University of Stavanger

HASSAN GHOLAMI FACULTY OF SCIENCE AND TECHNOLOGY

Feasibility Study of Building Integrated Photovoltaic (BIPV) as a Building Envelope Material in Europe

PhD: Thesis UiS No. 608 - October 2021

Feasibility Study of Building Integrated Photovoltaic (BIPV) as a Building Envelope Material in Europe

by

Hassan Gholami

Thesis submitted in fulfilment of
the requirements for the degree of
PHILOSOPHIAE DOCTOR
(PhD)

University of Stavanger

Faculty of Science and Technology
Department of Safety, Economic and Planning (ISØP)
2021

University of Stavanger
NO-4036 Stavanger
NORWAY
www.uis.no

ISBN: 978-82-8439-031-4
ISSN: 1890-1387
PhD: Thesis UiS No. 608

Preface

This thesis is submitted to fulfil the requirements for the degree of Doctor of Philosophy (PhD) at the University of Stavanger (UiS), Faculty of Science and Technology, Norway. The research work has been carried out between September 2018 and August 2021. In addition, part of my studies was carried out at the University of Cambridge as a visiting scholar at the Faculty of Architecture & History of Art, from September 2020 to December 2020. The compulsory courses were given and attended at the University of Stavanger (UiS) and the University of Bergen (UiB).

Acknowledgements

I would like to express my great appreciation to all the people who made this PhD endeavour possible.

I first would like to thank Professor and Architect MNAL Harald Nils Røstvik, my supervisor, for his patience, positivity, and motivation throughout this PhD program and during the whole three years of this journey. Thanks to my co-supervisor, Associate Professor Daniela Müller-Eie, for being so dedicated, professional, and involved with what you do.

I am particularly grateful to Fatemeh, my best friend and wife, for her patience and motivation during these three years. I want to thank my family and friends who always provided support from a long distance.

Thanks to all my colleagues at the UiS for sharing this process with me and the conversations and guidance through the highs and lows. This endeavour would not have taken place without their support.

Thanks to the Smart Sustainable Cities Research Network and Future Energy Hub at the University of Stavanger for their support.

To Zahra, my innocent, sweet, intelligent, kind and gentle niece, who withered before blooming (January 2003- June 2021)

June 2021, Stavanger, Norway

Summary

Buildings play a vital role as regards the energy efficiency of urban areas since they are responsible for a significant portion of the energy demand of urban areas. In Europe, building energy use accounts for 41% of the total energy consumption of the cities [1]. Urban energy transition has recently come about by intensifying the endeavour towards promoting distributed or decentralised energy generation (DG) and realign the energy production and consumption of buildings.

One of the leading solutions which can be of great assistance to contribute towards such an approach is building integrated photovoltaic (BIPV) systems. BIPV is a PV system on the building skin serving as both a building envelope material and a power generator. An alternative that is not covered here is PV systems nearly – in the landscape or garden.

There is a tendency currently in the market to use BIPV systems in the part of the building skins with the highest incident solar radiation and, therefore, higher electricity production as an output. These areas in the northern hemisphere are roof and south façade. However, employing other facades and areas of building skins also results in many advantages. The possibility to achieve zero energy buildings (ZEB) or even plus energy building goals, using different facades and orientations of buildings to have a distributed electricity generation during the day, and the system's contribution in reinforcing the energy performance of the building skin are some advantages. To place PV modules so that they deliver energy when the energy need in the building is highest is also of importance as it reduces the need for storage.

Therefore, this thesis focuses on building integrated photovoltaic systems (BIPV) and their feasibility as a building envelope material in Europe. The main research question is defined as follows:

Is the BIPV system as an alternative for the more usual building envelope materials feasible for the entire skin of buildings in Europe?

The goal is to investigate the technical and economic aspects of such a solution in two steps. Finally, the project seeks to briefly discover the potential and challenges of such a solution in the energy transition of cities.

Both qualitative and quantitative methodologies are employed in this project, and most of the analyses are based on the data obtained from the Photovoltaic Geographical Information System (PVGIS) and the Surface Solar Radiation Data Set - Heliosat (SARAH) dataset.

The results are expected to help the end-users, architects and urban planners to acknowledge the BIPV system as a suitable option for the building skins in Europe and steer governments or decision-makers to promote the technology by rational subsidies and incentives (where it is needed). This can contribute towards making cities as well as more rural areas into “power stations”.

Table of Contents

List of Figures

List of Tables

1 Introduction

"The coldest year in the future will be warmer than the hottest year in the past". This is an excerpt from the paper published in 2013 [2] by Camilo Mora et al. The research calculated that by 2047 plus or minus five years, the average temperatures in each year would be warmer in most locations of the globe than they had been at those parts in any year between 1860 and 2005 if no measure be taken. In other words, under the business-as-usual scenario, the temperature of a given location on earth will shift to a state continuously out of the historical variability bounds.

Furthermore, the National Oceanic and Atmospheric Administration [3] reported that the average temperatures of the earth's surface just between 1880 and 2016 increased 0.95 degrees centigrade and that the rise has sped up in recent years. Finally, 159 countries signed the Paris Agreement in 2017 [4] to cease climate change by keeping global warming at 1.5 degrees centigrade warmer than the earth's average temperature prior to the industrial age (1870-2100).

After four years, the new IEA report, "Net Zero by 2050: A Roadmap for the Global Energy", states that the global energy sector in 2050 is based mainly on renewables, with solar the single largest source of supply [5]. Moreover, solar PV would be the dominant approach to capture solar energy, according to the report. Photovoltaics (PV) is a technology that is capable of converting sunlight to electricity directly.

Other than PV technologies, there are two more main technologies by which solar energy can be harnessed: concentrating solar power (CSP) and solar heating and cooling (SHC) systems. CSP uses the thermal energy of incident solar radiation to drive utility-scale electric turbines. SHC collects thermal energy from the incident solar radiation to provide hot water or air for heating or cooling purposes. Solar thermal can also be used for drying of crops and fish, desalination and cooking.

Solar PV can be deployed in two forms: large scale or centralised PV power plants and small scale or decentralised PV systems. Some examples of large-scale PV systems are PV farms or Floating PV. The latter has recently gained increased attention [6]. Decentralised PV solution has also developed rapidly. They range from urban integrated PV solutions such as PV cycle path and artificial PV tree to building integrated and attached PV as well as vehicle integrated PV. However, this PhD deals with decentralised PV systems in urban areas and, more specifically, buildings.

Photovoltaic systems deployed in buildings are generally divided into two main types [7]:

BAPV or Building Attached PV is added to the building without directly affecting the structure's function, like regular solar cell systems installed on the roofs. Figure 1-1 depicts a building with a BAPV system.

Figure 1-1 An example of a BAPV system [2]

The second type is BIPV or Building Integrated PV, which is photovoltaic materials that are used to replace conventional building materials in parts of the building envelope such as roofs, skylights, or facades [8, 9]. They are increasingly being incorporated into new buildings as a principal or ancillary electrical power source [10]. However, existing buildings may be retrofitted with similar technologies. The climate also plays a key role in the performance of such a system [11]. BIPV can also be used in other industries, such as the ship manufacturing industry [12]. BIPV systems play two roles in buildings. First, they perform as building envelope materials and therefore, they must retain the building skin materials' specifications like weather and noise protection, heat insulation, privacy, etc. Second, they produce electrical energy on the building skins [10]. Figure 1-2 depicts a residential and commercial buildings equipped with BIPV systems.

Figure 1-2 Examples of building equipped with BIPV systems [13, 14]

BIPV systems are intertwined with buildings in several aspects such as design, safety, maintenance, environmental issues, performance, aesthetic, durability, buildability, standards and regulation, etc. [15]

The main discussion in this PhD project is to investigate the techno-economic feasibility of BIPV systems as an alternative for traditional building envelope materials in the market such as wood, glass, brick, stone, etc.

When it comes to the use of solar energy in urban areas, one generally thinks about challenges like aesthetic aspects or low potential because of shading etc. However, there are more benefits, and this study aims to investigate them more in detail. One of the advantages is the reflection in urban areas to boost the potential of untraditional facades for PV application (like the north facade) and have a more homogeneous incident solar radiation on building skins. Figure 1-3 shows the example of reflection from white-painted facades in a Greek tourist village where radiation and reflection hence is all over.

Figure 1-3 An example from Oia, Santorini, Greece, illustrating the potential of reflected radiation (photo by Harald N Røstvik)

By having a more homogeneous incident solar radiation on building skins and use the entire skins for the PV application, the building could benefit from a more evenly distributed electricity generation timewise during the day.

Furthermore, cities and urban areas are critical players in climate change. Urban areas fill only 2% of the earth's land mass [16]. However, urban areas leave an enormous footprint on earth and nature. Cities consume more than two-thirds of the world's total energy need and are responsible for more than 70% of all global GHG emissions [17]. Moreover, the world population will increase by 30% by 2050, and 68% will be settled in urban areas [18, 19]. Therefore, structural shift and change from the consumption of fossil energy resources to the consumption of renewable energy resources as well as energy efficiency notions in urban areas is inevitable [20]. Thus, urban areas are where the concentration and focus need to be on it. Cities are on the frontline of climate change and also well-positioned to take the leadership role in driving global action to tackle climate change.

Solar energy could play a remarkable role among renewable energy resources due to its uniformity in distribution globally [21] and potential energy scale [9, 10, 22]. Solar energy in urban areas could also be harnessed using various methods and technologies [8, 23-30]. Therefore, the European Union (EU), and under the framework of the Paris agreement, emphasises the prominence of the role of cities in moving towards a low carbon economy [31]. However, each country and region of the world has its drivers and challenges in this energy transition [32, 33].

The buildings themselves play a vital role in the energy efficiency of urban areas since they are responsible for a significant percentage of the energy demand of urban areas [34, 35]. In Europe, building energy use already accounts for 41% of the total energy consumption of the cities [1]. If we add energy need for the production of building materials and their transport to the site as well as energy need for refurbishment, demolishing and recycling of building components, the percentage is much higher. As a result, buildings as a sector could be viewed as the single most energy consuming of all sectors.

Therefore, a transition to buildings producing as much as possible of their own energy need in cities is a prominent course of action towards nearly zero-energy cities. The urban energy transition (UET) has recently come about to intensifying the endeavour towards promoting distributed generation (DG) and realign the energy production and consumption of buildings [20]. One of the leading solutions which can be of great assistance to reach such a goal is the energy prosumer notion [36]. Prosumers are consumers who can, because of their energy production capacity and by virtue of the regulatory conditions of the market and power systems, export their surplus energy to the distribution grid. The nearly zero-energy city concept is currently the frontier of this sector. It is mainly based on the consumption of (self-generated) renewable energy resources in buildings [37, 38].

Therefore, this doctoral study aims to research the feasibility of taking the most advantage of BIPV on building skins to contribute to the transition from the consumer concept of buildings to the prosumer concept. The main perspective in this doctoral study is the techno-economic aspects of such a solution by taking advantage of both qualitative and quantitative methodologies.

2 Background

2.1. The advent of BIPV

One of the first “modern” fully integrated BIPV buildings in Europe and the first in Norway was built in 1988, as shown in Figure 2-1. Chanelle building, a nearly zero energy building with building integrated PV and solar thermal solutions, was designed in 1985 and was built in 1988 by Harald N. Røstvik at the Buildings for the Future Exhibition in Godeset, Stavanger.

Figure 2-1 Chanelle building, 1988 [14]

Shortly after that, and in 1991, the first public BIPV building was implemented in Aachen, Germany [39], as shown in Figure 2-2. The system was photovoltaic elements integrated into a curtain wall façade with isolating glasses.

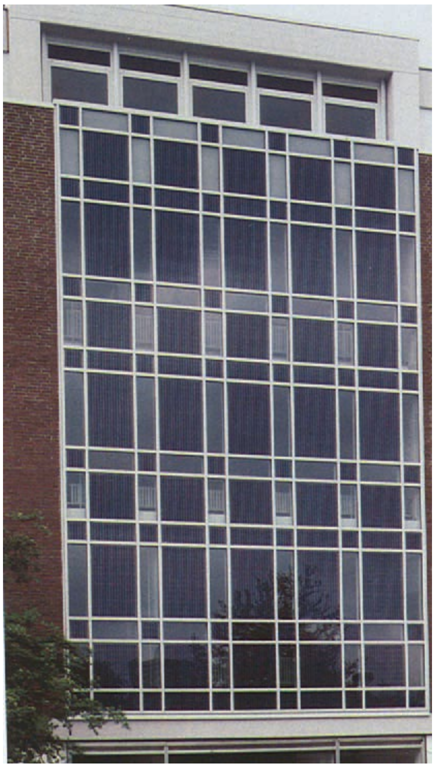


Figure 2-2 First public BIPV building in Europe [39]

These examples attest that the transition of buildings from energy users (consumers) to energy producers (prosumers) is not something that has only just appeared. Architectural, technical, structural, and aesthetic solutions involving integrating PV into the building envelope have been sought since PV first entered the market.

Different methods have been proposed to classify the BIPV systems. It can be classified based on solar cell composition, application, their types in the market and connection type to the grid. A comprehensive categorisation is presented in Figure 2-3, which is based on all the previous studies illustrated by the author [40-42].

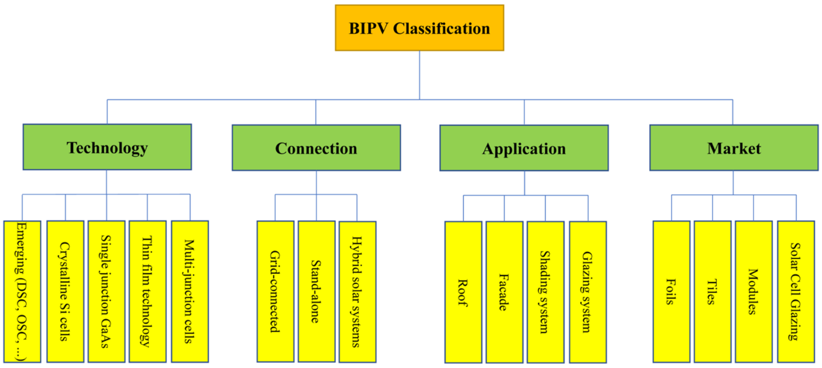


Figure 2-3 BIPV classification

The BIPV cell efficiency has increased considerably since its appearance, and a wide range of information has become available on the material behaviour when exposed to solar radiation. The National Renewable Energy Laboratory (NREL) is one of the leading organisations that publish yearly report on Solar PV efficiency improvements by their technologies and materials. The latest report from NREL, presented in Figure 2-4, shows the development of PV efficiency from 1976 to 2020 [43].

It should be recalled that NREL assesses the PV cell efficiency in laboratory standards, meaning the best environmental conditions are applied to find out the maximum efficiency of the PV cells and not the PV modules or panels.

The report suggests that the most efficient PV module available can reach up to 47% efficiency. However, the conventional PV cells that are available in the market for general applications are mostly mono-crystalline modules, shown in this chart with dark blue lines. The report indicates that mono-crystalline PVs can reach up to 27.6% efficiency in laboratory conditions [43]. The slope of the chart demonstrates the changes in crystalline PVs over the past few decades.

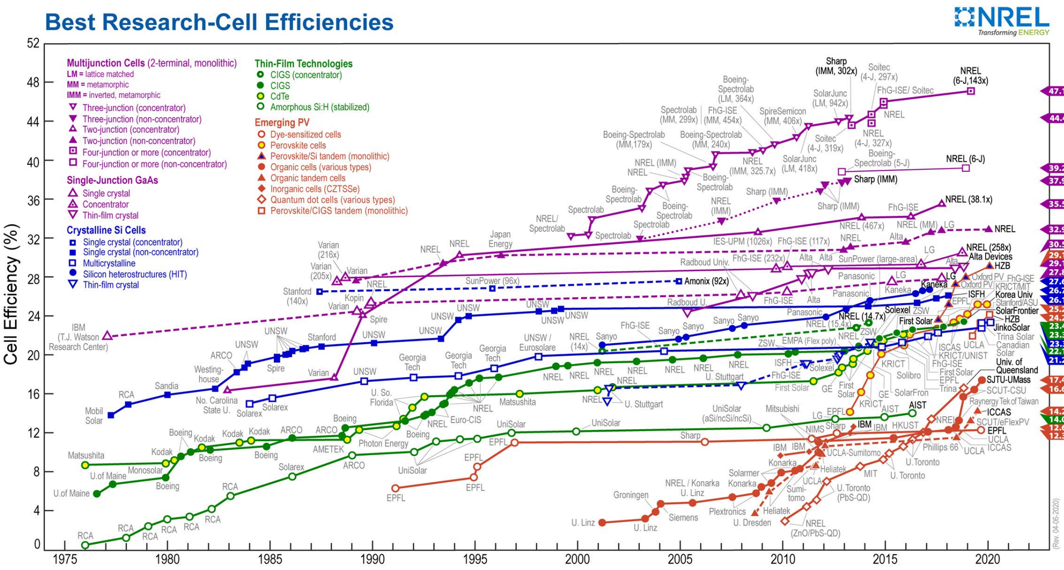


Figure 2-4 NREL Best Research-Cell Efficiency Chart

According to a study by Fraunhofer Institute for Solar Energy Systems, the best performing commercial modules are based on mono-crystalline silicon with 24.4% efficiency in the laboratory. However, in real-world conditions, several factors like thermal function, snow cover, cloud cover might affect the PV efficiencies. Hence, the average efficiency for the commercial mono-crystalline PV system lies between 15 to 20% now in the market [44].

Recently and due to developments in the BIPV industry, new types of modules have emerged, such as transparent and semi-transparent PV modules that can replace windows and let the light through while generating electricity. According to the manufacturers, these PV modules can currently reach 7% efficiency [45].

To be able to discuss the potential of solar radiation in Europe, some definitions and clarifications are presented here.

2.2. Solar Radiation Components

In order to acknowledge the incident solar radiation on different orientations of a building and study their potential, it is crucial to be familiar with the different solar radiation components. For example, a significant portion of incident solar radiation on north-facing facades (in the northern hemisphere) is reflected radiation. The incident solar radiation to a surface on earth has three components explained below [11].

- Direct radiation

Direct radiation is also called "beam radiation" or "direct beam radiation". It is used to describe solar radiation coming on a straight line from the sun and down to a surface on earth. For sunny days with a clear sky, most of the solar radiation is such direct radiation. On overcast days, the sun is shadowed by clouds, and the beam radiation is zero.

- Diffuse radiation

Diffuse radiation is sunlight that has been dispersed or scattered by particles and molecules in the atmosphere and still made its way down to the surface. Diffuse radiation is commonly referred to as sky radiation because it comes from all parts of the sky. The amount of diffuse radiation can be up to 100% of the total radiation for cloudy skies and 10% to 20% of the total radiation for clear skies.

- Reflected radiation

Reflected radiation is the reflection of both direct and diffuse radiation on the ground or objects like buildings. This contribution is small unless the collector is tilted at a steep angle from the horizontal, like a vertical building façade.

2.3. Solar Radiation Spectrum

The spectral response of different BIPV technologies to a great extent depends on the incident solar radiation spectrum explained here. The radiation spectrum coming from the sun to the earth is divided into three main groups of ultraviolet, visible light, and infrared.

- Ultraviolet

Ultraviolet (UV) includes wavelengths from 250 nanometers to 380 nanometers. UV rays are invisible to the human eyes and may be dangerous in the case of overexposure because they damage surfaces, colours and age materials.

- Visible light

Visible light is wavelengths from 380 nanometers (violet) to 740 nanometers (red). Visible light rays are detectable by the human eye and enable the sight of shapes, relief and colours.

- Short wave infrared

Short wave infrared (IR) constitutes wavelengths from 740 nanometers to 2500 nanometers. IR is invisible and is felt as heat. It constitutes most of the sun's energy that hits the earth.

Figure 2-5 shows the solar irradiance outside (Airmass equal to 0) and inside (Airmass equal to 1.5) of the atmosphere (Standard number ASTM G-173-03). The letters T and D stand for total and direct incident radiation. In terms of solar radiation inside the atmosphere and at sea level, around 3% of solar radiation on earth is UV, around 42% is visible light, and the rest (55%) is IR.

