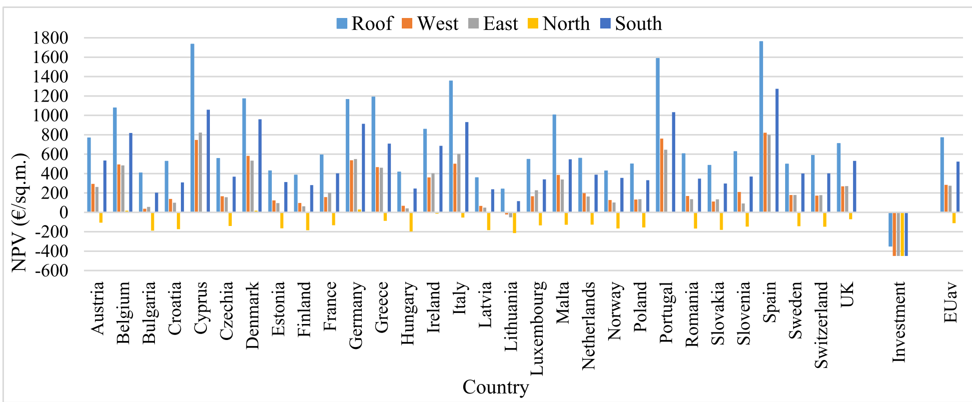
$$N_{Cn} = C_I - C_O \tag{10}$$

The cumulative NPV of the BIPV system can be computed as the following formula:

$$\mathrm{NPV} = -Q + N_{C1} / (1 + D_R)^1 + N_{C2} / (1 + D_R)^2 + \ldots + N_{Cy} / (1 + D_R)^y = -Q + \sum_{n=1}^{y} N_{Cn} \Big/ (1 + D_R)^n \tag{11}$$



(a)



(b)

Fig. 2. The cumulative NPV of BIPV systems for building skins with different orientations in the European countries: (a) NPV per watt-peak, (b) NPV per square meter.

D_R Represents the discount rate. The DPP of the BIPV system can be determined by solving the following equation:

$$\sum_{n=1}^{Ypp} N_{Cn} \Big/ (1+D_R)^n = Q \tag{12}$$

Y_{pp} represents the number of the year in which the investment is equal to the cumulative net present value of the incomes (payback time).

Finally, the IRR of the BIPV system can be determined. The formula for calculating IRR is the same formula as Eq. (10) except that zero replaces the NPV and the discount rate (D_R) is replaced by the internal rate of return (IRR), as shown in Eq. (12):

$$-Q + \sum_{n=1}^{y} N_{Cn} \Big/ (1+IRR)^n = 0 \tag{13}$$

2.3. Constraints

This study does not take the amounts of GHG emissions during the manufacturing/disposal of the BIPV panels into consideration.

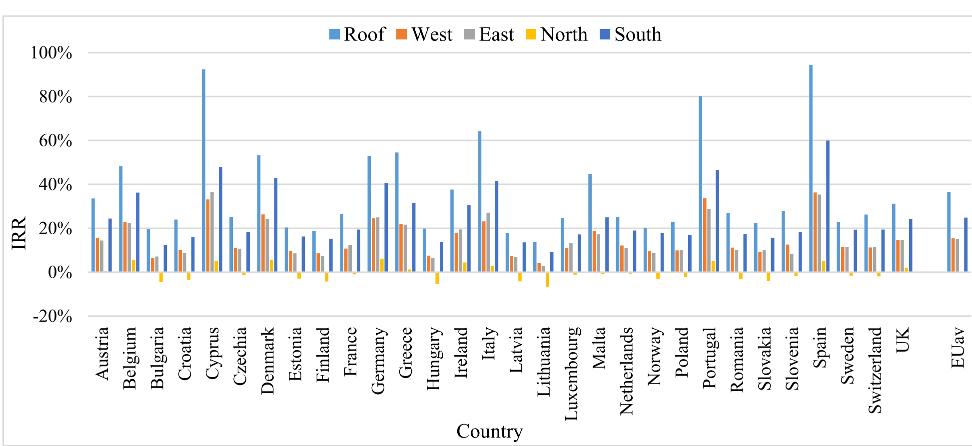


Fig. 3. IRR of BIPV systems for building skins with different orientations in the European countries.