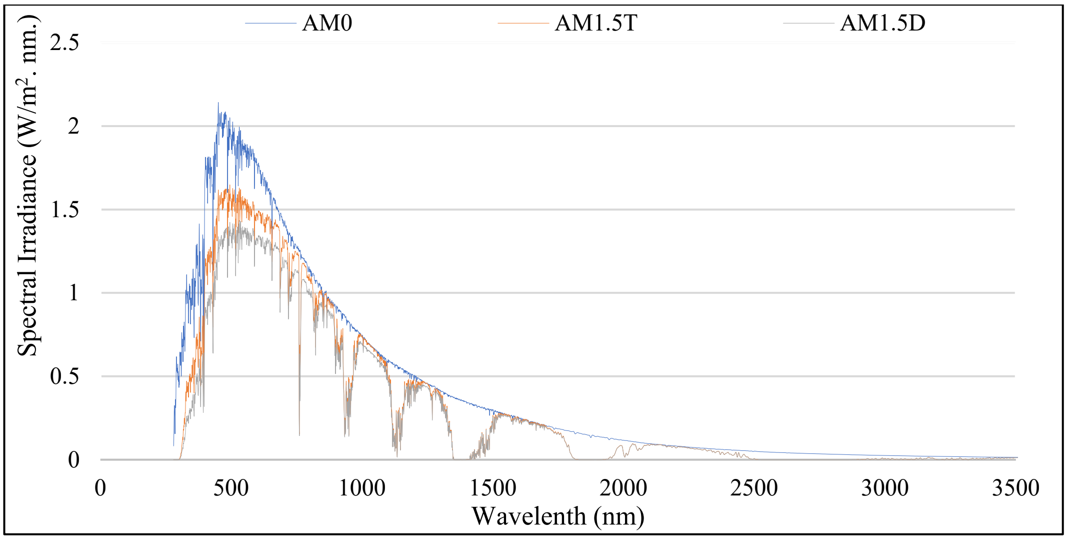


Figure 2-5 Solar spectral irradiance outside and inside of the atmosphere

Figure 2-6 represents the spectral responses of a variety of BIPV technologies. They can be divided into three categories based on their spectral responses.

The dye-sensitised solar cell (DSC) and organic solar cell (OSC) are placed in the first group. The spectral responses of this group are almost adjusted to the visible light spectrum. It means that the efficiencies of these technologies are only correlated to the visible light spectrum.

The second group includes Copper Indium Gallium Selenide (CIGS), monocrystalline Silicon (c-Si), and multi-crystalline Silicon (mc-Si). Their spectral responses cover wavelengths less than 1200 nanometers but with different efficiencies. Two remaining technology, Gallium Arsenide (GaAs) and Cadmium Telluride (CdTe), constitute the third group. These materials are sensitive to UV, visible, and IR radiation of less than 900 nanometers.

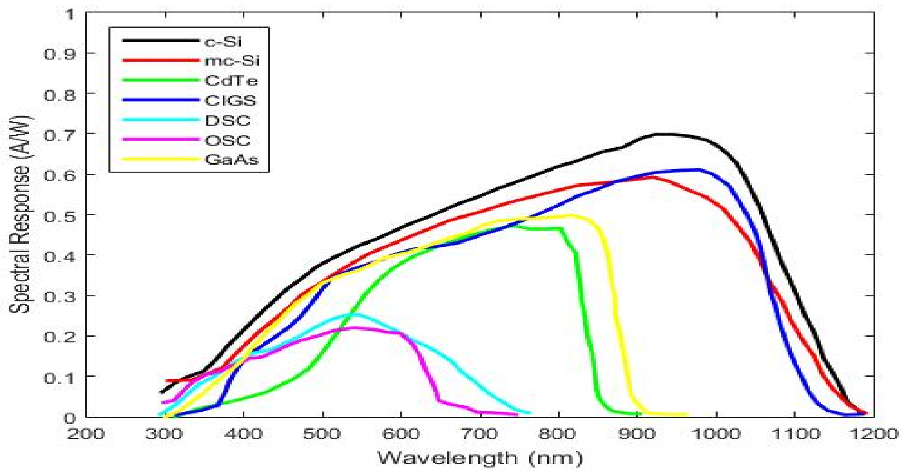


Figure 2-6 Spectral responses from a variety of BIPV cell technologies [46]

There are currently different methods to classify and define solar energy potential [47-51] and not the potential of BIPV systems. This is mainly because the intention is to either investigate the incident solar radiation on a horizontal surface on earth or the optimal orientation to grasp the maximum irradiance, say over the year, when it comes to the solar energy potential. However, when it comes to the BIPV potential, usual orientations of different parts of building skins are different from the mentioned directions and the intention is to see the incident solar radiation potential on those orientations. Therefore, the aim of the next section is to define actual "BIPV potential" and present methodologies for actual BIPV potential assessment.

2.4. BIPV Potential

BIPV potential can be divided into four categories of theoretical, geographical, technical, and economic potential.

2.4.1. BIPV theoretical potential

BIPV theoretical potential is the solar incident radiation gained by a region (on a horizontal surface) without taking any geometrical or technical constraint into account. A solar incident radiation map that indicates global horizontal irradiance (GHI) falls within this category. GHI is total irradiation delivered from the sky to a horizontal surface on earth. The GHI map of Europe is presented in Figure 2-7. In this sense, the BIPV theoretical potential is the same as the PV theoretical potential. The GHI is a metric to investigate the suitability of a land area to be considered for any type of solar technology to grasp the incident radiation. However, it just evaluates a horizontal surface in the location. Therefore, this metric is not very suitable when it comes to the BIPV technology, and other types of data are needed, which are explained in this section.

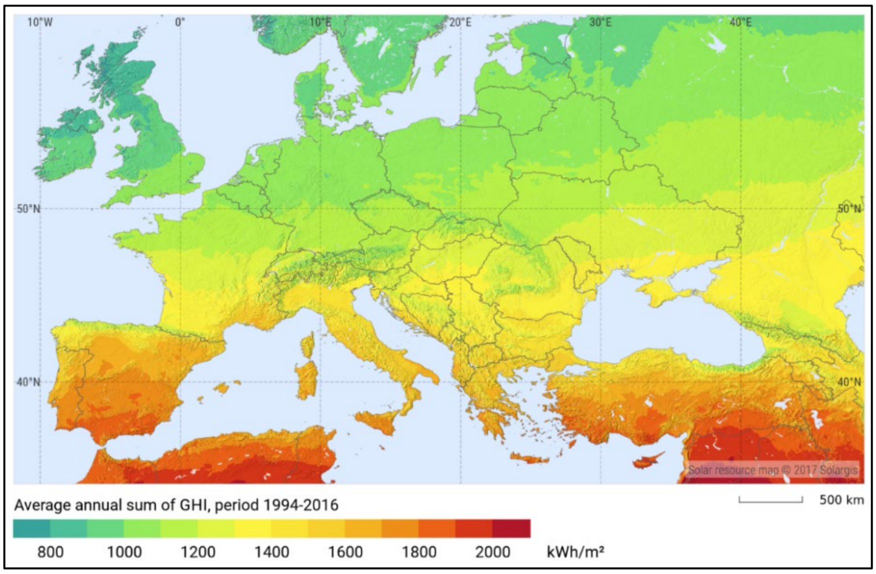


Figure 2-7 Theoretical potential map BIPV in Europe [52]

2.4.2. Geographical potential

The exploitable or utilizable portion of BIPV theoretical potential is called BIPV geographical potential. The geographical potential is a portion of the BIPV theoretical potential, capable of being exploited as input for BIPV systems. The BIPV geographical potential for a city is, therefore the total incident solar radiation on the building skins of the city. Figure 2-8 depicts the average annual BIPV geographical potential of the selected countries' capitals - cities - selected for this PhD study. The figures are based on the average radiation data between 2005 and 2016 from the Photovoltaic Geographical Information System database [52]. Newer data are not obtainable, and these are the latest available data on PVGIS.

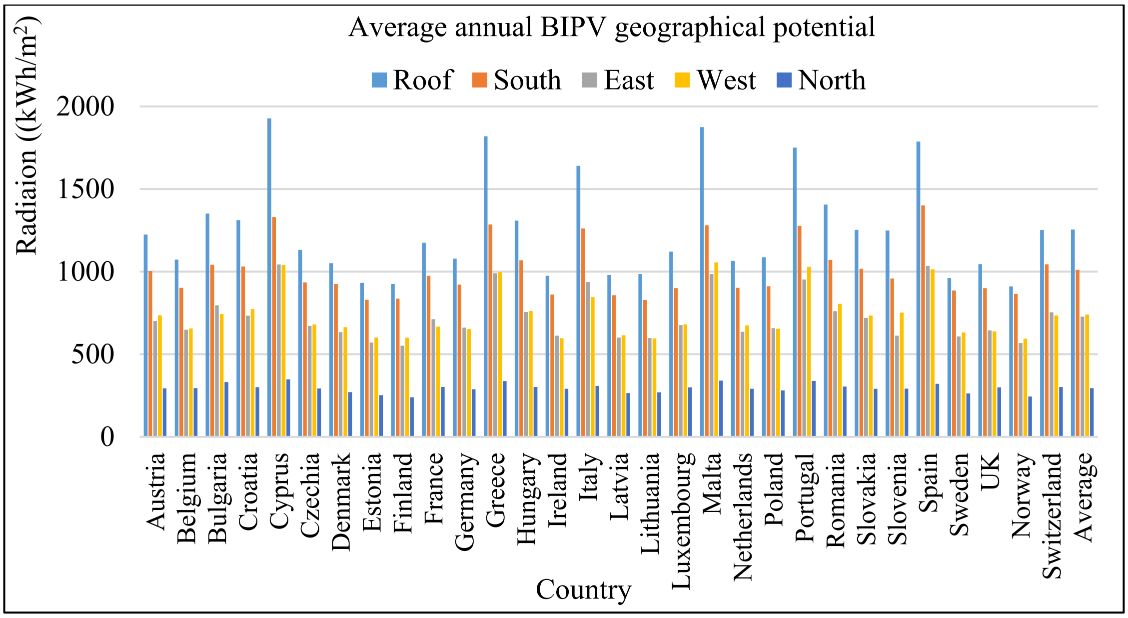


Figure 2-8 Geographical potential of the BIPV system in Europe

The figures are based on satellite-based data of radiation for the capitals of all the European member states plus the capitals of Norway and Switzerland. The potential is the sum of direct, diffuse and reflected radiations without taking the constraints of urban areas such as mutual shading of buildings into account. As can be seen from Figure 2-8, for a flat roof, the average annual geographical potential of a BIPV system in Europe varies from 911 (kWh/m^2) in Oslo, Norway to 1928 (kWh/m^2) in Nicosia, Cyprus, which shows 111% growth. This value for a vertical south façade varies from 820 (kWh/m^2) in Vilnius, Lithuania to 1401 (kWh/m^2) in Madrid, Spain, which shows a 69% increase. This variation for the east, west and north facades is 89%, 78%, and 45%, respectively.

2.4.3. BIPV technical potential

BIPV technical potential is the output power of the system by taking the technology and efficiency into account. It can be calculated by having access to the technical potential, technology and efficiency of the BIPV system.

The efficiency of BIPV systems varies depending on the technology, climate of the site, configuration, ventilation of modules etc. [42, 53]. The average efficiency of BIPV panels in the market is 18% [9]. This efficiency is the average efficiency of commercialized BIPV panels/modules in the market and not the total BIPV system. BIPV technical potential can be calculated by multiplying the efficiency of the BIPV panel by its geographical potential. The result is depicted in Figure 2-9.

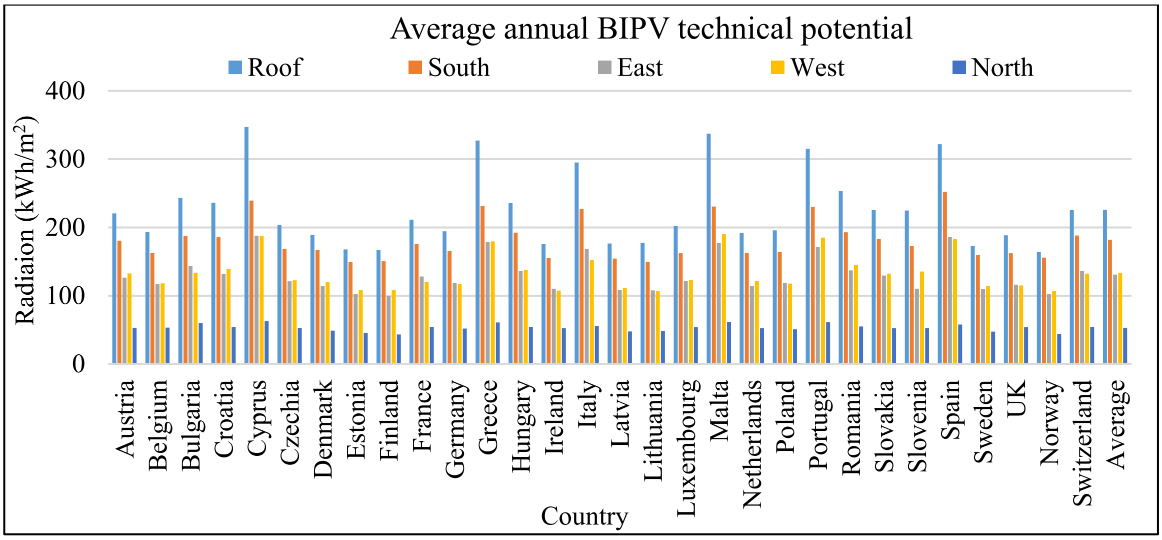


Figure 2-9 Technical potential of the BIPV system in Europe

2.4.4. BIPV economic potential

The economic potential of BIPV is naturally only a fraction of the total BIPV technical potential, and that which is economically exploitable. Such a figure generally needs more investigation because of various involved parameters, e.g. technology, energy tariffs, system degradation rate, market price, annual production, possible subsidies, etc. This has been discussed and analyzed in articles I, V, and VII.

In order to do a BIPV economic potential assessment, one of the key tools is the Lifecycle cost assessment (LCCA) of such a technology. In the following section, a state-of-the-art review of such an analysis for BIPV systems is presented.

2.5. State of the art of LCCA

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 [54]. 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 and their role in building material offset because of their dual service as building skins and PV functionality [10].

Sorgato et al. [55], in 2018, examined the economic and technical feasibility of the BIPV system with thin-film Cadmium telluride (CdTe) materials for a four-storey office building in six Brazilian cities (six different climates). Their results showed that the annual energy demand of each of the investigated buildings could be supplied by using the building's roofs and façades for the BIPV application. The research also illustrated that climate plays an essential role in energy production by the BIPV systems and the net annual energy consumption of the building.

Aste et al. in 2016 [56] 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. After thirteen years of operation, the degradation rate of the BIPV system was equal to 0.37% per year. It is significantly less than the general degradation rate of the multi-crystalline silicon system (approximately 0.5% per year) [57]. Moreover, visual inspection and infrared spectroscopy showed that no BIPV module was damaged.

Wang et al. [58] also conducted a study for environmental and economic assessments of a BIPV system by calculating the net present values (NPV, which is a tool to show the net difference between the profits and costs of the system in present or annual values [59]) and the payback period (DPP, which is the minimum time it takes to recoup investment costs [60]) 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 [61] examined the performance of an 8.6 kW BIPV system with polycrystalline PV cells. The building was located at Awali Town, Kingdom of Bahrain, in an arid zone with high annual solar radiation. Because of the low electricity price in Bahrain and lack of a feed-in tariff (FiT) program, the payback time of the BIPV system was more than 600 years. The study concluded that if the FiT (which is a fixed price that system owners are paid for the energy they deliver to the power grid) were set to 1 (USD/kWh) of solar electricity, the payback time would be equal to five years. Furthermore, by assuming the CO_2 emission of one (kg/kWh) from the electricity production in Bahrain, the study found that system saving from GHG emissions would be nine tons annually (compared to the GHG emission from the electricity production of the country, which is mainly fossil fuel based power plants).

2.6. Problem statement and the scope

First, previous studies [55-58, 61] have not dealt with the impact of the societal and environmental effects of the BIPV system on the economic analysis or LCCA. This has given a limited view of the actual holistic economics at hand. When a more total/holistic approach is applied, the figures and the conclusion alters. Moreover, the total cost introduced to the economic analysis of BIPV systems has generally been the sum of both system functions (building skins and PV functionality). This project hypothesises that in the economic analysis of BIPV systems, what should be inserted into the calculations is the extra charges that the BIPV system causes due to its power production role and not the overall cost (including the system's role as a substitute for the conventional building envelope).

Second, there is a lack of studies, actual tests and literature investigating the potential of untraditional facades in urban areas for BIPV applications. There seems to have been an assumption that these orientations and, more specifically, northern façades are unfeasible economically because the radiation there is low [25, 41, 42, 55, 56, 58, 61-70]. But these studies disregard the reflection from a neighbouring building, pavements, objects etc., although there is a common knowledge that reflection from white snow is considerable (0.96–0.98 across the ultraviolet (UV) and visible spectrum and 0.15 for infrared (IR) spectrum [71]). Only lately have we seen some projects emerging that are testing bifacial PV, for example, on roofs where one side faces reflected radiation from light-coloured roof materials [72, 73].

Third, 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 entire skin of building [42, 53, 62, 74-80].

Fourth, researchers have not evaluated the contribution of BIPV technology in the energy transition of cities [62]. Introducing BIPV as a building envelope material for the entire building skin of cities could significantly contribute to the energy transition of cities. Challenges ahead of such a contribution and a widespread rollout of BIPV technology is also another issue that is not well elaborated.

Fifth, when it comes to the levelised cost of electricity (LCOE), which is the unit cost of electricity (kWh or MWh) over the economic life or full life of a project [81, 82], there is a lack of literature on the LCOE of BIPV systems. Several studies have investigated the LCOE of photovoltaics systems [83-94], but none of them investigated the BIPV systems. However, the economic analysis of BIPV systems and their LCOE is different from the PV systems. This is among other factors because the BIPV system has dual functionality in the building and in addition to its application as a power generator, it also serves as a building envelope material for the building.

Therefore, this doctoral study is defined to address these issues by designing a research study, which will be discussed in detail in the next chapter and with the following main research question: is the BIPV system as an alternative for the more usual building envelope materials feasible for the entire skin of buildings in Europe?

3 Methodology

The presented flowchart in Figure 3-1 is developed and followed up in this PhD project to address the mentioned problems. The project is divided into four steps: main research question, technical aspects, economic aspects, and BIPV technology contribution in the energy transition of cities in Europe. Each step afterwards is addressed in a number of articles. Each topic (or box) in the flowchart is discussed in a separate journal paper.

The research methodology of each paper is discussed in the same paper in detail and briefly explained in this section. There are two approaches in the research methodology, which are quantitative and qualitative technique [95]. Depending on the scope of each research study, one or a combination of techniques are employed.

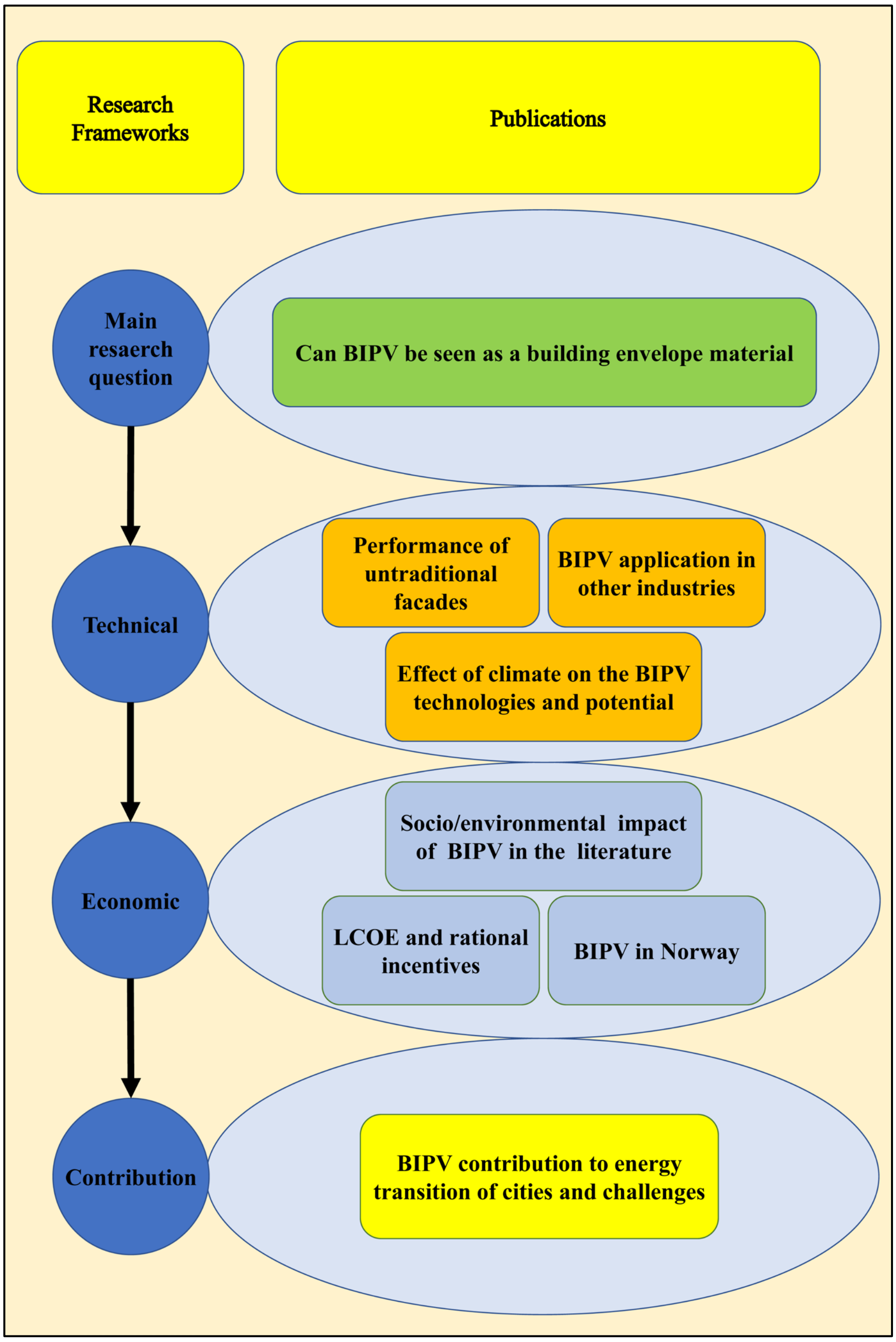


Figure 3-1 Flowchart of the roadmap of the project

Table 3-1 shows the datils of published papers.

Table 3-1 details of the published papers

No	Title	Journal	Date	DOI
I	Economic analysis of BIPV systems as a building envelope material for building skins in Europe	Energy	1 August 2020	doi.org/10.1016/j.energy.2020.117931
II	Dataset for the solar incident radiation and electricity production of building integrated photovoltaics (BIPV) system on the northern\southern façade in dense urban areas	Data	26 May 2021	doi.org/10.3390/data6060057
III	A novel method for optimal performance of ships by simultaneous optimisation of hull-propulsion-BIPV systems	Energy Conversion and Management	1 October 2019	doi.org/10.1016/j.enconman.2019.111879
IV	The Effect of Climate on the Solar Radiation Components on Building Skins and Building Integrated Photovoltaics (BIPV) Materials	Energies	26 March 2021	doi.org/10.3390/en14071847
V	Holistic economic analysis of building integrated photovoltaics (BIPV) system: case studies evaluation	Energy and Buildings	15 November 2019	10.1016/j.enbuild.2019.109461
VI	Levelised Cost of Electricity (LCOE) of Building Integrated Photovoltaics (BIPV) in Europe, Rational Feed-In Tariffs and Subsidies	Energies	28 April 2021	doi.org/10.3390/en14092531
VII	Lifecycle cost analysis (LCCA) of tailor-made building integrated photovoltaics (BIPV) façade: Solsmaragden case study in Norway	Solar Energy	15 November 2020	doi.org/10.1016/j.solener.2020.09.087
VIII	The contribution of building integrated photovoltaics (BIPV) to the concept of nearly zero-energy cities in Europe: potential and challenges ahead	Solar Energy	Under review	NA

The research framework and associated articles are briefly discussed as follows.

3.1. Main research question

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

This step deals with the main research question. It aims to first investigate the economic feasibility of the BIPV system as an alternative for the usual building envelope materials on the skin of the buildings in Europe. The other objective of this step is 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) plus the capitals of Norway and Switzerland by taking the quantified environmental and societal benefits of the BIPV systems into consideration. Paper I entitled: "Economic analysis of BIPV systems as a building envelope material for building skins in Europe" is published in 2020 in the journal of Energy tried to deal with this question (see 7.I.)

Methodology: First, a new classification of BIPV, as discussed before in chapter 2.5, is introduced. Then all the parameters required to conduct an LCCA for the BIPV systems are investigated and discussed, and their corresponding values are defined. The most important of them are operation and maintenance (O&M) costs, inverter replacement cost, BIPV degradation rate, BIPV lifetime, GHG emission, electricity tariff and its growth rate, discount rate, BIPV degradation rate, BIPV price and building envelope material price etc. Afterwards, a new LCCA formulation by taking the quantitative values of some of the most critical environmental and societal advantages of the BIPV system into the calculation is proposed. These values are saving in transmission line lost power, saving in power delivery cost, saving in societal cost of carbon (SCC) and saving in building envelope material cost.

Since BIPV price depends on many factors like BIPV type, location, technical specification, system size, etc., it is not possible to set a specific price for BIPV per unit kW or square meter, even for a country or region or city. The same is for the building envelope materials. Therefore, we tried to set average prices to evaluate the system and, in the end, investigate the impact of the inputs on the output with a sensitivity analysis. Table 3-2 depicts the average cost of conventional façades and roofs in European countries [38] and the adopted prices for this analysis.

Table 3-2 End-user costs of conventional façades and roof materials in Europe (including VAT) [96]

Category	Material	Price Range (€/m^2)	Average Price (€/m^2)	Adopted prices for this study
Facade	Wood	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 3-3 represents the price range of a complete BIPV system in Europe (including structure, equipment and BOS) based on market research accomplished by the Swiss BIPV Competence Centre at the University of Applied Sciences and Arts of Italian Switzerland [96, 97] and the adopted values for this study.

Table 3-3 End-user costs of conventional façades and roof materials in Europe[96, 97]

Category	Price Range (€/m^2)	BIPV Power (Wp/ m^2)	Average Price (€/ m^2)	Adopted values for this study	
				BIPV Power (Wp/ m^2)	BIPV Price (€/ m^2)
Facade	100-700	50-150	450	120	450
Roof	300-400	80-160	350	150	350

BIPV roof products cost on average about 200 (€/m^2) more expensive than conventional roof products (extra-cost) [96]. Moreover, the cost of BIPV facade products varies from 100 to 150 (€/m^2) for a thin film BIPV façade (with simple sub-structures and a low-efficiency PV technology) to 500–700 (€/m^2) 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) [96].

The basis of the 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. The 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 [10, 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 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.

3.2. Technical aspect

The technical aspects of this project are subdivided into three topics as follows.

3.2.1. Performance of untraditional facades

Paper: Dataset for the solar incident radiation and electricity production of building integrated photovoltaics (BIPV) system on the northern\southern façade in dense urban areas

An experimental study is designed to address the performance of untraditional facades by investigating the northern facade's potential and comparing it with the southern façade. The aim is to collect solar incident radiation and PV electricity production data on the north façade and evaluate the south façade materials' effect as a reflector to the opposite north-facing façade of the neighbouring building. Article II entitled: "Dataset for the solar incident radiation and electricity production of building integrated photovoltaics (BIPV) system on the northern\southern façade in dense urban areas" is published in 2021 in the journal of Data (see 7.II.)

Methodology: A site at the University of Stavanger is selected for this experimental study with a mix of glass/white panels on the south facade to monitor the incident solar radiation and electricity production of back-to-back PV panels in front of the south facade. The input (incident radiation) and output (electricity production) of the PV systems are monitored and recorded. Therefore, the panels' efficiency is calculated and compared to the nominal efficiency of the panels and each other to investigate their performance. Figure 3-2 shows a picture of the site with all components and the location of the site.

Figure 3-2 A picture of the site and the system

The specifications of the data are also presented in Table 3-4.

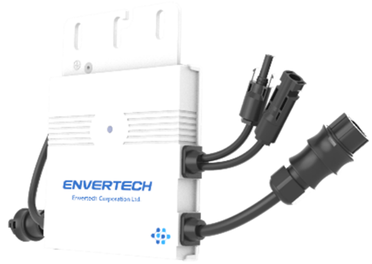
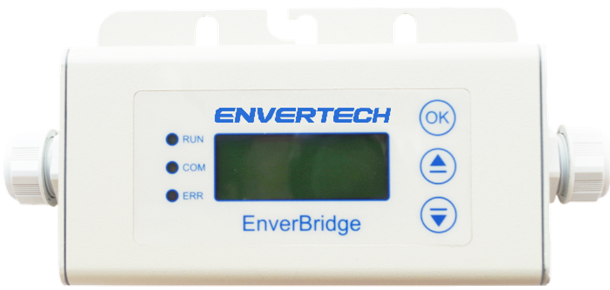
Table 3-4 Specifications table of the presented data

Specific subject area	BAPV/BIPV potential in urban areas Solar energy in compact urban blocks BAPV/BIPV efficiency in different orientations of building skin BAPV/BIPV panels' performance on north/south façades
Type of data	Table Image Figure
How data were acquired	Data are measured, monitored and logged by the equipment as follows: Two sets of SR30 sun[e] Pyranometer "ISO Secondary Standard"+ met[log] data logger Two sets of EVT300 microinverters with an EVB202 data logger
Data format	Raw time series data in csv format. The data are available with a sample resolution of a minute.
Parameters for data collection	Incident solar radiation and BIPV electricity production were collected at the site.
Description of data collection	Incident solar radiation data are logged with a minute sample resolution as raw data. PV electricity production and temperature data are logged with a sample resolution of three minutes as raw data. System efficiency is calculated, and the data are processed using Microsoft Excel as secondary data.
Data source location	Institution: University of Stavanger City/Town/Region: Stavanger

	Country: Norway Latitude and longitude for collected data: 58.9380454722466° N, 5.692057201993845° E
Data accessibility	With the article

Table 3-5 indicates the components of the system and the implemented items.

Table 3-5 List of system components

Item	Schematic
TP660P Talesun 275 Wp panel Quantity: 2	
EVT300 Microinverters Quantity: 2	
EVB202 Data logger Quantity: 1	

SR30 Sun[e] Pyranometer Quantity: 2	
Met[log] data logger Quantity: 2	
Power[cube] 150W Quantity: 2	

3.2.2. BIPV application in other industries

Paper: A novel method for optimal performance of ships by simultaneous optimisation of hull-propulsion-BIPV systems

The scope of this section is to evaluate the potential of BIPV systems in industries other than the building construction sector. A research study in collaboration with researchers from the Department of Maritime Engineering at the Amirkabir University of Technology conducted to address this issue. The result is published in 2019 in paper III in the Energy Conversion and Management journal entitled: "A novel method for optimal performance of ships by simultaneous optimisation of hull-propulsion-BIPV systems " (see 7.III.)

The reason behind investigating the ship industry is that ships have “walls” facing different directions, “roofs” and canopies, not very unlike buildings apart from the fact that a ship moves and turns and the “walls” hence changes direction. The goal of the paper is to present a novel strategy for the optimal performance of ships in minimising the GHG emission and the operating cost by taking advantage of the BIPV system on the ship.

Methodology: In this research, the optimisation of a planning ship equipped with the hybrid BIPV/diesel/battery power system is done through a well-known multi-objective optimisation algorithm named NSGA_II. This algorithm proposed by Deb [98] and is capable of finding an entire set of optimal solutions in a single run. A benefit of a multi-objective optimisation technique for a ship designer is the selection of desirable design solutions from a variety of optimal solutions that range over objectives. This requires a search for a set of Pareto optimal solutions for conflicting objectives for which it is impossible to provide a single solution that optimises all competing objective functions. In this study, the NSGA-II is employed by MATLAB optimisation toolbox. The optimization algorithm stops when the maximum number of generations is reached, or the average change in the spread of the Pareto frontier over the maximum stall generations is less than the tolerance function. A comparison analysis is also conducted to evaluate the performance of the proposed method compared to conventional approaches. In total, eight cases are compared (four of them is with BIPV) to demonstrate the effectiveness and the promise of the proposed approach in different ship design problems with different displacements and BIPV area-to-deck area ratios. In this study, the ship deck, which is equivalent to a roof section in a building, is considered to install the BIPV system. As seen in Table 3-6, the annual radiation on the horizontal surface of the ship is 2212 kWh/, which is considerable compared to other orientations.

Table 3-6 Annual solar radiation on the skin of ship for the selected location in 2018.

Orientation	South Skin	East Skin	West Skin	North Skin	Horizontal Surface
Annual radiation (Wh/m^2)	1,339	1,137	1,161	401	2,212

To assess the impact of the BIPV area-to-deck area ratio (A_{BIPV}/A_D) on the performance of the proposed method, the optimisation algorithm is run for different quantities of the defined factor as well. The lifetimes of the battery, the inverter, and the BIPV system are 5, 10, and 30 years, respectively. In addition, the BIPV degradation rate per year is 0.5% [57]. The maintenance cost per year for the BIPV system is also 1% of the investment cost [55].

3.2.3. Effect of climate on the BIPV technologies and potential

Paper: The Effect of Climate on the Solar Radiation Components on Building Skins and Building Integrated Photovoltaics (BIPV) Materials

This section investigates the effect of climate on the solar radiation components on building skins and BIPV materials in the northern hemisphere. The results are published in 2021 in the Energies journal in paper IV entitled: "The Effect of Climate on the Solar Radiation Components on Building Skins and Building Integrated Photovoltaics (BIPV) Materials" (see 7.IV.)

This study set out with four aims, which are as follows: assessing the incident solar radiation components on building skins considering different climates, analysing the solar radiation potential of the entire building skins for the BIPV application (if BIPV is seen as a building envelope material for the entire building skin), evaluating the effect of climates on the overall efficiencies of different BIPV technologies and materials which are currently available in the market, and finally investigating the effect of building orientation on the irradiance values of the building skins and the contribution of each solar radiation component. The selected cities are Stavanger in Norway, Bern in Switzerland, Rome in Italy and Dubai in UAE.

Methodology: Solar radiation components and spectrum are discussed. Then, different methods of incident solar radiation measurement at the earth's surface are introduced and reviewed thoroughly, which are radiation measuring devices, satellite-based irradiation data, and climate reanalysis data. Four cities with different climates are selected. Then the paper discussed three topics of solar radiation on building skins, climate and radiation, climate and technology in detail.

3.3. Economic aspect

Similar to the technical aspects of the main research question, the economic aspects are also classified into three topics as follows.

3.3.1. Socio/environmental impact of BIPV in the literature

Paper: Holistic economic analysis of building integrated photovoltaics (BIPV) system: case studies evaluation

In this section, an innovative approach for LCCA of the BIPV systems is defined to consider socio/environmental advantages of the BIPV system in the financial analysis. Then the new model was applied to the recent studies in the literature, which were economically analysed a BIPV system without considering the societal and environmental consequences of BIPV technology. In other words, the recent case studies are reanalysed by the suggested LCCA. Therefore, the traditional LCCA and the suggested LCCA for the same case studies could be easily compared. The results are published in paper V in 2019 in the journal of Energy and Buildings entitled: "Holistic economic analysis of building integrated photovoltaics (BIPV) system: case studies evaluation" (see 7.V.)

Methodology: A new approach for the economic analysis of BIPV systems is developed. In the new approach, the impact of societal and environmental factors on the financial analysis of a system is monetised. Then, four case studies in the literature are selected in order to apply the suggested method and evaluate the effect of societal and environmental factors on the economic feasibility of a system.

Table 3-7 represents a brief overview of the case studies and their properties.

Table 3-7 Some of input data from the case studies

city	Belem	Brasília	Curitiba	Florianopolis	Rio de Janeiro	Sao Paulo	Milan	Awali	Shanghai
Roof area (m^2)	600	600	600	600	600	600	106	60	66
Façade area (m^2)	607.6	607.6	607.6	607.6	607.6	607.6	0	0	0
BIPV (kWp)	180	180	180	180	180	180	10.95	8.64	10
Annual production (MWh)	197.2	223.5	201.2	190.3	197.6	170.1	9.7	8.9	9.9
Electricity tariff ($/kWh)	0.22	0.17	0.19	0.19	0.24	0.17	0.22	0.06	0.082
Investment ($)	231,152						25,000	43,000	19,474
Application	Roof / Facade						Roof		
Technology	Thin-film CdTe						Poly Crystalline Si		Mono Crystalline Si

3.3.2. LCOE and rational incentives

Paper: Levelised Cost of Electricity (LCOE) of Building Integrated Photovoltaics (BIPV) in Europe, Rational Feed-In Tariffs and Subsidies

Levelised cost of electricity (LCOE) is an approach to formulate and calculate the unit cost of electricity (kWh or MWh) over the economic life or full life of a project [99]. LCOE is a metric widely used among policymakers, investors, project managers, and researchers to evaluate the competitiveness and feasibility of different technologies and decide whether to invest in specific renewable energy projects or not [81, 82]. Furthermore, policymakers and authorities could set renewable energy policies by means of the LCOE approach. Authorities generally rely on LCOE to delineate support plans for renewable-based electricity generation technology against carbon-based electricity generation technology [100]. The studies in the literature have investigated the LCOE of the photovoltaics systems and not the BIPV systems. However, the economic analysis of PV and BIPV systems and the LCOE of those systems are two different topics. This is mainly, among other factors, because the BIPV system has dual functionality, which in addition to its application as a power generator, serves as a building envelope material.

Therefore, a research study is defined to investigate the LCOE of BIPV as a building envelope material in the European countries and present a metric for the appropriate subsidy or incentive. The results are published in 2021 in paper VI entitled: "Levelised cost of electricity (LCOE) of building integrated photovoltaics (BIPV) in Europe, rational feed-in tariff and subsidies" in the journal of Energies (see 7.VI.)

Methodology: An approach and formulation to calculate the LCOE of the BIPV systems is introduced. The formulation is based on the calculation of LCOE of usual PV systems while taking the fundamental differences of BIPV, such as the dual functionality of BIPV systems and socio/environmental impact of BIPV into account. Then, the average

LCOE of BIPV for the capital of all the European member states plus the capitals of Norway and Switzerland is calculated and compared to the network price of the location. Then proper subsidies for the BIPV systems and based on the LCOE and network price are discussed.

Levelised profit of environmental benefits (LPOE) with the unit of Euro per kWh is also introduced to investigate how much of the LCOE can be reimbursed by the environmental benefits.

The required parameters to calculate the LCOE of a BIPV system together with their values are listed here. Table 3-8 presents the value of the rest of the parameters in 2020.

- Operation and maintenance (O&M) cost: 0.5% of the initial investment in Europe.
- Inverter replacement cost: 10% of the initial investment.
- BIPV degradation rate: 0.5%.
- BIPV Lifetime: 30 years.
- Building envelope material cost: 230 Euro per m^2 for the façade and 130 Euro per m^2 for the roof.
- Transmission line lost power: see Table 3-8.
- Power delivery cost: 20% of the grid electricity tariff.
- Societal cost of carbon (SCC): 50 Euro per ton with a growth rate of 4%.
- GHG emission: Table 3-8, with a mitigation rate of 2.1%.
- Electricity tariff: Table 3-8, with a growth rate of 2%.
- Discount rate: 3%.
- BIPV efficiency: 16%.
- BIPV initial investment: 450 Euro per m^2 for facades and 350 Euro per m^2 for roofs.