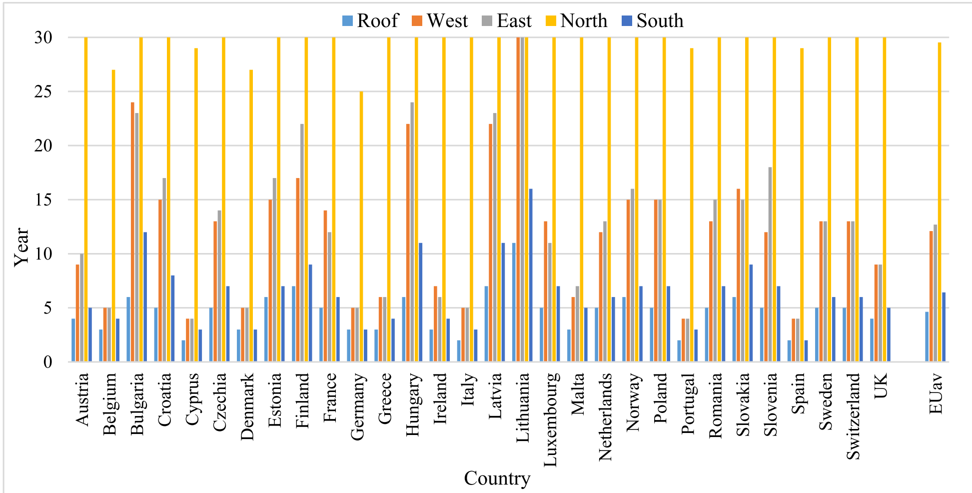


Fig. 4. DPP of BIPV systems for building skins with different orientations in the European countries.

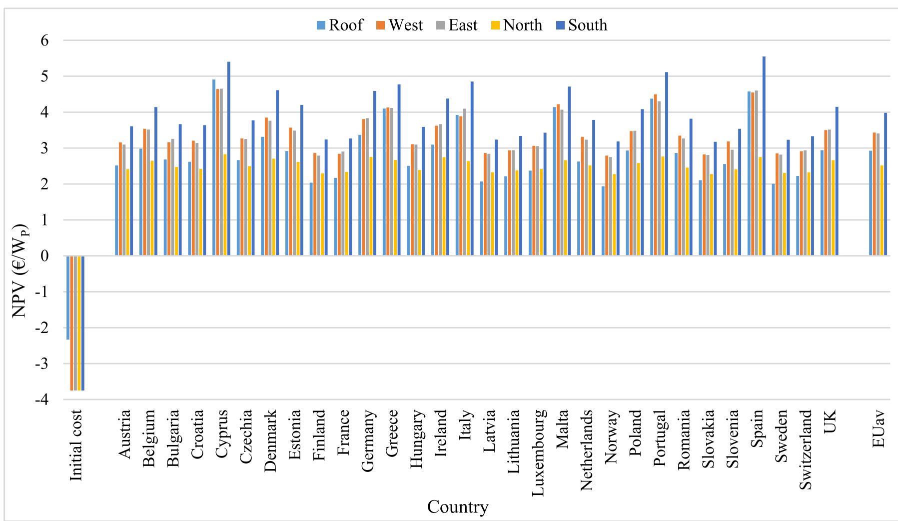


Fig. 5. The cumulative NPV advantages of BIPV systems for building skins with different orientations in the European countries.

However, the BIPV modules and components contain glass, aluminum and semiconductor materials that can be successfully recovered and reused, either in new modules or other products. There have been recent suggestions on methods for end-of-life recovery of these materials. However, there is still a lack of reliable scientific or empirical data and established recycling strategies [60]. A contribution to this research could be to investigate the effect of the manufacturing/disposal procedure of BIPV products and their alternatives for building skins applications on this LCCA analysis.

Moreover, the constraints related to the urban context of the case studies such as buildings' shading, building barriers, historical, architectural and regulatory constraints were not taken into account for this study because of two reasons; first, the goal of this study is to compare the status of the BIPV technology in European countries and such constraints would affect all cases. Second, such considerations would make the analysis much more complicated because the urban context of each city is different from other cities. Another contribution to this work could be evaluating the effect of the urban context of the capitals or urban constraints on the outcome of this study.

Finally, in terms of the energy mix, the study is dealing with the energy production of the countries and not the energy consumption. For example, the average GHG emission factor in Norway, which is caused by electricity production, was estimated at 18,9 g/kWh in 2018 [61]. However, by selling this almost clean energy to other countries and purchasing electricity from other countries with mostly fossil fuel resources, the average GHG emission of electricity consumption rises to more than 100 g/kWh [62]. Therefore between two approaches of choosing either energy production or energy consumption as reference for GHG emission, this study adopted the energy production of the countries.

3. Results

The analysis was done in Excel and the data together with the

Table 8
The cumulative NPV of societal and environmental benefits per watt peak for different orientations of building skins in the European countries.

Parameter	Saving from carbon tax (€/W_P)					Saving from electric power transmission and distribution losses (€/W_P)					Saving from power delivery cost (€/W_P)					Saving from equivalent building envelope cost (€/W_P)	
Orientation Country	Roof	West	East	North	South	Roof	West	East	North	South	Roof	West	East	North	South	Roof	Facades
Austria	0.22	0.16	0.16	0.07	0.22	0.29	0.22	0.21	0.09	0.29	1.15	0.86	0.82	0.34	1.17	0.87	1.92
Belgium	0.28	0.22	0.21	0.10	0.30	0.37	0.28	0.28	0.13	0.39	1.47	1.12	1.11	0.50	1.54	0.87	1.92
Bulgaria	0.90	0.62	0.66	0.28	0.87	0.28	0.20	0.21	0.09	0.27	0.63	0.43	0.47	0.19	0.61	0.87	1.92
Croatia	0.42	0.31	0.29	0.12	0.41	0.52	0.39	0.37	0.15	0.51	0.81	0.59	0.56	0.23	0.79	0.87	1.92
Cyprus	1.69	1.14	1.15	0.38	1.46	0.39	0.26	0.26	0.09	0.34	1.96	1.32	1.32	0.44	1.69	0.87	1.92
Czechia	0.76	0.57	0.56	0.24	0.78	0.21	0.16	0.15	0.07	0.22	0.83	0.63	0.62	0.27	0.86	0.87	1.92
Denmark	0.46	0.36	0.35	0.15	0.51	0.46	0.36	0.35	0.15	0.50	1.53	1.21	1.15	0.49	1.68	0.87	1.92
Estonia	1.22	0.98	0.93	0.41	1.36	0.22	0.17	0.16	0.07	0.24	0.61	0.50	0.47	0.21	0.68	0.87	1.92
Finland	0.22	0.18	0.16	0.07	0.25	0.22	0.18	0.16	0.07	0.25	0.73	0.59	0.54	0.24	0.83	0.87	1.92
France	0.12	0.09	0.09	0.04	0.13	0.20	0.14	0.15	0.06	0.20	0.98	0.70	0.74	0.32	1.02	0.87	1.92
Germany	0.70	0.53	0.53	0.23	0.74	0.30	0.23	0.23	0.10	0.32	1.51	1.14	1.15	0.50	1.61	0.87	1.92
Greece	1.56	1.07	1.06	0.36	1.38	0.28	0.19	0.19	0.06	0.25	1.39	0.95	0.95	0.32	1.23	0.87	1.92
Hungary	0.55	0.40	0.40	0.16	0.56	0.41	0.30	0.29	0.12	0.42	0.68	0.50	0.49	0.20	0.69	0.87	1.92
Ireland	0.62	0.47	0.48	0.23	0.68	0.46	0.35	0.36	0.17	0.51	1.15	0.88	0.90	0.43	1.27	0.87	1.92
Italy	0.83	0.53	0.59	0.19	0.80	0.58	0.37	0.41	0.14	0.55	1.65	1.06	1.18	0.39	1.59	0.87	1.92
Latvia	0.21	0.16	0.16	0.07	0.23	0.31	0.24	0.24	0.10	0.34	0.69	0.54	0.53	0.23	0.75	0.87	1.92
Lithuania	0.29	0.22	0.22	0.10	0.31	0.55	0.42	0.42	0.19	0.58	0.50	0.38	0.38	0.17	0.53	0.87	1.92
Luxembourg	0.36	0.27	0.27	0.12	0.36	0.26	0.20	0.20	0.09	0.27	0.88	0.67	0.67	0.29	0.88	0.87	1.92
Malta	1.85	1.30	1.22	0.42	1.58	0.28	0.20	0.19	0.06	0.24	1.14	0.80	0.75	0.26	0.97	0.87	1.92
Netherlands	0.70	0.56	0.53	0.24	0.75	0.21	0.17	0.16	0.07	0.22	0.85	0.67	0.63	0.29	0.90	0.87	1.92
Norway	0.02	0.02	0.02	0.01	0.02	0.24	0.20	0.19	0.08	0.29	0.81	0.66	0.63	0.27	0.96	0.87	1.92
Poland	1.15	0.86	0.87	0.37	1.20	0.21	0.16	0.16	0.07	0.22	0.71	0.53	0.53	0.23	0.74	0.87	1.92
Portugal	0.71	0.52	0.48	0.17	0.64	0.93	0.69	0.64	0.23	0.85	1.87	1.37	1.27	0.45	1.70	0.87	1.92
Romania	0.66	0.47	0.45	0.18	0.63	0.47	0.34	0.32	0.13	0.45	0.86	0.62	0.58	0.23	0.82	0.87	1.92
Slovakia	0.30	0.22	0.22	0.09	0.31	0.09	0.06	0.06	0.02	0.09	0.85	0.62	0.61	0.25	0.87	0.87	1.92
Slovenia	0.50	0.38	0.31	0.15	0.48	0.24	0.18	0.15	0.07	0.23	0.95	0.72	0.58	0.28	0.91	0.87	1.92
Spain	0.62	0.44	0.45	0.14	0.61	1.03	0.73	0.75	0.23	1.01	2.06	1.46	1.49	0.46	2.02	0.87	1.92
Sweden	0.03	0.02	0.02	0.01	0.03	0.22	0.18	0.18	0.08	0.26	0.89	0.73	0.70	0.30	1.03	0.87	1.92
Switzerland	0.05	0.04	0.04	0.02	0.05	0.34	0.25	0.25	0.10	0.35	0.97	0.71	0.73	0.29	1.01	0.87	1.92
UK	0.69	0.53	0.54	0.25	0.75	0.39	0.30	0.30	0.14	0.42	0.98	0.75	0.76	0.35	1.06	0.87	1.92

formulation and method is publicly available in the Mendeley database. The starting date for the system evaluation is the year 2020. Considering an expected lifetime of 30 years, the system will operate until 2050. Fig. 2 depicts the cumulative net present value of the different orientations of building skins in the European countries per watt peak as well as square meter. Watt peak (W_P) is the output power achieved by a BIPV module under full solar radiation and standard test conditions. From Fig. 2 can be seen that even with a high electricity tariff in some countries such as Denmark and Germany, countries with higher radiation potential like Spain, Cyprus and Portugal still have a higher cumulative net present value out of the expected lifetime of the BIPV system. The figure also reveals that the BIPV system as an envelope for the north facade has economic feasibility in some countries like Belgium,