Table 3-8 Electricity tariffs, GHG and electric power transmission and distribution losses of the European countries

No	Country	Capital	Transmission line lost power (%) [101]	GHG emission (g/kWh) [102]	Electricity tariff (Euro/kWh) [103]
1	Austria	Vienna	5%	156	0.20
2	Belgium	Brussels	5%	233	0.29
3	Bulgaria	Sofia	9%	585	0.10
4	Croatia	Zagreb	13%	282	0.13
5	Cyprus	Nikosia	4%	773	0.22
6	Czechia	Prague	5%	587	0.16
7	Denmark	Copenhagen	6%	386	0.31
8	Estonia	Tallinn	7%	1152	0.14
9	Finland	Helsinki	6%	209	0.17
10	France	Paris	4%	92	0.18
11	Germany	Berlin	4%	567	0.30
12	Greece	Athens	4%	755	0.16
13	Hungary	Budapest	12%	368	0.11
14	Ireland	Dublin	8%	555	0.25
15	Italy	Rome	7%	444	0.22
16	Latvia	Riga	9%	185	0.15
17	Lithuania	Vilnius	22%	262	0.11
18	Luxembourg	Luxemburg	6%	283	0.17
19	Malta	Valleta	5%	868	0.13
20	Netherlands	Amsterdam	5%	582	0.17
21	Poland	Warsaw	6%	929	0.14
22	Portugal	Lisbon	10%	355	0.23
23	Romania	Bucharest	11%	413	0.13
24	Slovakia	Bratislava	2%	211	0.15
25	Slovenia	Ljubljana	5%	351	0.16
26	Spain	Madrid	10%	305	0.25
27	Sweden	Stockholm	5%	25	0.20
28	UK	London	8%	584	0.20
29	Norway	Oslo	6%	19	0.19
30	Switzerland	Bern	7%	37	0.17

By calculating the NPV_I, NPV_C and E_G, which are BIPV net present value of incomes, BIPV net present value of costs, and BIPV total electricity production, the levelized cost of electricity (LCOE) and levelised profit of environmental benefits (LPOE) can be achieved.

3.3.3. BIPV in Norway

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

The Solsmaragden building in Oslo went under investigation to evaluate a specific and novel BIPV system in the Scandinavian climate. The building façade is a BIPV system. The total area of the BIPV on the west, south, south-west and east facade is 523, 462, 125, and 36 m^2, respectively. The first project in the world applying a printed, decoration only, layer on the inside of the front glass of the PV glazing to replicate a green wall. The research is defined to conduct an LCCA of the already implemented BIPV façade system in Norway based on on-field recorded data after four years of BIPV operation (2016–2019). The outcome is published in paper VII in 2020 entitled: "Lifecycle cost analysis (LCCA) of tailor-made building integrated photovoltaics (BIPV) façade: Solsmaragden case study in Norway" In the journal of Solar Energy (see 7.VII.)

Methodology: An implemented BIPV system after four years of operation and the recorded data of the system performance went under investigation in this article. The LCCA formulation takes the different BIPV end of life material recovery and societal benefits into account to evaluate their effects on the output. Three different end-of-life material recovery approaches are explained for this specific case. The granted subsidy for the project is also discussed. A brief overview of the proposed methodology is presented in Figure 3-3.

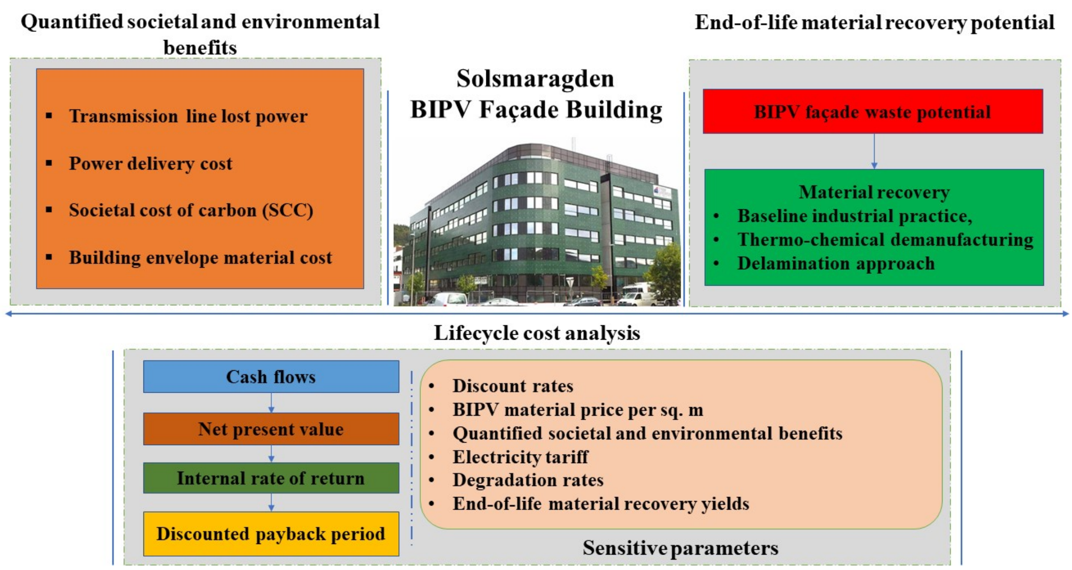


Figure 3-3 The proposed methodology for LCCA of BIPV systems

Parameters such as operation and maintenance (O&M) costs, inverter replacement cost, BIPV degradation rate, BIPV life-time, building envelope material cost, transmission line lost power, power delivery cost, societal cost of carbon (SCC), GHG emission, electricity tariff and its growth rate, discount rate, and end-of-life modelling of BIPV façade are studied and LCCA is conducted considering the mentioned parameters.

Table 3-9 shows the cost breakdown for this BIPV project. The BIPV project ended up with a total investment of 4,625,794 NOK for an active area of 1146 m^2 of BIPV panels (total investment of 4,036 (NOK/m^2)). The building also received 1,553,236 NOK support from Enova for the BIPV project.

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

Table 3-9 BIPV project estimated cost breakdown

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

The BIPV façade weight is 20.5 kg per m^2 and 1146 m^2 of BIPV façade is installed, which accounts for a cumulative weight of 23.5 tonnes. The weight of recovered materials varies depending on EOL approaches. The percentages of materials recovery yields, which are based on the industrial data (WEEE treatment plant in the Flemish region of Belgium) as well as the literature support [104-107] are provided in Table 3-10.

Table 3-10 Percentage of material recovery yields

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

3.3.4. BIPV contribution to energy transition of cities and challenges

Paper: The contribution of building integrated photovoltaics (BIPV) to the concept of nearly zero-energy cities in Europe: potential and challenges ahead

Finally, in the last step of the project, the contribution of BIPV to the concept of nearly zero-energy cities in Europe was discussed. A research study is designed to answer two questions: First, the possibility of establishing nearly zero-energy cities in Europe by changing buildings' role from energy consumers to energy prosumers (using their skins for BIPV application.) Second, investigating the challenges and barriers ahead to reach such a goal.

This topic is investigated in paper VIII entitled: " The contribution of building integrated photovoltaics (BIPV) to the concept of nearly zero-energy cities in Europe: potential and challenges ahead," which is submitted to the journal of Solar Energy and is currently under review (see 7.VIII.)

Methodology: The research methodology of this study is depicted in Figure 3-4. Both general approaches in the research methodology are employed by this study, which are quantitative and qualitative approaches [95].

The designed quantitative and qualitative approaches are novel and have not been taken in the literature. The quantitative methodology is designed to reveal the potential of building to be shifted from energy consumer to energy prosumer by effective use of its skin, and in a bigger picture, the role of building skins in the energy transition of the cities. Furthermore, the proposed qualitative methodology is striving to analyse the hurdles ahead of actualising the discovered potential in the quantitative approach.

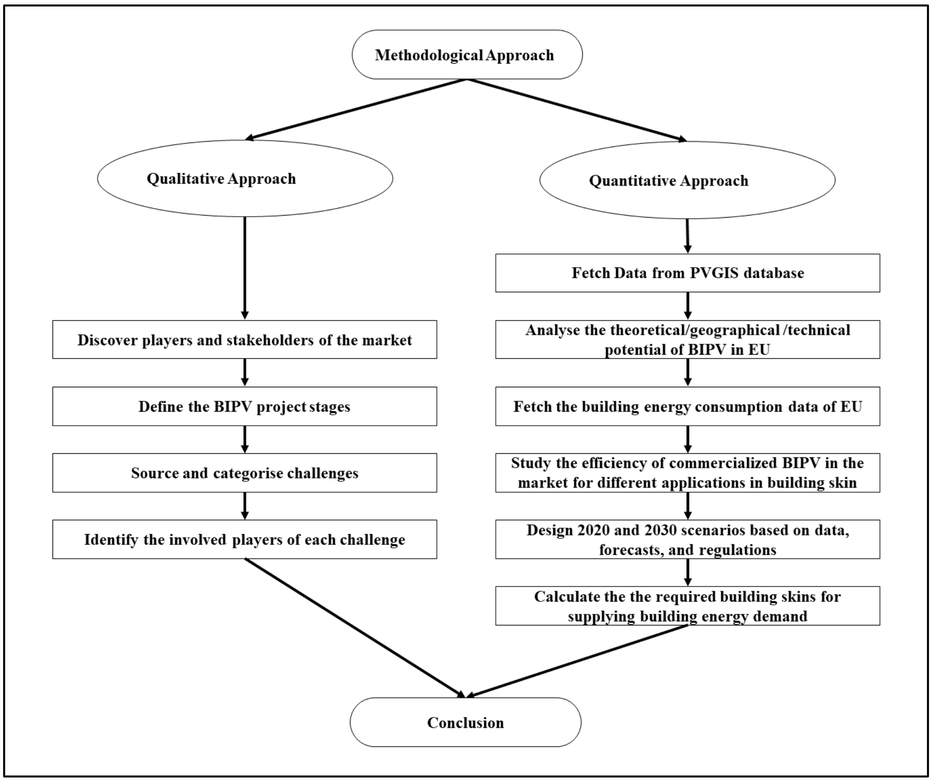


Figure 3-4 Flowchart of the methodology

The paper defines some terminologies which is used as a tool to evaluate the potential contribution of BIPV to zero energy cities.

Building gross area (BGA), which is the total area within the walls of a building structure, including unliveable spaces (such as interior walls, outer walls, and internal ducts) as well as the walls themselves.

Building net area (BNA), which is the gross floor area of a building, excluding the area occupied by walls and partitions, the circulation area (where people walk), and the mechanical area (where there is mechanical equipment). The values of building energy consumption are associated with the building net area. The energy consumption of BNA is called EBNA in this study.

Building skins (BS) which is the total area of the outer skin of a building. The technical potential of BIPV on the BS is called EBS in this study.

Building skin glazing ratio (BSGR) is the proportion of the glazed surface to the total surface of the building skin.

4 Contributions and constraints

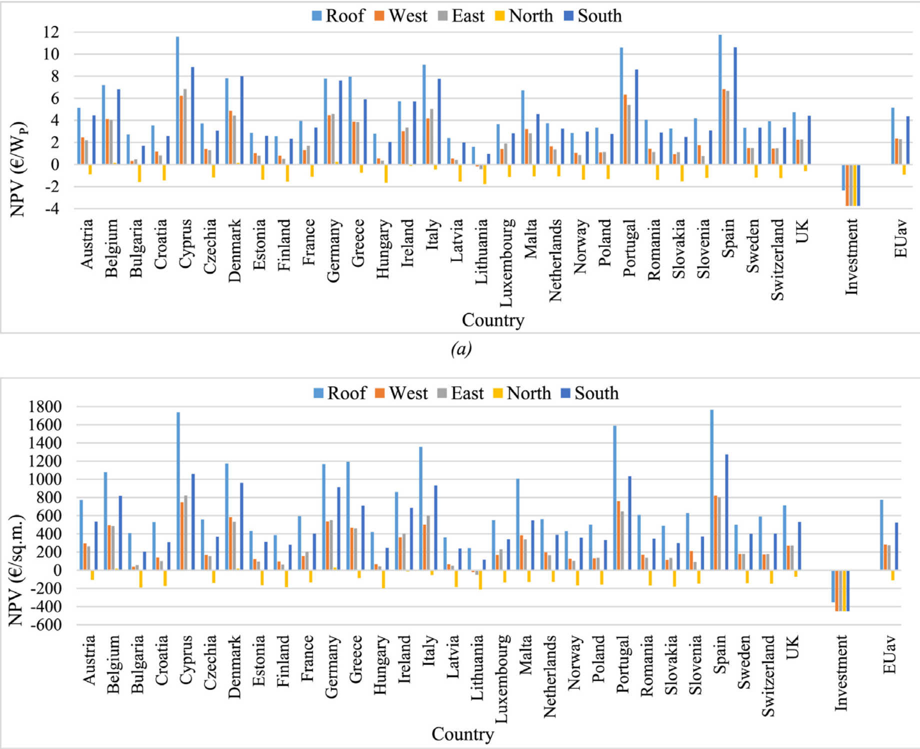
This section describes the main contributions and constraints of each paper. The contributions are both methodological and empirical.

4.1. Can BIPV be seen as a building envelope material?

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

The main contribution of this article is the assessment of the economic viability of the BIPV systems as an envelope material for the whole skin of buildings with different orientations in the capitals of all the European Union member states (EU) and the capitals of Norway and Switzerland. The paper takes the environmental and societal advantages of BIPV systems into the economic analysis.

Figure 4-1 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 (Wp) is the output power achieved by a BIPV module under full solar radiation and standard test conditions. From Figure 4-1 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, 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.



(b)

Figure 4-1 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

Figure 4-2 shows the cumulative net present values of BIPV advantages as a building envelope material with different orientations in the European countries. In order to grasp 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 Euro per Wp, respectively.

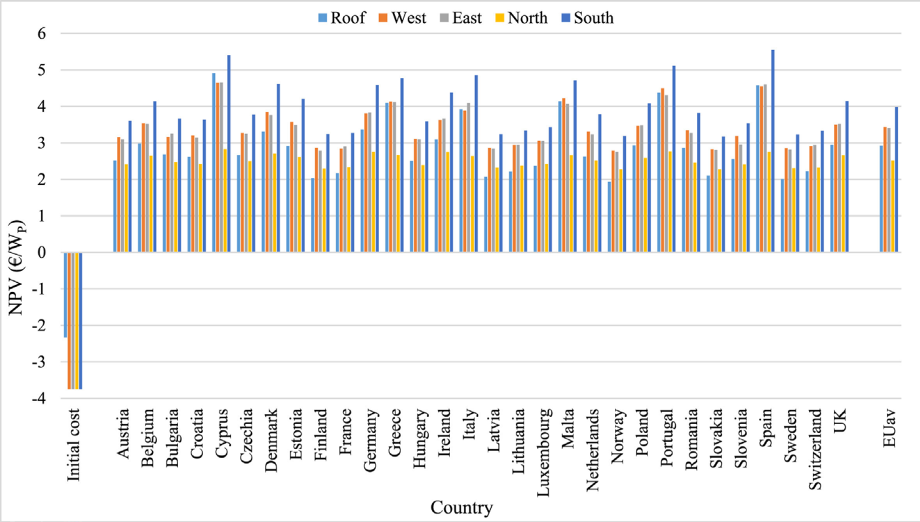


Figure 4-2 The cumulative NPV advantages of BIPV systems for building skins with different orientations in the European countries

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 Figure 4-3. "Absolute value of initial investment" represents the cost of BIPV for its energy supplying role. 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.

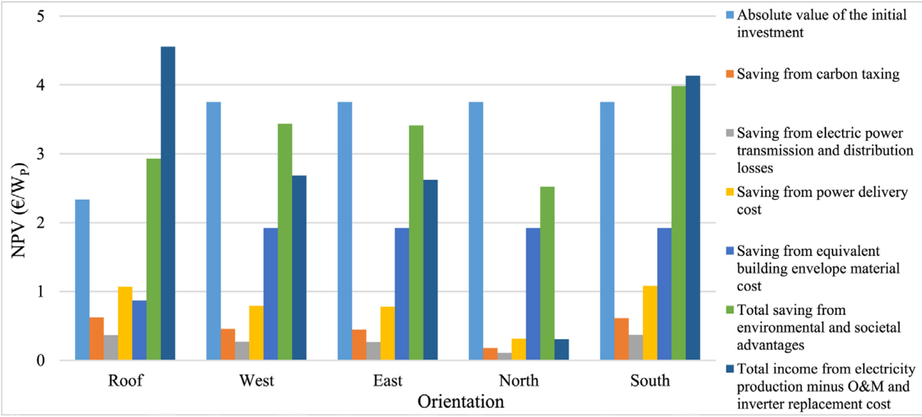


Figure 4-3 The average cumulative NPV of factors for different orientations in Europe.

Finally, Figure 4-4 shows the average lifetime cumulative NPV of the BIPV envelope in Europe.

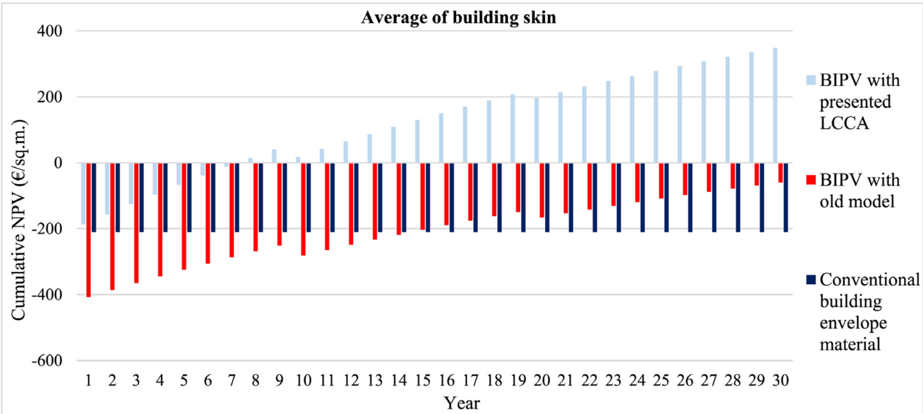


Figure 4-4 The average lifetime cumulative NPV of building envelope in Europe.

One of the most significant findings to emerge from this paper 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. This investigation also shows 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. 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 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.

However, the paper does not take the amounts of GHG emissions during the manufacturing/disposal of the BIPV panels into consideration. Although, the BIPV modules and components contain glass, aluminium and semiconductor materials that can be successfully recovered and reused, either in new modules or other products. Supplementary works to this research can 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 mutual shading of buildings, building barriers, historical, architectural and regulatory constraints, are not taken into account. Another future research could be evaluating the effect of urban contexts of the capitals or urban constraints on the outcome of this article.

Finally, in terms of the energy mix, the paper deals with the countries' energy production and not the energy consumption. For example, the average GHG emission factor in Norway caused by electricity production was estimated at 18,9 g/kWh in 2018 [108]. This is a low figure because of Norway's huge hydropower capacity. 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 [109]. Therefore, between the two approaches of choosing either energy production or energy consumption as a reference for GHG emission, this study adopts the countries' energy production.

4.2. Performance of untraditional facades

Paper: Dataset for the solar incident radiation and electricity production of building integrated photovoltaics (BIPV) system on the northern\southern façade in dense urban areas

This article presents a dataset for the solar incident radiation and electricity production of PV systems in the north and south orientations in a dense urban area (in the northern hemisphere) with reflection from a south wall with different cladding material (glass and white wooden panels). The solar incident radiation and the electricity production of two back-to-back PV panels with a ten centimetres gap have been monitored and logged as primary data sources. Using Microsoft Excel, both panels' efficiencies are also presented as a secondary source of data. The implemented PV panels are composed of polycrystalline silicon cells with an efficiency of 16.9 %.

Figure 4-5 illustrates the PV panels' average operational efficiency while there is no shading on the south-facing panel on the discussed dates.