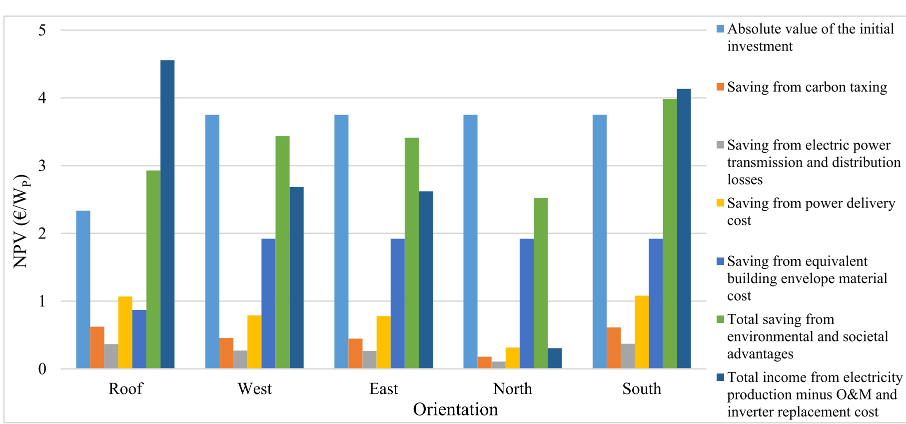


Fig. 6. The average cumulative NPV of factors for different orientations in Europe.

Table 9
BIPV cumulative NPV of cash inflows and cash outflows for different orientations of building skins in the European countries.

Parameter	Total income from electricity production minus O&M and inverter replacement cost (€/sq.m.)					Total saving from environmental and societal advantages (€/sq.m.)					Total investment cost (€/sq.m.)	
Orientation Country	Roof	West	East	North	South	Roof	West	East	North	South	Roof	Facades
Austria	741	364	340	54	552	378	379	372	289	433	350	450
Belgium	981	520	513	150	772	447	424	422	317	497	350	450
Bulgaria	356	108	127	−36	213	402	380	391	297	440	350	450
Croatia	486	204	186	−14	323	393	385	377	290	436	350	450
Cyprus	1350	640	643	113	861	736	557	558	339	648	350	450
Czechia	508	224	220	10	365	400	392	390	300	453	350	450
Denmark	1027	571	538	143	857	497	462	451	325	553	350	450
Estonia	343	145	130	−28	258	438	428	418	313	504	350	450
Finland	430	203	175	−10	343	306	344	335	276	389	350	450
France	618	266	295	37	460	325	341	348	280	392	350	450
Germany	1011	530	539	149	813	505	457	460	330	551	350	450
Greece	926	420	416	42	586	615	496	494	320	573	350	450
Hungary	392	145	143	−34	265	375	373	372	287	430	350	450
Ireland	745	377	391	105	611	464	435	440	330	525	350	450
Italy	1118	485	554	81	799	588	466	492	316	582	350	450
Latvia	398	172	165	−13	300	311	344	341	279	388	350	450
Lithuania	259	76	77	−49	165	333	352	353	285	400	350	450
Luxembourg	543	249	247	25	379	356	367	366	290	411	350	450
Malta	736	329	297	3	431	621	507	488	319	565	350	450
Netherlands	516	250	226	21	385	394	397	388	302	454	350	450
Norway	488	243	226	11	423	291	335	330	273	382	350	450
Poland	411	166	168	−15	292	440	416	418	310	490	350	450
Portugal	1282	671	610	119	869	656	539	516	332	614	350	450
Romania	528	218	197	−12	340	429	401	392	295	458	350	450
Slovakia	521	223	215	−4	367	316	339	337	273	381	350	450
Slovenia	595	277	198	15	395	383	382	354	289	424	350	450
Spain	1426	725	742	125	1058	686	546	552	330	666	350	450
Sweden	549	286	270	30	463	301	342	338	277	388	350	450
Switzerland	606	273	284	22	452	333	349	352	279	400	350	450
UK	620	299	303	60	483	441	420	422	319	498	350	450

Cyprus, Denmark, Germany etc. Several factors such as high electricity tariff, high carbon emission per kilowatt-hour, high irradiation potential, etc. could lead to the economic feasibility of the north façade in such countries.

Fig. 3 provides the internal rate of return of BIPV systems for building skins with different orientations in the European countries. The internal rate of return for the roof-mounted BIPV systems in three countries is more than 80%, which are Cyprus, Portugal and Spain. Furthermore, the average internal rate of return for the BIPV system on the north facades of the buildings in Europe is equal to zero. It means that, contrary to expectations, the north façade-mounted BIPV system can reimburse all the invested money during its lifetime with a discount rate of zero percent.