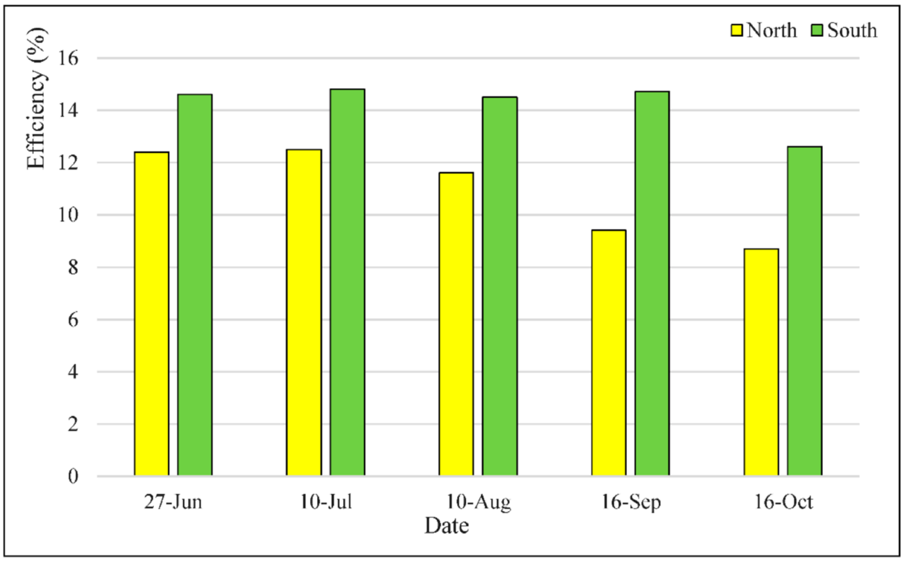


Figure 4-5 The average efficiency of the PV panels in a clear sky condition

As can be seen from Figure 4-5, the efficiency of the north façade panel is always more than 2% less than the efficiency of the south façade panel on sunny days. The efficiency of the south-facing panel is between 12% to 15%. However, the efficiency of the north-facing panel is between 8% to 12% (on sunny days of the year). This gap becomes even more significant on cloudy days or overcast days.

The gap can be explained by the spectral response of the silicon-based PV cells to the incident solar radiation and the fact that the main radiation on the south-facing panel is direct radiation. In contrast, the main radiation on the north-facing panel is the reflected and diffuse radiation. That is why the south-facing panel's efficiency is closer to the standard efficiency of the panel compared to the north-facing panel.

Figure 4-6 depicts the peak production of each month of panels.

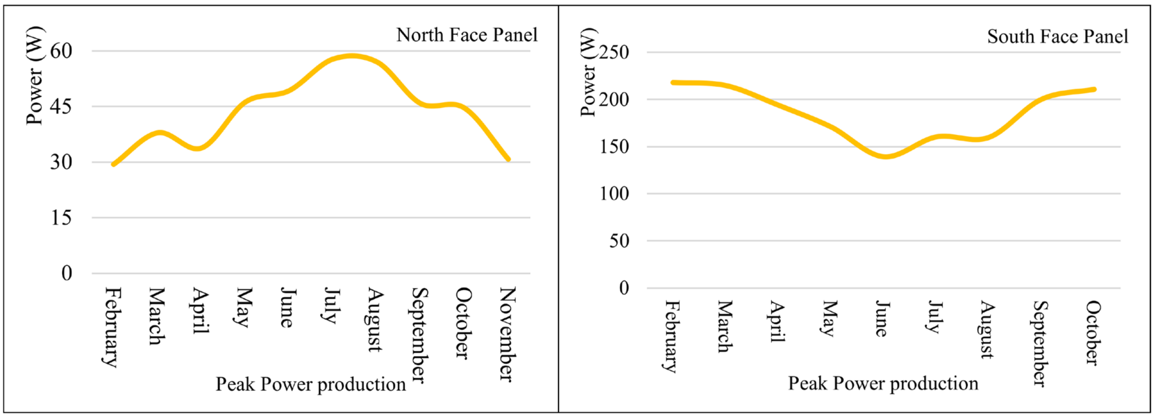


Figure 4-6 Recorded peak power production of each panel during the monitoring time.

The most interesting observation to emerge from the data comparison in Figure 4-6 is that the peak power production of the south-facing panel on sunny days in winter is more than its production on sunny days in summer, which is because of two reasons. The first reason is the angle of solar radiation. In winter, the sun is more inclined towards the horizon and therefore, the solar altitude is smaller. Therefore, the incident radiation to a vertical south-faced panel is close to perpendicular, resulting in higher efficiency.

The second reason is the effect of temperature. The cold weather in winter contributes to a better performance of PV panels.

This also leads to a helpful match between electricity production and consumption in Scandinavian countries. Clear sky days in winter are generally the coldest days in these countries. Therefore, the energy consumption is high exactly when the PV system is producing at maximum power. Moreover, the result shows that the production of the north-facing panel follows the opposite trend of the south-facing panel, and its peak power production in summer is more than its peak power production in winter. The reason is the reflected radiation. In summer and because of higher solar altitude, the reflected radiation from the south façade on the north-facing panel is greater. However, in winter and because of the site's lower solar altitude and boundary condition, the contribution of reflected radiation is less.

The findings observed in this article mirror those of the findings in another study of this PhD, which has examined the effect of climate on the performance of different BIPV materials and technologies. Therefore, the data is a suitable source to compare this technology's performance with other emerging technologies such as perovskite and organic solar cell as a building envelope material in cities and investigate the impact of quality and quantity of solar radiation components on the performance and efficiency of PV panels with different orientations.

A contribution could be to use the database to compare this technology's performance with other emerging technologies such as perovskite and organic solar cell as a building envelope material in cities.

4.3. BIPV application in other industries

Paper: A novel method for optimal performance of ships by simultaneous optimisation of hull-propulsion-BIPV systems

The paper proposes a novel method for the optimal performance of ships based on the simultaneous optimisation of the hull-propulsion-BIPV system. The proposed method's effectiveness is evaluated by designing a planning craft equipped with the waterjet propulsion system and the hybrid BIPV/diesel/battery power system. For this purpose, different comparison analyses with traditional ship design approaches are studied to demonstrate the high performance of the suggested method in different ship problems with different design requirements and BIPV area-to-deck area ratios. Moreover, future scenario studies are also provided to demonstrate the promise of the presented method.

It may speculate that by designing a ship based on the proposed method, the deck area of the ship would increase to have the larger available area for the BIPV installation and therefore increase the power generated by the BIPV system. However, the result shows increasing the available area for installation of the BIPV system may have negative effects on the ship resistance and the propulsion system efficiency and thus result in high fuel consumption and non-optimal solution.

The contribution of such a technology in the performance of the emerging generation of ships, which are electric ships, would be of interest as well.

4.4. Effect of climate on the BIPV technologies and potential

Paper: The Effect of Climate on the Solar Radiation Components on Building Skins and Building Integrated Photovoltaics (BIPV) Materials

This paper studies the effect of climate on the solar radiation components on building skins and BIPV materials in the northern hemisphere. The selected cities are Stavanger in Norway, Bern in Switzerland, Rome in Italy and Dubai in UAE. Although the paper is based on four case studies, the findings suggested that the solar radiation potential of BIPV material as a building envelope material for the whole building skins is significant (576, 869, 1043, 1284 kWh per square meters for Stavanger, Bern, Rome and Dubai). These values are slightly more than the morning and evening façade potentials of the associated case study. For example, in Stavanger, the average annual radiation on the east façade is 535 kWh per square meter, while the average annual radiation on the building skins is 577 kWh per square meter.

It is also concluded that the climate is a significant factor when it comes to the contribution of incident solar radiation components on a surface. The evidence from this article suggests that in climates with higher diffuse radiation, the contribution of IR radiation decreases. Therefore, the efficiency of BIPV materials that their spectral responses are dependent on the IR radiation (like Si and CIGS) in such a climate would decline. On the other hand, the organic and dye-sensitised solar cells could be a good option for a cloudy climate since they have more stable performance even in such a climate. Although, their efficiency compared to other BIPV materials such as Si-based BIPV solar cells are still significantly less until now.

Finally, when it comes to the impact of the climate on the BIPV system, BIPV performance is also very much dependent on temperature, and it should also be considered simultaneously with other factors mentioned in this article. The effect of some of the parameters being considered in this study (spectral response versus type of solar radiation availability) may be of the same order of magnitude as those coming from temperature. Soiling and snowfall are, of course, other critical issues in some of the climates considered. Therefore, these are important issues for future research and a further study with more focus on the mentioned issues is suggested.

4.5. Socio/environmental impact of BIPV in the literature

Paper: Holistic economic analysis of building integrated photovoltaics (BIPV) system: case studies evaluation

In this paper, an innovative approach is presented in order to calculate the NPV and DPP of BIPV systems in the recent case studies considering the environmental and societal consequences of the system. The considered factors in this paper are the societal cost of carbon, the transmission line loss, the transmission line cost, and the equivalent material cost.

Figures 4-7 and 4-8 illustrate the simulation results for the cumulative net present value (NPV) and discounted payback period (DPP) of the case studies.

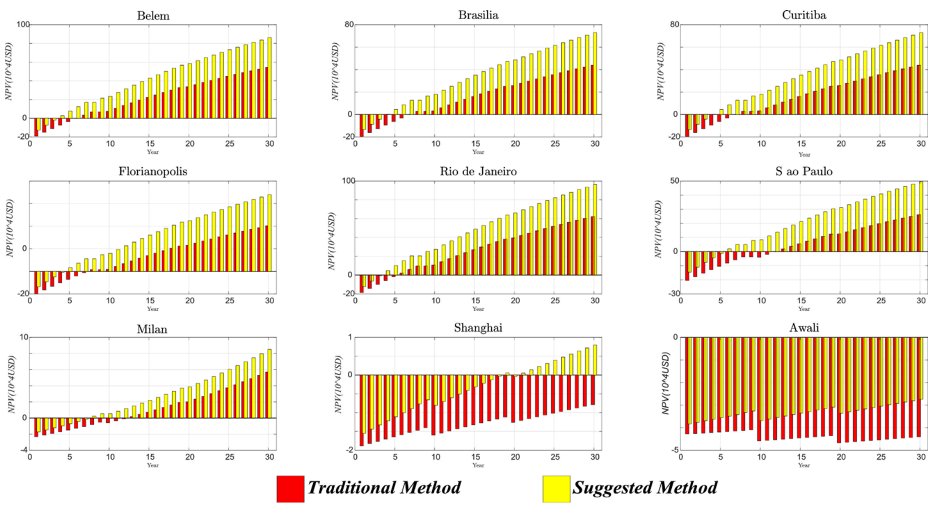


Figure 4-7 NPV calculation considering the traditional method and suggested method

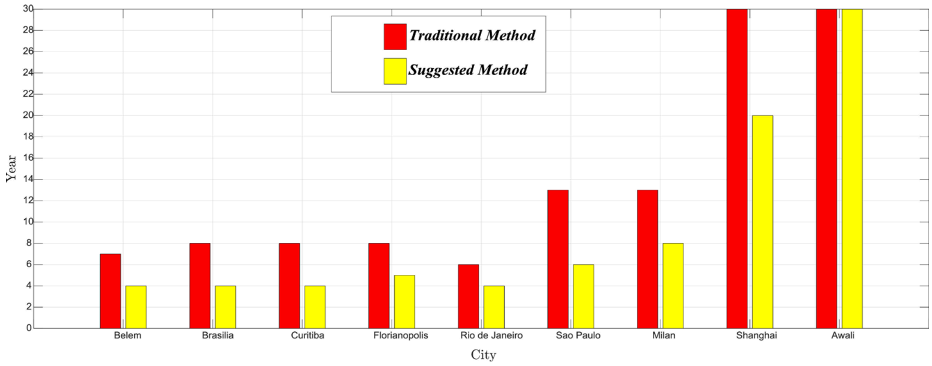


Figure 4-8 DPP considering the traditional method and suggested method

As can be seen from the pictures, the suggested method improves the economic feasibility of the BIPV system. For instance, the DPP for Belem has been decreased from seven years to four years. Regarding the Awali case study, the system is still unfeasible considering a 30-year lifecycle of the BIPV system, even when applying the suggested method. Figure 4-9 depicts the BIPV price per watt peak, electricity tariff, social cost of carbon (CSCCs), transmission line loss of the case studies.

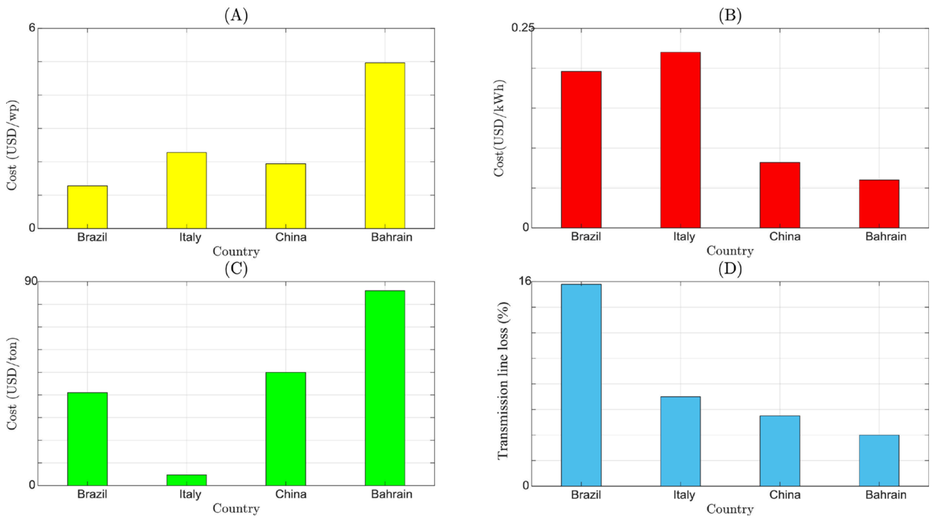


Figure 4-9 (A) BIPV price, (B) Electricity tariff, (C) CSCCs, and (D) Transmission line loss of the different countries.

The result discovers that the NPV value of environmental and societal advantages for the studied countries could vary from 1.403 USD per watt peak to even 2.710 USD per watt peak depending on the values of the examined factors for each case study. This method can be applied to other countries to calculate the NPV and DPP of the BIPV system. The suggested method shows the economic viability of all the case studies except Bahrain. The DPP of the BIPV system in Bahrain is still more than its life cycle because of low electricity tariffs and high initial cost (more than twice of other case studies). Moreover, the suggested method brings the DPP of the BIPV system in China to 20 years while it was more than the system's lifetime by the traditional method. The NPV of societal and environmental advantages of the BIPV system has its highest value for Italy according to the simulation, which is because of the high electricity tariff in Italy.

Since there is no data regarding the cost of the carbon emissions during the manufacturing/transportation/disposal of the BIPV panels in referenced studies, these parameters are not considered. However, the BIPV modules and components contain glass, aluminium 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 [59].

4.6. LCOE and rational incentives

Paper: Levelised Cost of Electricity (LCOE) of Building Integrated Photovoltaics (BIPV) in Europe, Rational Feed-In Tariffs and Subsidies

The study is set out to present a method, calculate and report the LCOE of BIPV systems for the EU countries and, more specifically, the LCOE for the BIPV system as a building envelope material for the outer skin of the buildings.

Figure 4-10 depicts the lifetime electricity production of the BIPV system (E_{GT}) as a building envelope material for the skins of the buildings in the EU countries. The total production is between 2819 kWh per m^2 (in Finland) and 5084 kWh per m^2 (in Cyprus). The average production for the EU is 3601 kWh per m^2.

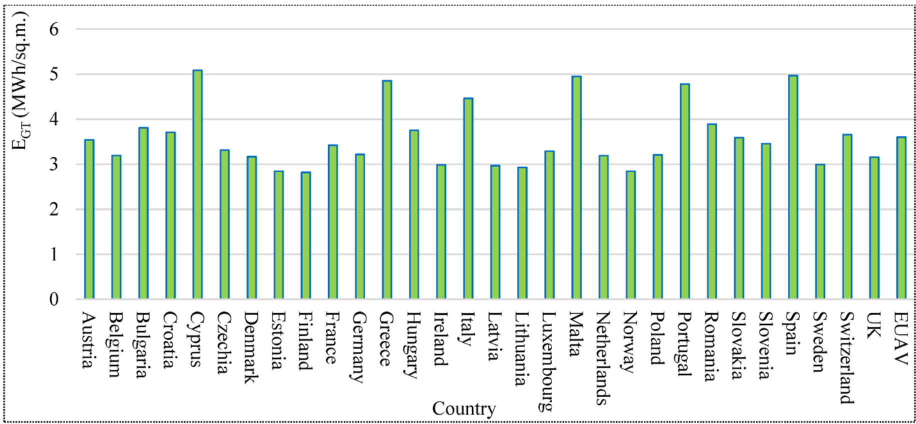


Figure 4-10 Lifetime electricity production of the BIPV system (EGT) as building envelope material

Figure 4-11 illustrates the electricity price of the grid and LCOE of BIPV as a building envelope material for the entire building by taking the total investment related to both roles of the system as the net present value of the total cost (NPV_C).

As can be seen from Figure 4-11, the LCOE in Bulgaria, Croatia, Czechia, Estonia, Finland, Hungary, Latvia, Lithuania, Netherlands, Norway, Poland, Romania and Slovakia is more than the network price. In order to make the BIPV system economically feasible, a FiT rate is required (generally equal to the difference of NP and LCOE plus NP, in order to reach the grid parity). Furthermore, the analysis unfolds that on average in Europe, the BIPV system does not need a feed-in tariff if the selling price to the grid is equal to the purchasing price from the grid.

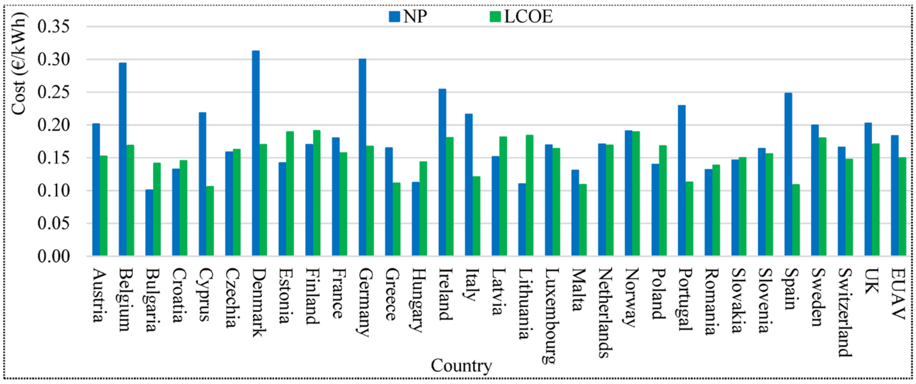


Figure 4-11 NP and LCOE of the system (considering cost related to both role of BIPV as the investment)

Figure 4-12 illustrates the electricity price of the grid and LCOE of BIPV as a building envelope material for the entire building by taking the investment related to the energy supplying role of the system as the net present value of the total cost (NPV_C).

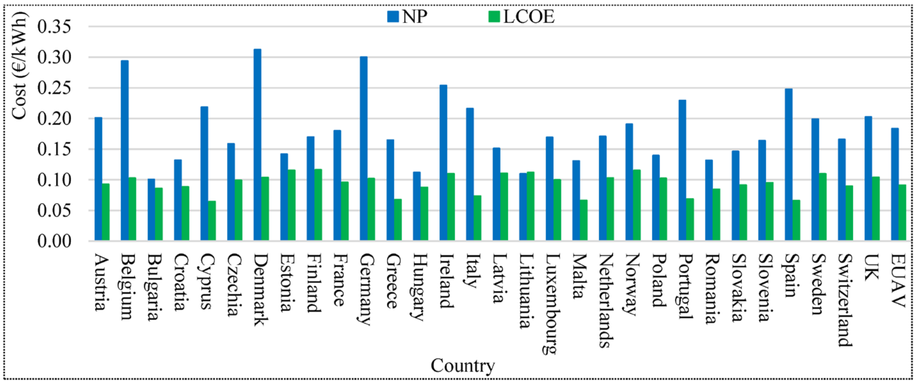


Figure 4-12 NP and LCOE of the system (considering cost related to the energy supplying role of BIPV as the investment)

Figure 4-12 reveals that the implementation of BIPV systems as a building envelope material has already passed the grid parity (which means the energy can be generated or delivered to the grid at the same cost as it can be purchased from the grid) in 29 out of 30 EU countries if the corresponding cost to its role as a power generator is taken into economic analysis. The only country in which BIPV needs support schemes to reach grid parity is Lithuania. The average LCOE for the EU (0.09 (€/kWh)) in this scenario is half of the average grid price in the EU (0.18 (€/kWh)).

Although BIPV technology has reached grid parity in almost all of the investigated countries, what is critical is the question of whether the local grid is willing to buy the electricity at the same price that sells it to the end-user or not. The answer to this question has a remarkable effect on the proper designing of subsidies for this technology.