Fig. 4 illustrates the discounted payback time of BIPV systems as a substitute for the traditional building envelope materials with different orientations in the European countries. The DPP is limited to up to 30 years, which is equal to the general expected lifetime of the system by the manufacturers. It means that the manufacturers guarantee that BIPV panels can still produce at least 80% of their initial rated power of peak power after 30 years. A DPP of 30 years means that the investment will not be refunded during the system's expected lifetime. The average DPP of the BIPV system in Europe at a discount rate of 5% on the roof, south, east, west and the north facades are 5, 6, 13, 12 and 30 years, respectively.

Fig. 5 shows the cumulative net present values of BIPV advantages as a building envelope with different orientations in the European countries. In order to comprehend the societal and environmental advantages of a BIPV system and be able to compare, the initial investment of the system is indicated in the figure as well. It is worth mentioning that the figure is based on the discount rate of 5%. The average cumulative net present values of societal and environmental advantages of the BIPV system in Europe on the roof, south, east, west and the north facades are 2.9, 4, 3.4, 3.4 and 2.5 years, respectively.

Table 8 presents the cumulative net present values of the societal and environmental advantages per watt peak for different orientations of building skins in the European countries. The advantages are categorized into four subgroups of saving from carbon tax, electric power transmission and distribution losses, power delivery cost and equivalent building envelope cost. The average amounts of the societal and environmental advantages of the BIPV system in Europe together with the total NPV income from electricity production minus O&M and inverter replacement cost for different orientations of a building is illustrated in Fig. 6. It can be seen that in terms of the east, west and north façade, the quantified amount of societal and environmental advantages of the BIPV system in Europe is higher than the income from electricity production. In terms of the south façade and the roof orientations, the total NPV income from electricity production is more significant compared to the monetized amount of societal and environmental benefits of the BIPV system.

Table 9 demonstrates the components of cumulative net present values of BIPV systems on the different directions of the building envelope for all 30 countries in detail. In other words, the numbers represent the cumulative net present values of the cash inflows and cash outflows during the expected lifetime of the system.

Fig. 7 represents the average lifetime cumulative net present value of BIPV with different orientations for Europe. The analysed surfaces are roof area, south, west, east and north facades. As could be predicted, the roof area has the best economic feasibility for the BIPV systems in Europe. On the other hand, the result shows that taking the societal and environmental benefits of BIPV systems into