The paper also illustrates that a non-optimal design of BIPV systems (BIPV system with an efficiency of 10%, a lifetime of 25 years and an inverter replacement requirement for every ten years) could double the LCOE, highlighting the importance of system design, system component selection, and system implementation.

The article also presents a metric to the EU countries to investigate the current situation of the BIPV and determine whether the technology needs any incentive and subsidy or not by employing the discussed approach in this paper.

Although the current study is based on average values of parameters, the finding presents the underlying part and foundation of further studies regarding the LCOE of BIPV in the EU and the reasonable amount of subsidies or incentives for this technology to drive a faster rollout of BIPV in the EU. Further work needs to be done to investigate and assess the impact of urban areas (shading, reflection, etc.) and the effect of climate on the system efficiency considering different technologies on the presented analysis.

4.7. BIPV in Norway

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

This paper deals with the LCCA of a 127.5 kW_P of BIPV façade system with the estimated annual production of 55.5 MWh/m^2 in Drammen, Norway, which has received a government subsidy. The paper analyses the system's economic performance based on the monitored data after four years of operation and explains the effect of the subsidy on the LCCA of such a system. The LCCA indices, including NPV, DPP, IRR and LCOE, are calculated.

Figure 4-13 shows the cumulative NPV of the BIPV system based on three scenarios of initial investment and also NPV of the façade if the glass option was selected (without taking the EOL benefits into account) as follows:

> *Scenario-A:* Gross investment, which is the total invested money by the client without taking the Enova support and BIPV function as a building envelope material into consideration (4,625,794 NOK);
>
> *Scenario-B:* Net investment without Enova support, which is the total invested money by the client considering the system functionality as a building envelope material (an alternative for glass façade) but without taking the Enova support into the evaluation (4,625,794 NOK - 2,125,830 NOK = 2,499,964NOK);
>
> *Scenario-C:* Net investment with Enova support, which is the total invested money by the client by taking the system functionality as a building envelope material (an alternative for glass façade) and the Enova support into the evaluation

(4,625,794 NOK - 2,125,830 NOK - 1,553,236 NOK = 946,728NOK);

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

By taking the subsidy granted by Enova into the calculation, the cumulative NPV of the BIPV system becomes positive, with a total value of 478,934 NOK (0.48 Million NOK). It means the BIPV system could reimburse the invested money and become a source of income for the building. It is also found out that with a subsidy equal to 1,074,301 NOK, the cumulative NPV of the BIPV system would become zero. On the other hand, and in terms of the glass façade option, the cumulative NPV of the system will be -2,125,830 NOK.

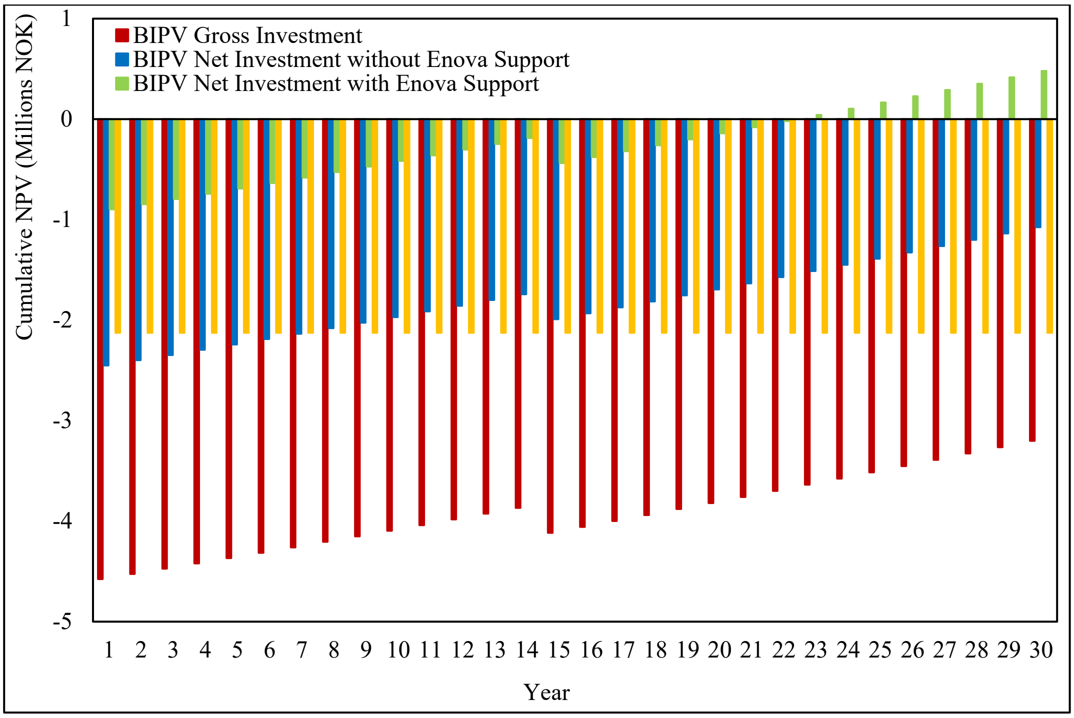


Figure 4-13 The cumulative NPV of investment for different scenarios (without EOL benefits)

Figure 4-14 presents and sums up all the factors involved in this project's LCAA and economic analysis. The total carbon saving from the BIPV system of this building over a 30-years lifetime is equal to 105 Tons of CO_2. It is apparent from Figure 4-13 that the Enova support greatly covers the societal and environmental benefits of the BIPV system, which has been quantified (saving in transmission loss, saving in power delivery cost and carbon tax).

What is interesting in Figure 4-14 is that for every BIPV project, such a graph could be plotted, and then decision-makers could discuss and decide on the amount of incentive or subsidy. The graph varies from country to country or even from project to project, but the principles are the same.

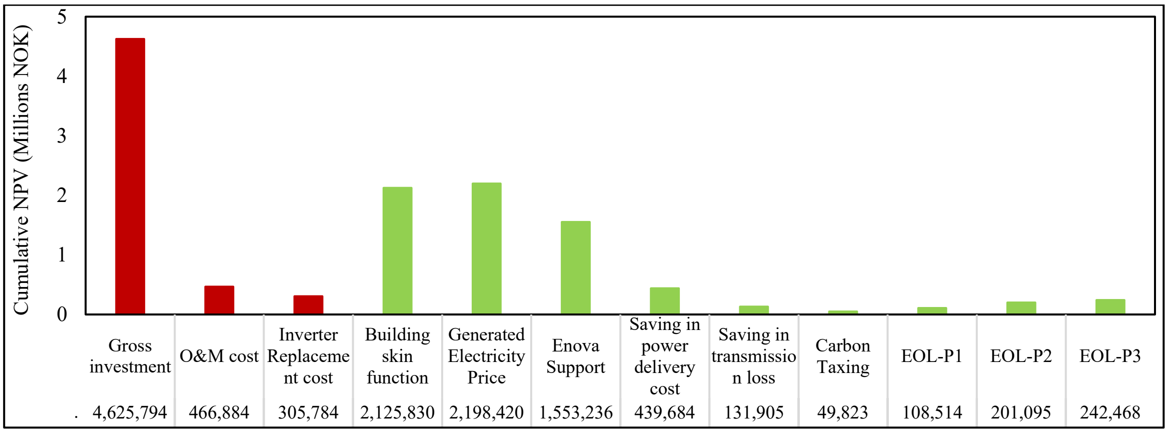


Figure 4-14 The absolute cumulative NPV of different items for this project

The provided output demonstrates that the case study system is economically feasible with a DPP of 22 years, IRR of 6%, cumulative NPV of 478,934 NOK and LCOE of 1.28 NOK/kWh (sum of first six items in Figure 4-14). Furthermore, with an average annual solar irradiance of 707 kWh/ m^2 on the system, the average annual electricity production of the system, based on the monitored data, is 40 kWh/ m^2.

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

A parametric analysis is also conducted in this article to show the effect of various input parameters on the system's output. The output is defined as the cumulative NPV of the BIPV system over the lifetime of the system. The examined input parameters are the discount rate, BIPV price, conventional building envelope material price, BIPV electricity Production, electricity tariff and degradation rate.

Regarding the different end-of-life material recovery approaches in this study, recovering different materials from BIPV glazing is a complex process and depends on PV technology. This paper does not mention who will perform the material recovery task and what the cost would be. This cost will have an impact on the end-of-life financial gain calculation as well. A contribution to this work would be to investigate this discussion more in detail.

4.8. BIPV contribution to energy transition of cities and challenges

Paper: The contribution of building integrated photovoltaics (BIPV) to the concept of nearly zero-energy cities in Europe: potential and challenges ahead

The paper defines a metric for architects and urban planners to grasp how much of the energy consumption of buildings in Europe could be supplied by BIPV systems as building envelope materials for the whole building envelope surface areas. The results show how much different

European countries can rely on BIPV technology in the energy transition journey in urban areas.

Table 4-1 depicts the ratio of energy consumption of BNA (EBNA) to the energy production of BS (EBS) per square meter for the European capitals. In other words, the numbers illustrate how much of the building skin surface is required to supply the energy consumption of one square meter of the building net area. For example, the table shows that in terms of Vienna with BSGR equal to 30% and BIPV implementation date of 2030, the energy consumption of one square meter of a building net area could be supplied by 0.8 square meters of building skin. In other words, a building with a building skin to the building net area ratio of 0.8 in Vienna could be Zero-energy in 2030 building by employing BIPV technology.

It is worth highlighting that the correlation between EBS and EBNA is linear. It means that in terms of the previous example, a building with a building skin to the building net area ratio of 0.6 could supply 80% of the energy consumption of the building considering all the mentioned assumptions. Moreover, there is a clear trend that by increasing the BSGR ratio, the value of EBNA to EBS rises as well, which make sense because the more a building skin is glazed, the more surface area is covered by glass BIPV, which has less efficiency compared to BIPV panel.

The result illustrates that BIPV technology could contribute to a great extent to supplying the energy demand of urban areas. The study of the capitals of all the European Union member states (EU) together with the capitals of Norway and Switzerland, depicts that on average, by a building skin to the building net area ratio of 0.78, building skin glazing ratio (BSGR) of 30%, BIPV glass and BIPV panel efficiency of 13% and 25%, building energy consumption of 135 kWh/ m^2.year in 2030, the EU cities could reach the target of zero-energy urban areas.

Table 4-1 The ratio of energy consumption of BNA (EBNA) to the energy production of BS (EBS)

No	Country	Capital	EBNA/EBS					
			BSGR 30%		BSGR 40%		BSGR 50%	
			2020	2030	2020	2030	2020	2030
1	Austria	Vienna	1.37	0.80	1.49	0.84	1.62	0.90
2	Belgium	Brussels	1.52	0.88	1.65	0.93	1.79	0.99
3	Bulgaria	Sofia	1.28	0.74	1.38	0.78	1.50	0.83
4	Croatia	Zagreb	1.31	0.76	1.42	0.81	1.54	0.86
5	Cyprus	Nikosia	0.96	0.55	1.03	0.59	1.12	0.62
6	Czechia	Prague	1.47	0.85	1.59	0.90	1.73	0.96
7	Denmark	Copenhagen	1.54	0.89	1.66	0.94	1.81	1.00
8	Estonia	Tallinn	1.71	0.99	1.85	1.05	2.01	1.12
9	Finland	Helsinki	1.72	1.00	1.86	1.06	2.03	1.13
10	France	Paris	1.42	0.82	1.54	0.87	1.67	0.93
11	Germany	Berlin	1.51	0.88	1.63	0.93	1.78	0.99
12	Greece	Athens	1.00	0.58	1.08	0.62	1.18	0.65
13	Hungary	Budapest	1.30	0.75	1.40	0.80	1.52	0.85
14	Ireland	Dublin	1.63	0.94	1.76	1.00	1.92	1.06
15	Italy	Rome	1.09	0.63	1.18	0.67	1.28	0.71
16	Latvia	Riga	1.64	0.95	1.77	1.01	1.93	1.07
17	Lithuania	Vilnius	1.66	0.96	1.79	1.02	1.95	1.08
18	Luxembourg	Luxemburg	1.48	0.86	1.60	0.91	1.74	0.97
19	Malta	Valleta	0.98	0.57	1.06	0.60	1.16	0.64
20	Netherlands	Amsterdam	1.52	0.88	1.65	0.94	1.79	1.00
21	Poland	Warsaw	1.52	0.88	1.64	0.93	1.78	0.99
22	Portugal	Lisbon	1.02	0.59	1.10	0.62	1.20	0.66
23	Romania	Bucharest	1.25	0.73	1.35	0.77	1.47	0.82
24	Slovakia	Bratislava	1.36	0.79	1.47	0.83	1.59	0.88
25	Slovenia	Ljubljana	1.41	0.82	1.52	0.86	1.66	0.92
26	Spain	Madrid	0.98	0.57	1.06	0.60	1.15	0.64
27	Sweden	Stockholm	1.62	0.94	1.76	1.00	1.91	1.06
28	UK	London	1.54	0.89	1.67	0.95	1.81	1.01
29	Norway	Oslo	1.71	0.99	1.85	1.05	2.01	1.12
30	Switzerland	Bern	1.33	0.77	1.44	0.82	1.56	0.87
--	Average	--	1.35	0.78	1.46	0.83	1.59	0.88

Such a table is a great asset for the architecture to investigate how much of the energy demand of the designed building could be supplied by its skin, not only in the current stage but also for the future and possible renovation etc.

Challenges to a wide rollout of the BIPV system are also discussed in this paper. Figure 4-15 depicts the challenges when it comes to the different stages and players involved in these challenges.

The main players of the BIPV market, who are also primary stakeholders with high impact and power with respect to BIPV technology are fallen into eight categories of politicians, administrations, manufacturers, architects, consultancies, power grid, BIPV contractors/installers and end-users.

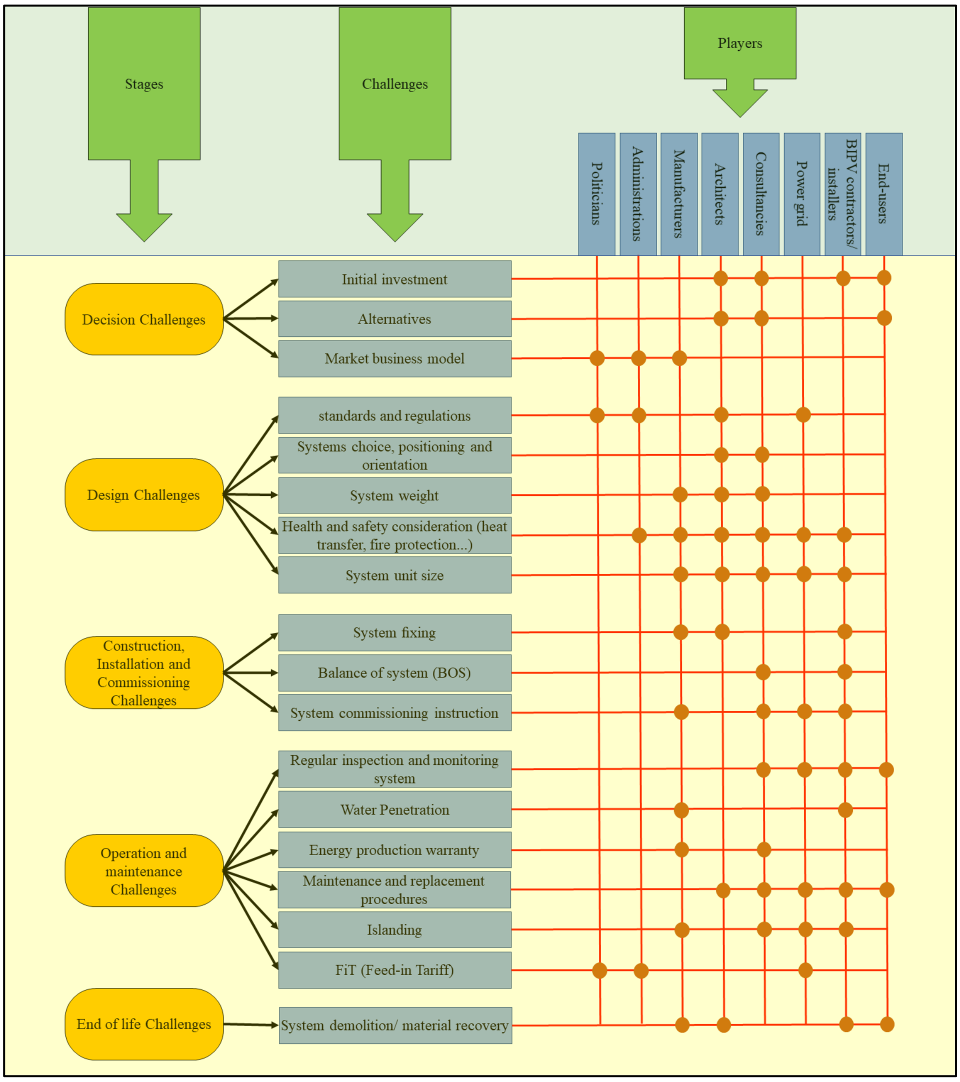


Figure 4-15 BIPV barriers` classification and involved stakeholders who could contribute to a solution

However, the study does not consider constraints related to the urban context of the case studies, such as shading issues, building barriers, historical, architectural and regulatory constraints. A contribution to this work could be evaluating the effect of the urban context on the outcome of this research study. Another contribution could be the effect of climate and different technology on the results of this article.

5 Conclusion

Cities are experiencing an energy policy transition to minimise and finally zeroing their carbon footprint. A significant part of this carbon footprint originates from energy consumption, and buildings play a vital role in this regard. Therefore, this PhD aimed to determine to what extent the BIPV can contribute to this goal in Europe by investigating the feasibility of building integrated photovoltaic (BIPV) systems as a building envelope material in Europe. Through its huge numbers of building facades and roofs, cities can become the power stations of the future.

The results are promising and show that the technology as an alternative for other building envelope materials has already become economically viable in a major part of Europe. The overall price of the BIPV system is going down annually, and simultaneously, its efficiency is increasing. Although, more efforts towards a more appropriate and fair procedure are needed when it comes to the regulation and policies and power trading schemes for the owners of buildings with BIPV solutions.

The footprint of the technology on the environment and society is also investigated. It is concluded that the technology could also avoid massive investment on the power grid and transmission line and their expansion because the technology is producing power where it would most likely be used. Moreover, BIPV also addresses the critics of exploited land use for solar power plants or wind farms by being implemented on the building skins.

Unfortunately, it is not possible to set a specific price for BIPV per unit kW or square meter, even for a country, region, or city. The BIPV price depends on many factors like BIPV type, location, technical specification, system size, etc. Therefore, in this PhD project, we tried to set average prices to evaluate the system and, in the end, investigate the impact of the inputs on the output with a sensitivity analysis.

Regarding technical investigations, emerging technologies such as organic solar cells and perovskite solar cells are progressing rapidly in terms of efficiency, performance, and other technical privileges such as spectral response and mechanical flexibility. These aspects will make the available types and models of BIPV in the market increasingly diverse and results in a more comfortable use of technology.

The result from the designed experiment to investigate the reflected radiation from the south facade of a neighbouring building to the north façade is also remarkable. The results illustrate that while the incident solar radiation of the north façades in urban areas like Stavanger is less than 30% of the incident solar radiation of the south façades, with a reflection from the south facade of a neighbouring building with glass and/or white panel materials, the incident solar radiation of the same north facade can increase to 50%. Although the electricity production might not scale up to the same portion when using silicon-based PV panels. This indicates that although some issues such as shading in urban areas would jeopardize the incident solar radiation of facades, a portion of this decline can be recouped by the reflection. From an urban planning point of view, if taken reflection seriously to legislation, it might have an impact on the use of urban spaces and the building of structures there, vegetation etc. Therefore, the planners will have to carefully balance how reflection needs are valued as supposed to need for parks, green spaces, and trees that obstruct reflection.

Other major findings from this doctoral study are briefly presented here:

- ❖ In Scandinavian countries and because of higher latitude (lower solar altitude), the geographical potential of façades is significant comparing to the roof. For example, for the south façade, the potential is similar to the roof if seen over the year. Moreover, challenges like snowfall for the roof-mounted PV systems not only does not count as an issue for the façade-mounted PV but also could be seen as an advantage because of the high reflection of the snow and the increased incident radiation on the facades.

❖ The average annual radiation potential of BIPV as a building envelope material for the entire skins of building in Europe is more than the average annual radiation potential of BIPV on the east or west façade. Figure 5-1 shows these values for Stavanger.

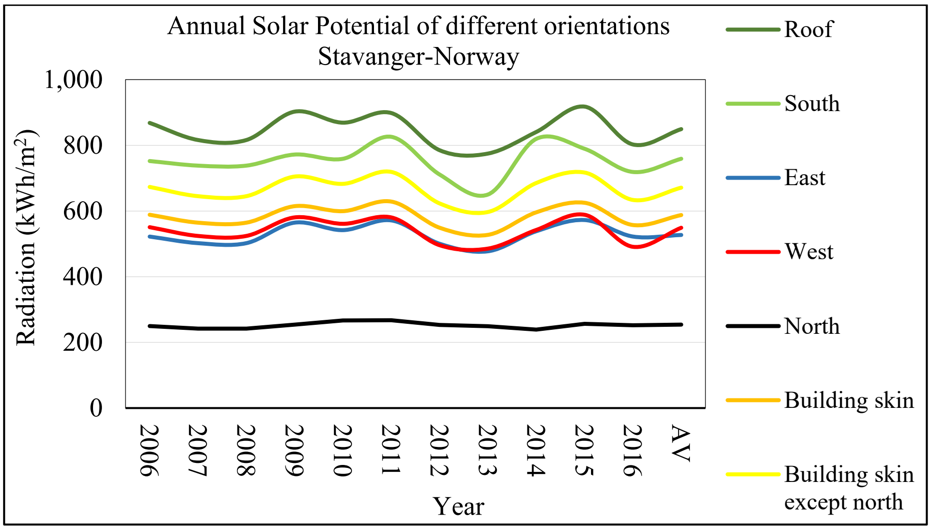


Figure 5-1 Historical data of annual solar incident radiation potential in Stavanger

❖ BIPV, for its building envelope role, should be regarded as its alternatives such as glass, stone, brick, wood etc. It means that the cost corresponding to its energy supplying role should be considered for the financial analysis and economic feasibility study.

❖ By considering the investment on the BIPV related to its power generation role as the initial investment for the financial analysis, the BIPV as a building envelope material on average and in all the capital of European member states plus Norway and Switzerland will reimburse all the investment in its lifetime. Non-optimal solutions or inappropriate technical design can violate this fact.

- ❖ BIPV as a building envelope material for the entire skin of buildings in urban areas of Europe can have an incredible contribution towards the energy transition of cities. For example, on average and in Europe, by a building skin to the building net area ratio of 0.78, building skin glazing ratio (which is the ratio of the glazed surface to the total surface of the building skin) of 30% and using BIPV on the entire skin of buildings in 2030, the EU cities could reach the zero-energy target.

Results of this study and theoretical and practical implications can guide end-users, architects and urban planners to decide more conscious about the BIPV systems and steer governments and decision-makers to support the technology by rational subsidies and incentive regulations.

6 Articles

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

Hassan Gholami [1], Harald Nils Røstvik [2]

Department of Safety, Economics and Planning, University of Stavanger, Kjell Arholmsgate 41, 4036 Stavanger, Norway

[1] PhD Researcher, + 47 96 95 72 95, hassan.gholami@uis.no
[2] Professor, + 47 92 22 67 10, harald.n.rostvik@uis.no

Energy
Volume 204, 1 August 2020, 117931

https://doi.org/10.1016/j.energy.2020.117931

Energy 204 (2020) 117931

Contents lists available at ScienceDirect

Energy

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

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

Hassan Gholami *, Harald Nils Røstvik

Department of Safety, Economics and Planning, University of Stavanger, Kjell Arholmsgate 41, 4036, Stavanger, Norway

ARTICLE INFO

Article history:
Received 18 March 2020
Received in revised form
7 May 2020
Accepted 20 May 2020
Available online 26 May 2020

Keywords:
BIPV
Building integrated photovoltaics
LCCA
Lifecycle cost analysis
NPV
Net present value
DPP
Discounted payback period
IRR
Internal rate of return
Carbon tax

ABSTRACT

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

* Corresponding author.
E-mail addresses: hassan.gholami@uis.no (H. Gholami), harald.n.rostvik@uis.no (H.N. Røstvik).

https://doi.org/10.1016/j.energy.2020.117931
0360-5442/

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

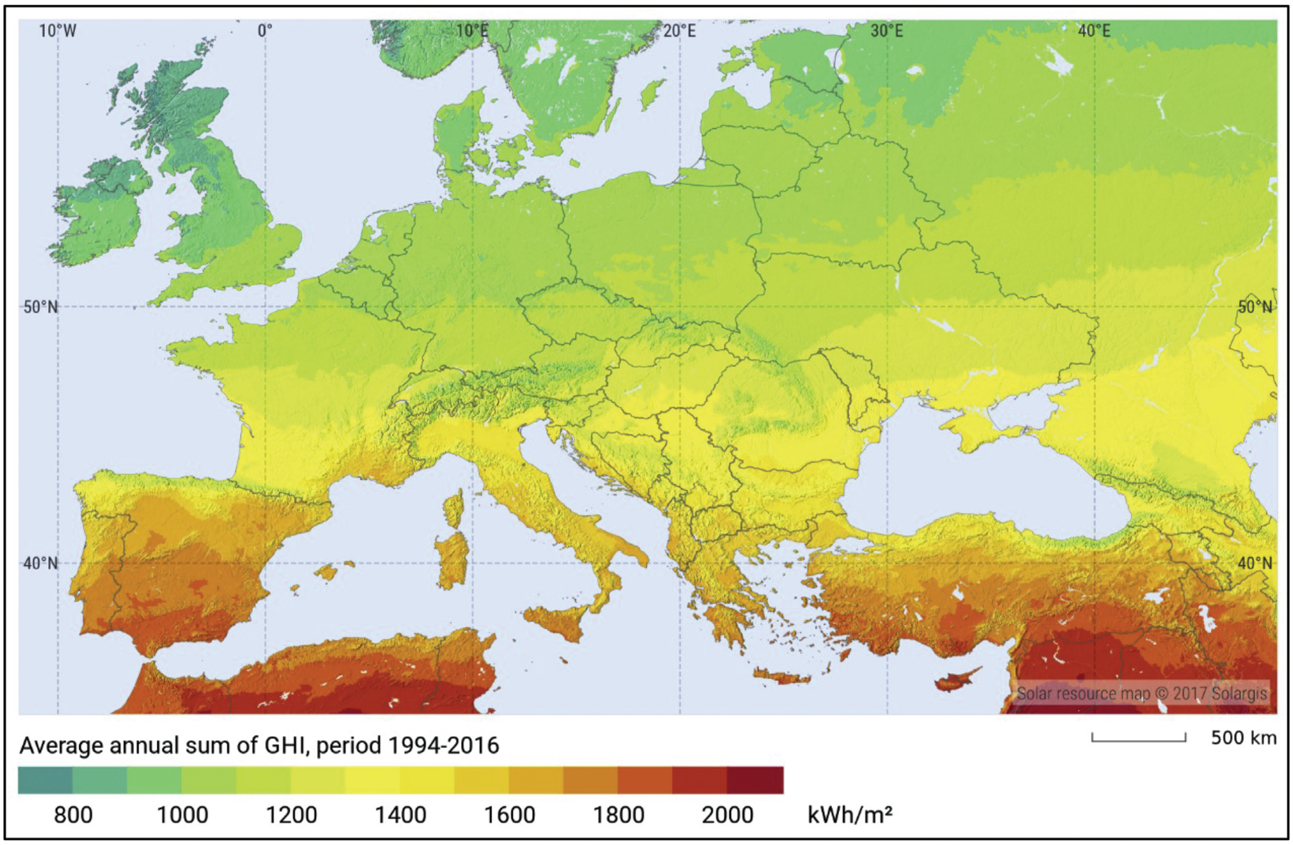


Fig. 1. The theoretical potential map of solar irradiance in Europe [44].

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.

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

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%.

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):

$$Q = I_{PIC} - I_{EMC} \tag{2}$$

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:

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

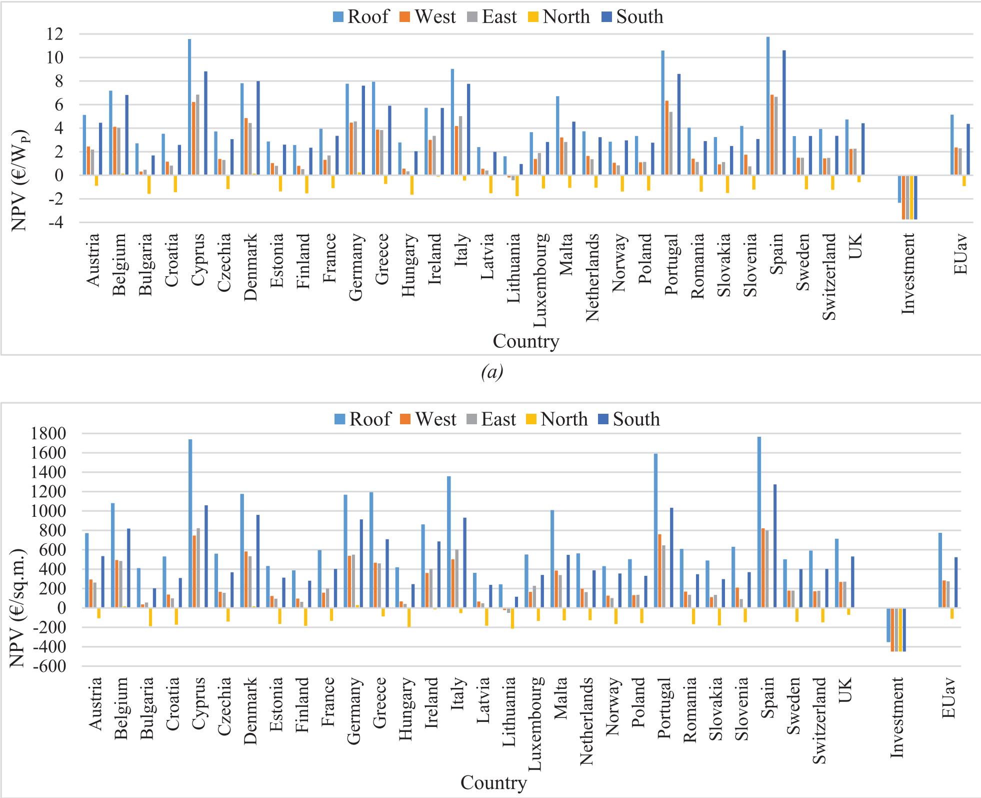


Fig. 2. The cumulative NPV of BIPV systems for building skins with different orientations in the European countries: (a) NPV per watt-peak, (b) NPV per square meter.

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.

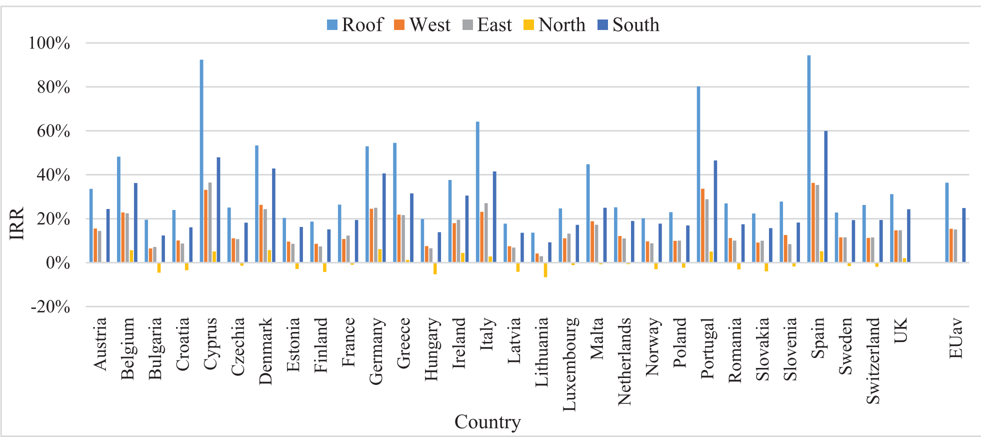


Fig. 3. IRR of BIPV systems for building skins with different orientations in the European countries.

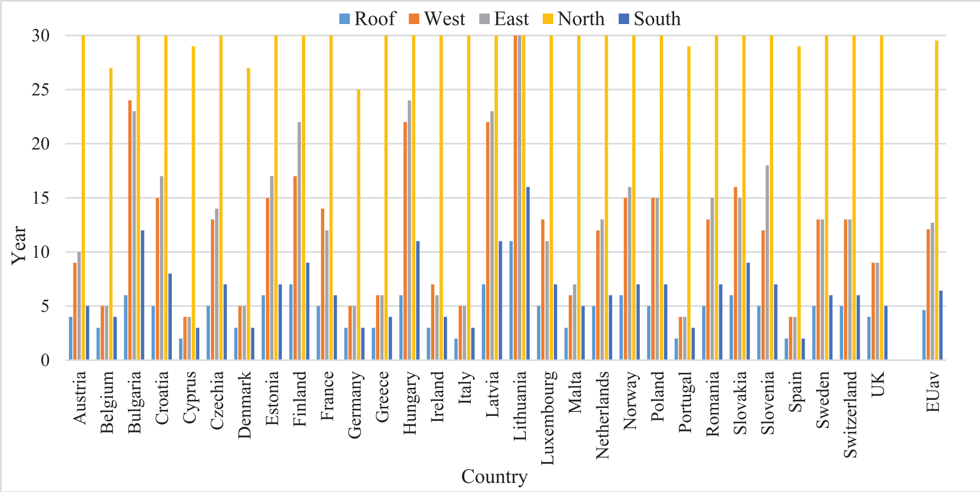


Fig. 4. DPP of BIPV systems for building skins with different orientations in the European countries.

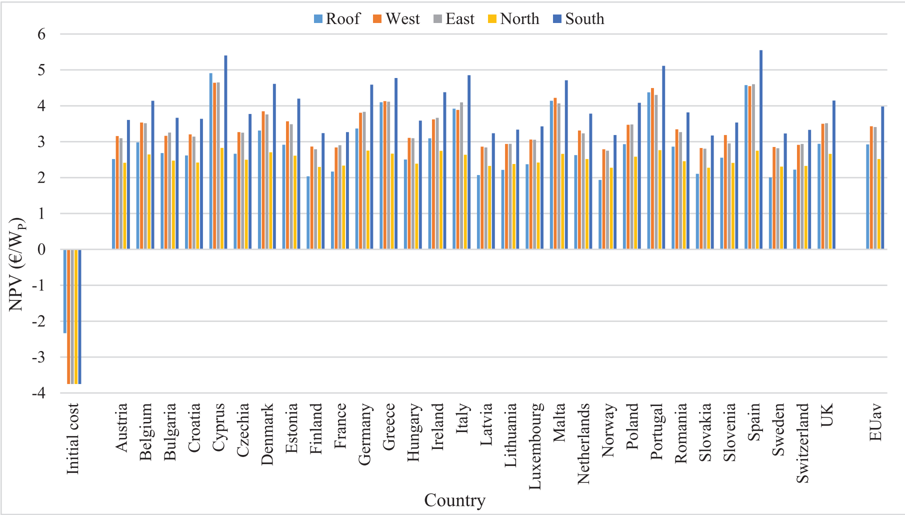


Fig. 5. The cumulative NPV advantages of BIPV systems for building skins with different orientations in the European countries.

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,

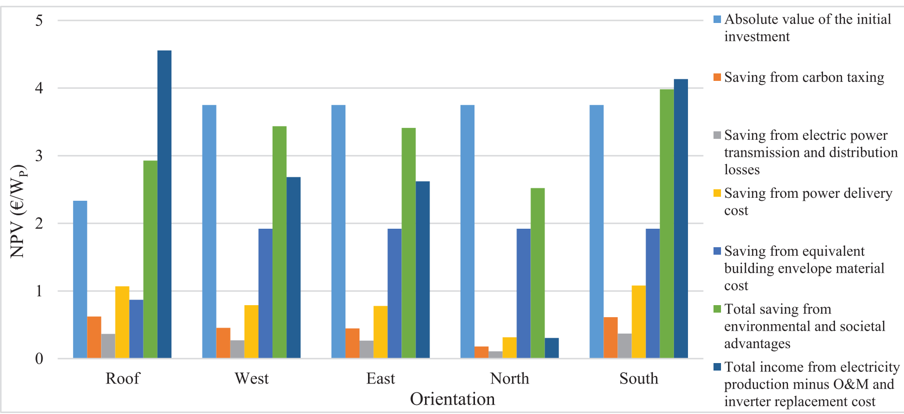


Fig. 6. The average cumulative NPV of factors for different orientations in Europe.

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

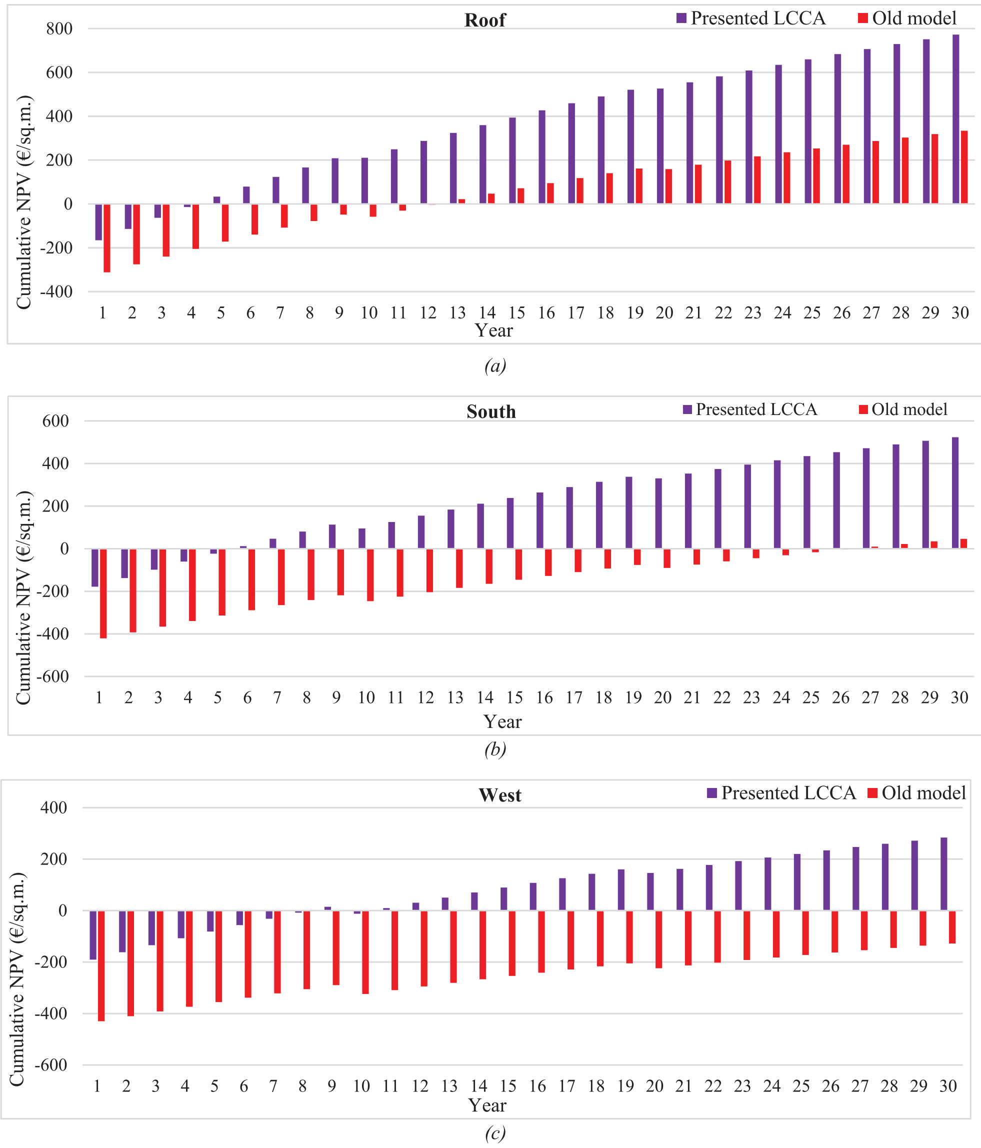


Fig. 7. The average lifetime cumulative NPV of BIPV with different orientation for Europe: (a)roof; (b)south; (c)west; (d)east; (e)north.