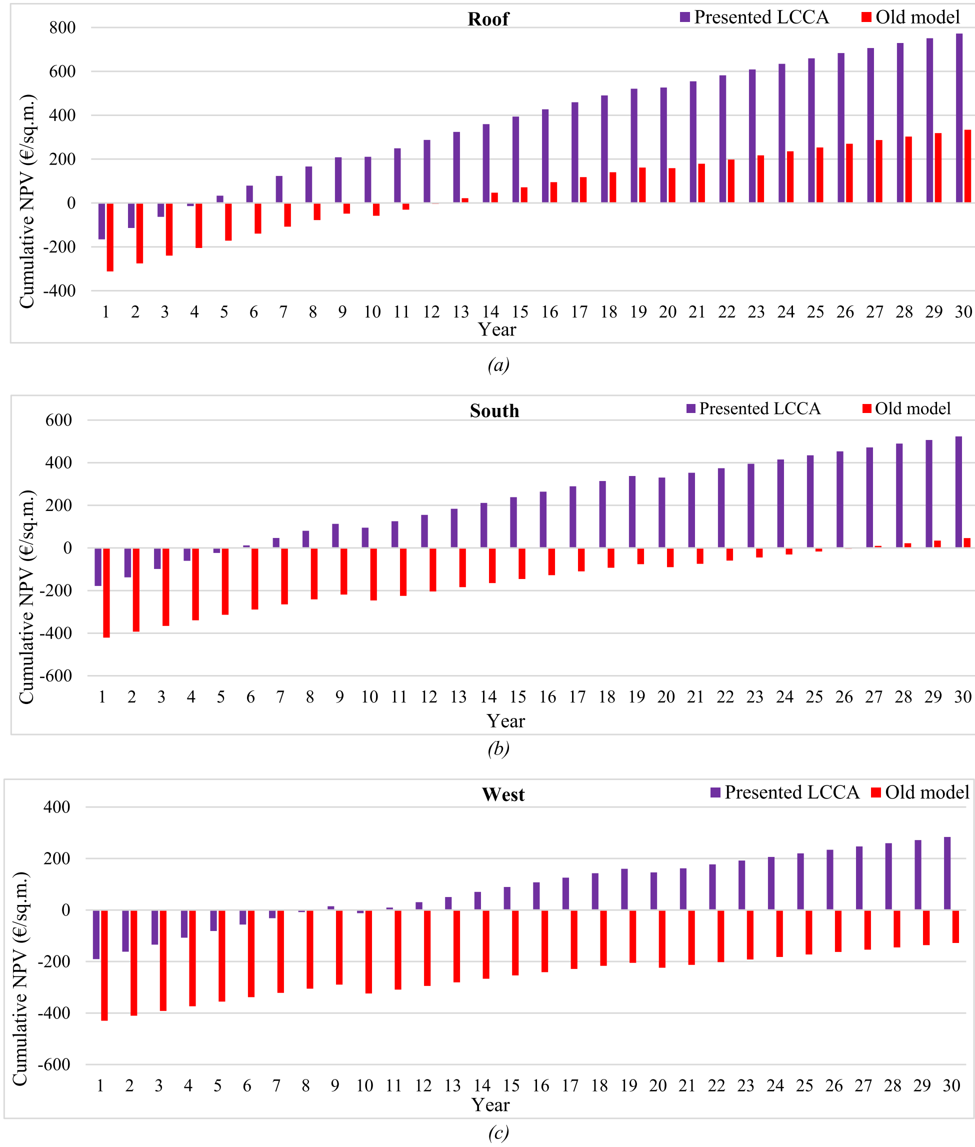


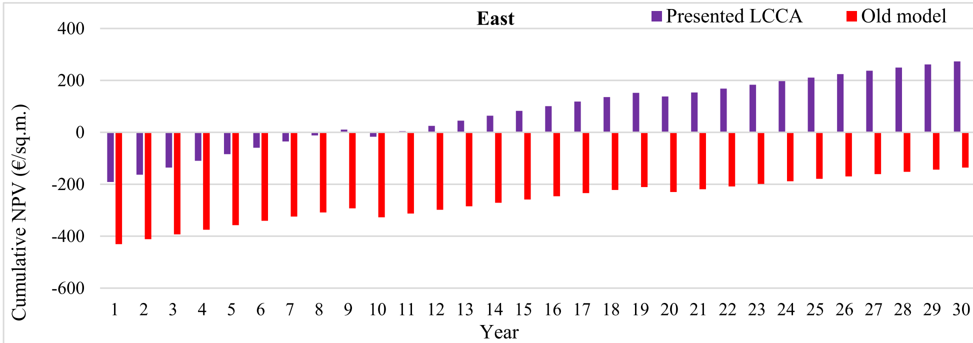
Fig. 7. The average lifetime cumulative NPV of BIPV with different orientation for Europe: (a)roof; (b)south; (c)west; (d)east; (e)north.

the economic analysis has the best impact on the south façade and increase the cumulative net present value of the system 478 (€/sq.m.) compared to the old model. This growth for the east, west, north and roof area is 409, 412, 302, and 439 (€/sq.m.), respectively.

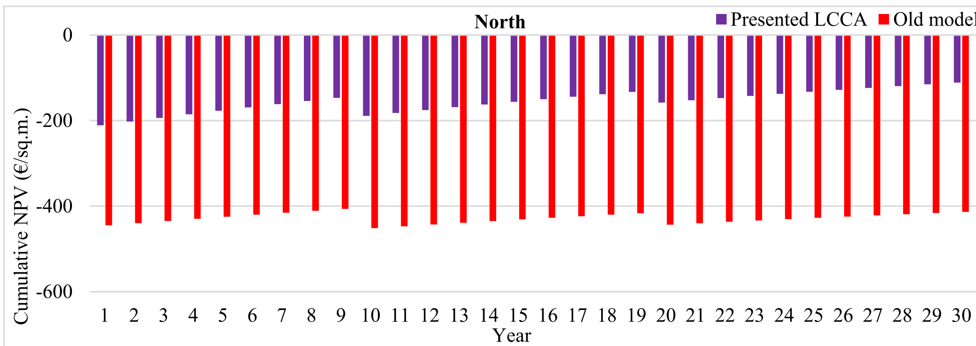
In order to see the performance of the BIPV system as a building envelope material for the whole building skins with all orientations (which in this study are south, east, west, north façade and roof area), the cumulative net present value of BIPV materials for the whole building envelope in European countries is presented in Fig. 8. To clarify the procedure of the calculation, the average price of conventional building envelope materials for the whole building skins as an example is calculated as follows:

$$C_{EU,AV,Conv} = (I_{EMC,S} + I_{EMS,W} + I_{EMC,E} + I_{EMC,N} + I_{EMC,R}) / 5 = (230 + 230 + 230 + 230 + 130) / 5 = 210 \quad (14)$$

$I_{EMC,S}$, $I_{EMC,W}$, $I_{EMC,E}$, $I_{EMC,N}$, $I_{EMC,R}$ and $C_{EU,AV,Conv}$ stand for equivalent envelope material cost of the south facade, west facade, east facade, north facade, roof, and the average price of conventional building envelope materials, respectively.



(d)



(e)

Fig. 7. (*continued*).

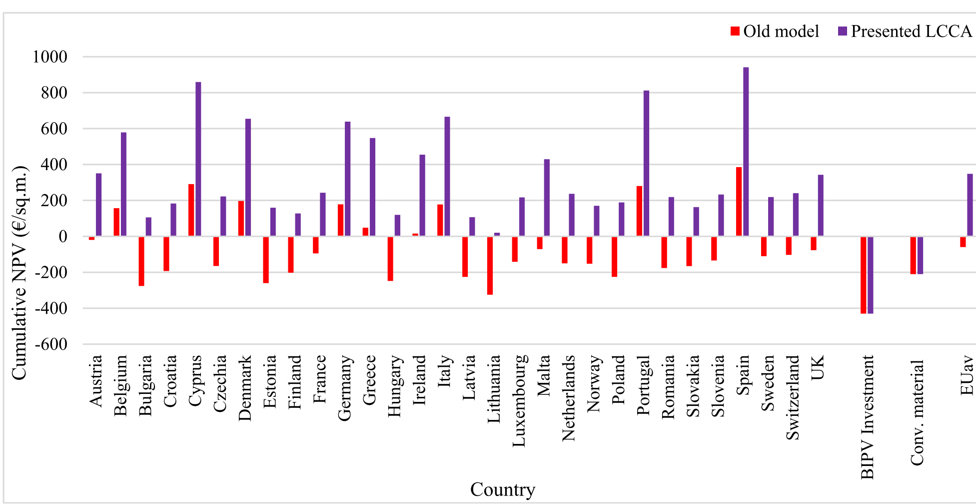


Fig. 8. The cumulative NPV of BIPV materials for the whole building envelope in European countries.

Finally, Fig. 9 shows the average lifetime cumulative NPV of the BIPV envelope in Europe. In other words, it can be said that the presented cash flows represent the average NPV of Europe for one square meter of a surface containing 0.2 square meters of south, east, west, north and roof orientations.

What is interesting in the results in Fig. 9 is that, if the building envelope with all directions is used for BIPV application, the total investment will be almost reimbursed even without taking the societal and environmental advantages of the BIPV system into account. In other words, the BIPV system in Europe has the potential to be introduced as a building envelope material that could refund its initial investment cost while the reimbursement or payback time even does not make sense when it comes to the economic feasibility of the alternative options (conventional

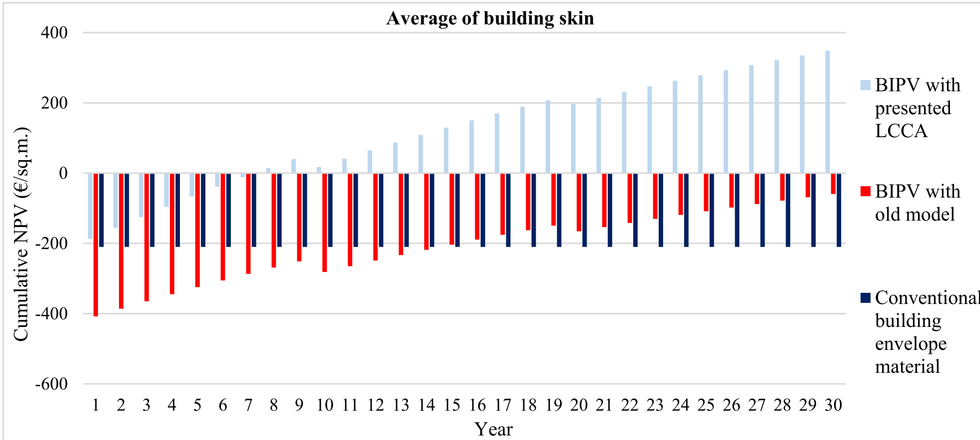


Fig. 9. The average lifetime cumulative NPV of building envelope in Europe.

building envelope materials.)

4. Sensitivity analysis

A sensitivity analysis is done to figure out how much the cumulative net present value of the BIPV system would change if the different variable changes. Sensitivity analysis is an assessment to depict how the uncertainty in the output of a mathematical model can be divided or allocated to the different uncertainty sources in its inputs. For this purpose, the dataset of Fig. 8 with light blue colors (the average cumulative NPV of BIPV with quantified values of societal and environmental benefits of the system in Europe) was selected as a reference.

Fig. 10 illustrates the sensitivity analysis of various inputs on the output. The relationship between the discount rate and cumulative NPV is a nonlinear concave relationship and the NPV varies from 700 (€/sq.m.) to zero for discount rate variation from one to 17%.

As can be predicted, the relationship between the BIPV price and cumulative NPV is a negative linear relationship and the NPV varies from zero to 700 (€/sq.m.) when the BIPV investment per square meter of building skins changes from 800 (€/sq.m.) to 100 (€/sq.m.).

The relationship between the cumulative net present value and the traditional building envelope material price, BIPV efficiency, electricity tariff, power delivery cost, electric power transmission and distribution losses rate, and carbon tax are all positive linear relationships with different growth rates.

5. Conclusion

The main goal of this study was to assess the economic feasibility of the BIPV systems as an envelope material for the whole skin of buildings with different orientations in the capitals of the all the European Union member states (EU) as well as the capitals of Norway and Switzerland. The study took the environmental and societal advantages of BIPV systems into the economic analysis and it has gone some way towards enhancing the understanding of the BIPV system as an option for the building skins and its economic feasibility in such a perspective.

One of the most significant findings to emerge from this study is that even the north façade is economically feasible in some countries in Europe if all the environmental and societal benefits of the BIPV system are being taken into consideration. The results of this investigation also showed that the BIPV system as a building envelope material for the whole building skins could reimburse all the investment costs and become even a source of income for the building.

The results that were provided throughout this research and the conclusions that were drawn should be taken into account by the government, academia, architects and the BIPV industry. It has become clear that the perception of BIPV technology as an unfeasible system on the building skins should change to the BIPV materials as an option for the building envelope no matter what direction or orientation. In other words, when an architect is looking for an option among building envelope materials in the market, the BIPV should be seen as a reasonable option with an at least one privilege compared to the other alternatives, which is the dual functionality of the system that makes the envelope a source of income for the building.

The presented study could not only help the end-user and architects to acknowledge the BIPV system as a suitable option for the building skins in Europe but also steer governments or decision-makers to promote the technology by rational subsidies and incentives.

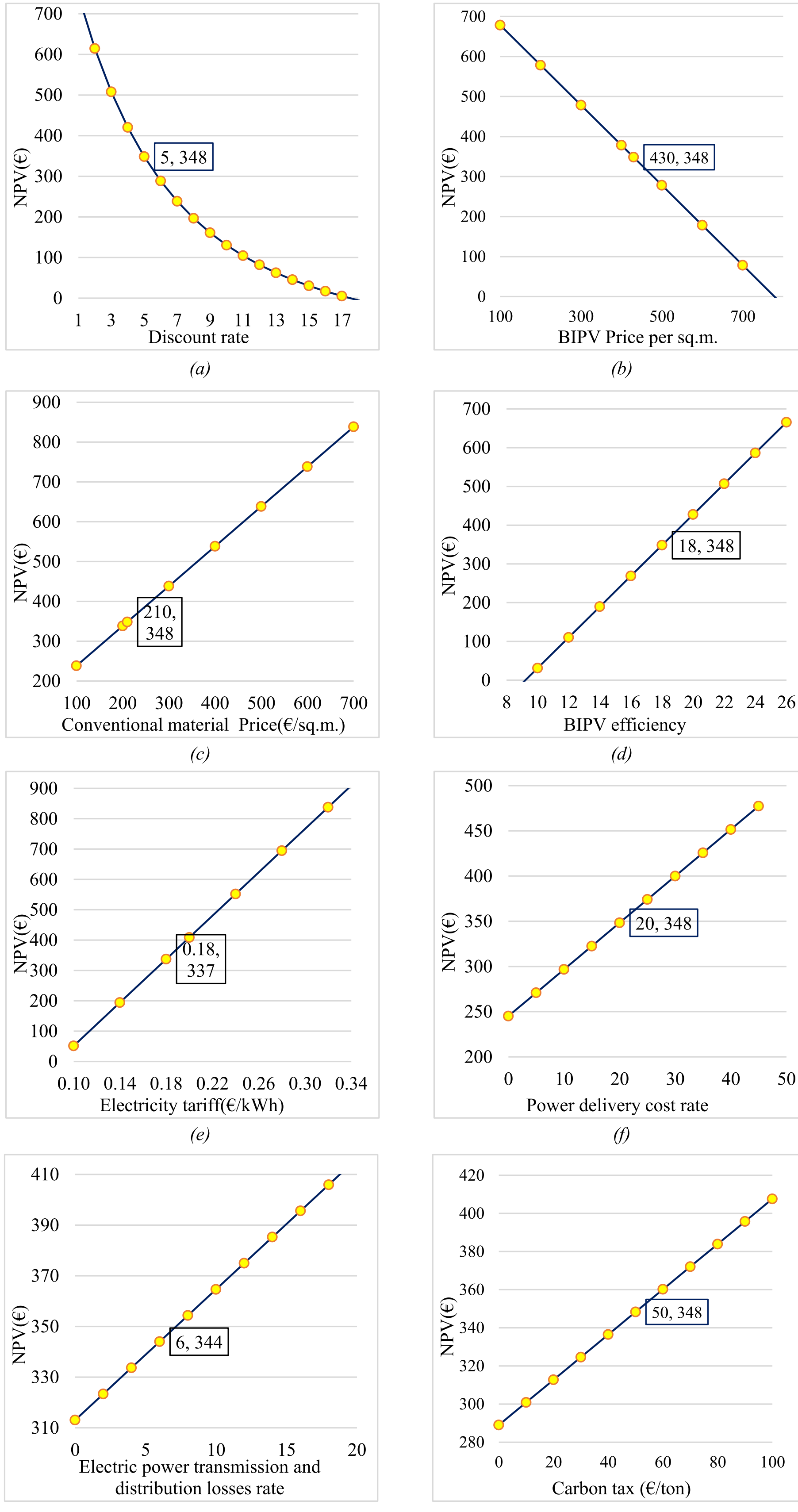


Fig. 10. Average cumulative NPV for BIPV as a building skin in Europe under variation of different parameters: (a)discount rate; (b) BIPV price; (c)conventional material price; (d) BIPV efficiency; (e)electricity tariff; (f)power delivery cost; (g) electric power transmission and distribution losses rate; (h)carbon tax.

Declaration of competing interest

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

CRediT authorship contribution statement

Hassan Gholami: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Writing - original draft, Visualization, Project administration. **Harald Nils Røstvik:** Methodology, Validation, Investigation, Resources, Writing - review & editing, Supervision.

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