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.

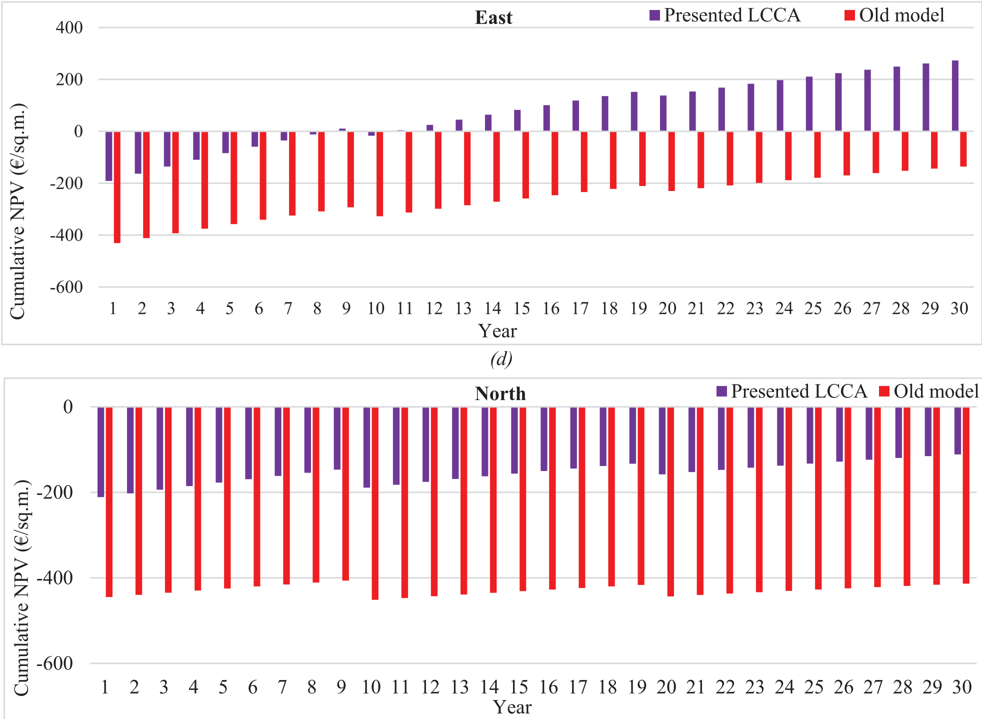


Fig. 7. (*continued*).

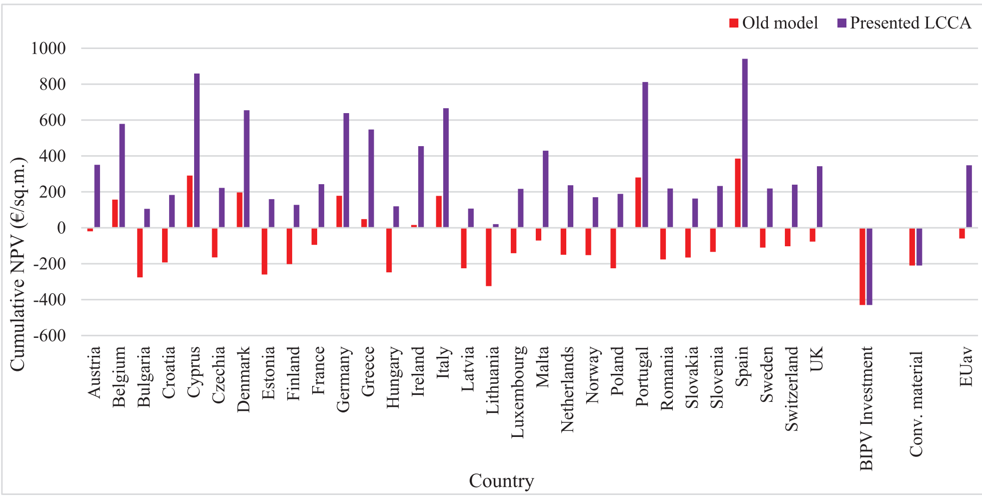


Fig. 8. The cumulative NPV of BIPV materials for the whole building envelope in European countries.

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

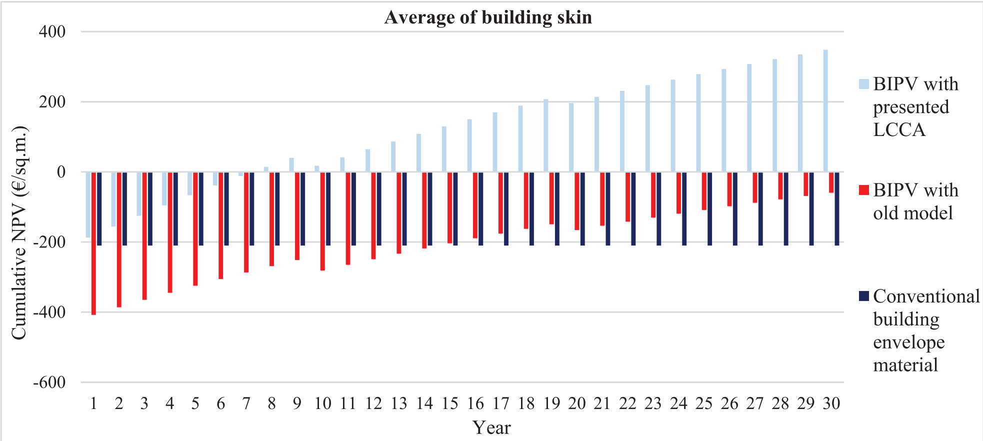


Fig. 9. The average lifetime cumulative NPV of building envelope in Europe.

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.

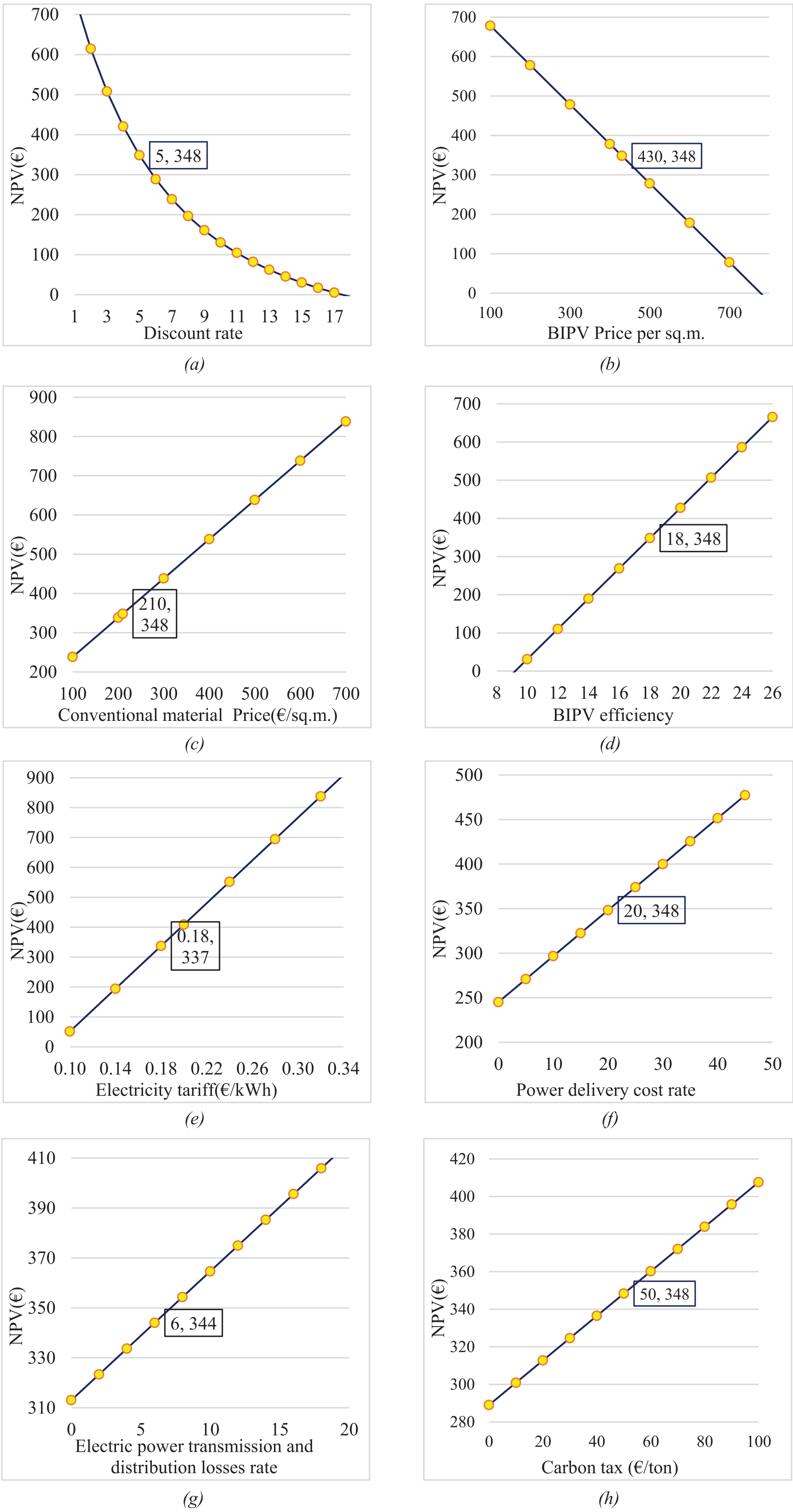


Fig. 10. Average cumulative NPV for BIPV as a building skin in Europe under variation of different parameters: (a)discount rate; (b) BIPV price; (c)conventional material price; (d) BIPV efficiency; (e)electricity tariff; (f)power delivery cost; (g) electric power transmission and distribution losses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

Acknowledgment

The work reported in this paper was supported by the Department of Safety, Economics, and Planning of the University of Stavanger (Project name: Building Integrated Photovoltaic (BIPV) in dense urban areas, Project number: IN-12011). Special thanks also goes to the Smart City Group and Future Energy Hub at the University of Stavanger for their support.

References

[1] Jäger-Waldau A. PV status report 2019. Publications Office of the European Union; 2019. Luxembourg2019, Available: https://ec.europa.eu/jrc.
[2] Gholami H, Røstvik HN, Müller-Eie D. Holistic economic analysis of building integrated photovoltaics (BIPV) system: case studies evaluation. Energy and Buildings 2019/11/15/2019;203:109461.
[3] Jing Yang R, Zou PXW. Building integrated photovoltaics (BIPV): costs, benefits, risks, barriers and improvement strategy. International Journal of Construction Management 2015;16(1):39–53.
[4] Nguyen KC, Katzfey JJ, Riedl J, Troccoli A. Potential impacts of solar arrays on regional climate and on array efficiency. International Journal of Climatology 2017;37(11):4053–64.
[5] Armstrong A, Waldron S, Whitaker J, Ostle NJ. Wind farm and solar park effects on plant–soil carbon cycling: uncertain impacts of changes in ground-level microclimate. Global Change Biology 2014;20(6):1699–706.
[6] Gholami H, Khalilnejad A, Gharehpetian G. Electrothermal performance and environmental effects of optimal photovoltaic–thermal system. Energy Conversion Management 2015;95:326–33.
[7] Gholami H, Sarwat A, Hosseinian H, Khalilnejad A. Evaluation of optimal dual axis concentrated photovoltaic thermal system with active ventilation using Frog Leap algorithm. Energy Conversion Management 2015;105:782–90.
[8] Mohammadi F, Gholami H, Menhaj MB. Effect of ventilation on yearly photovoltaic performance. 1st international conference on new research achievements in electrical and computer engineering, vol. 1. IEEE; 2016. p. 6. 1.
[9] Agrawal B, Tiwari G. Life cycle cost assessment of building integrated photovoltaic thermal (BIPVT) systems. Energy and Buildings 2010;42(9): 1472–81.
[10] Ibrahim A, Fudholi A, Sopian K, Othman MY, Ruslan MH. Efficiencies and improvement potential of building integrated photovoltaic thermal (BIPVT) system. Energy Conversion and Management 2014;77:527–34.
[11] Tripathy M, Joshi H, Panda S. Energy payback time and life-cycle cost analysis of building integrated photovoltaic thermal system influenced by adverse effect of shadow. Applied Energy 2017;208:376–89.
[12] Jelle BP, Breivik C, Røkenes HD. Building integrated photovoltaic products: a state-of-the-art review and future research opportunities. Solar Energy Materials and Solar Cells 2012;100:69–96.
[13] Shukla AK, Sudhakar K, Baredar P. A comprehensive review on design of building integrated photovoltaic system. Energy and Buildings 2016;128: 99–110.
[14] Esmailian E, Gholami H, Røstvik HN, Menhaj MB. A novel method for optimal performance of ships by simultaneous optimisation of hull-propulsion-BIPV systems. Energy Conversion and Management 2019;197:111879.
[15] Hammond GP, Harajli HA, Jones CI, Winnett AB. Whole systems appraisal of a UK Building Integrated Photovoltaic (BIPV) system: energy, environmental, and economic evaluations. Energy Policy 2012;40:219–30.
[16] Azadian F, Radzi M. A general approach toward building integrated photovoltaic systems and its implementation barriers: a review. Renewable Sustainable Energy Reviews 2013;22:527–38.
[17] Cerón I, Caamaño-Martín E, Neila FJ. 'State-of-the-art'of building integrated photovoltaic products. Renewable Energy 2013;58:127–33.
[18] Shukla AK, Sudhakar K, Baredar P. Recent advancement in BIPV product technologies: a review. Energy and Buildings 2017;140:188–95.
[19] Saretta E, Caputo P, Frontini F. A review study about energy renovation of building facades with BIPV in urban environment. Sustainable Cities and Society 2018;44:343–55.
[20] Vulkan A, Kloog I, Dorman M, Erell E. Modeling the potential for PV installation in residential buildings in dense urban areas. Energy and Buildings 2018;169:97–109.
[21] Sorgato M, Schneider K, Rüther R. Technical and economic evaluation of thin-film CdTe building-integrated photovoltaics (BIPV) replacing façade and rooftop materials in office buildings in a warm and sunny climate. Renewable Energy 2018;118:84–98.
[22] Gholami H, Røstvik HN, Müller-Eie D. Analysis of solar radiation components on building skins for selected cities. In: Proceedings of 14th conference on advanced building SkinsBern. Switzerland: Advanced Building Skins. ABS; 2019. p. 541–9.
[23] Brito M, Redweik P, Catita C. Photovoltaics and zero energy buildings: the role of building facades. In: présenté à 28th European Photovoltaic Solar Energy Conference and Exhibition, Paris; 2013.
[24] Freitas S, Brito MC. Solar façades for future cities. Renewable Energy Focus 2019/12/01/2019;31:73–9.
[25] Chiu M-S, Hou S-P, Tzeng C-T, Lai C-M. Experimental investigations on the thermal performance of the ventilated BIPV wall. Journal of Applied Sciences 2015;15(3):613–8.
[26] Asiedu Y, Gu P. Product life cycle cost analysis: state of the art review. International journal of production research 1998;36(4):883–908.
[27] Aste N, Del Pero C, Leonforte F. The first Italian BIPV project: case study and long-term performance analysis. Solar Energy 2016;134:340–52.
[28] Jordan DC, Kurtz SR. Photovoltaic degradation rates—an analytical review. Progress in photovoltaics: Research Applications 2013;21(1):12–29.
[29] Wang W, et al. Environmental assessments and economic performance of BAPV and BIPV systems in Shanghai. Energy and Buildings 2016;130:98–106.
[30] Alnaser NW. First smart 8.64 kW BIPV in a building in Awali Town at kingdom of Bahrain. Renewable and Sustainable Energy Reviews 2018;82:205–14.
[31] Biyik E, et al. A key review of building integrated photovoltaic (BIPV) systems. Engineering science technology, an international journal 2017;20(3):833–58.
[32] Brito M, Freitas S, Guimarães S, Catita C, Redweik P. The importance of facades for the solar PV potential of a Mediterranean city using LiDAR data. Renewable Energy 2017;111:85–94.
[33] Groppi D, de Santoli L, Cumo F, Garcia DA. A GIS-based model to assess buildings energy consumption and useable solar energy potential in urban areas. Sustainable Cities and Society 2018;40:546–58.
[34] Zhang T, Wang M, Yang H. A review of the energy performance and life-cycle assessment of building-integrated photovoltaic (BIPV) systems. Energies 2018;11(11):3157.
[35] Sivanandan A. BIPV hotspots in the EU. Renewable energy focus 2009;10(2): 54–5.
[36] Byrnes L, Brown C, Foster J, Wagner LD. Australian renewable energy policy: barriers and challenges. Renewable Energy 2013;60:711–21.
[37] Osseweijer FJ, Van Den Hurk LB, Teunissen EJ, van Sark WG. A comparative review of building integrated photovoltaics ecosystems in selected European countries. Renewable Sustainable Energy Reviews 2018;90:1027–40.
[38] Zanetti I, et al. Building integrated photovoltaics: product overview for solar building skins-status report 2017. In: Kidlington, UK; 2017.
[39] Kaltschmitt M, Wiese A. Potentiale und Kosten regenerativer Energieträger in Baden-Württemberg. Univ.; 1992.
[40] Kaltschmitt M, Wiese A. Erneuerbare Energieträger in Deutschland: potentiale und Kosten. Springer-Verlag; 2013.
[41] Mondal MAH, Denich M. Assessment of renewable energy resources potential for electricity generation in Bangladesh. Renewable and Sustainable Energy Reviews 2010;14(8):2401–13.
[42] Quaschning V. Systemtechnik einer klimaverträglichen Elektrizitätsversorgung in Deutschland für das 21. Jahrhundert. VDI-Verlag; 2000.
[43] Mainzer K, Fath K, McKenna R, Stengel J, Fichtner W, Schultmann F. A high-resolution determination of the technical potential for residential-roof-mounted photovoltaic systems in Germany. Solar Energy 2014;105:715–31.
[44] Solar resource map Solargis. Solar resource maps of Europe. Available: https://solargis.com; 2019.
[45] Eurostat. Electricity price statistics. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics#Electricity_prices_for_household_consumers; 2019.
[46] Moro A, Lonza L. Electricity carbon intensity in European Member States: impacts on GHG emissions of electric vehicles. Transportation Research Part D: Transport and Environment 2018/10/01/2018;64:5–14.
[47] 2019 The World Bank Group (WBG). Electric power transmission and distribution losses (% of output). Available: https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS; 2018.
[48] The International Energy Agency (IEA). Global energy & CO2 status report. Available: https://www.iea.org/geco/electricity/; 2018, February.
[49] Aniti L. Today in energy. Available: https://www.eia.gov/todayinenergy/detail.php?id=32812; 2017.
[50] The Energy Institute. The full cost of electricity (FCe-) executive summary: the full cost of electricity. The University of Texas at Austin; 2018. Available: https://energy.utexas.edu/sites/default/files/UTAustin_FCe_Exe_Summary_2018.pdf.
[51] Gotzens F, Heinrichs H, Hake J-F, Allelein H-J. The influence of continued reductions in renewable energy cost on the European electricity system. Energy

Strategy Reviews 2018/08/01/2018;21:71–81.
[52] Steinbach J, Staniaszek D. Discount rates in energy system analysis Discussion Paper. Berlin, Germany: BPIE; 2015.
[53] García-Gusano D, Espegren K, Lind A, Kirkengen M. The role of the discount rates in energy systems optimisation models. Renewable and Sustainable Energy Reviews 2016/06/01/2016;59:56–72.
[54] Bonomo P, Chatzipanagi A, Frontini F. Overview and analysis of current BIPV products: new criteria for supporting the technological transfer in the building sector. VITRUVIO-International Journal of Architectural Technology and Sustainability 2015;(1):67–85.
[55] National Oceanic and Atmospheric Administration (NOAA). State of the climate: global climate report for annual 2016. Available: https://www.ncdc.noaa.gov/sotc/global/201613; 2017.
[56] The International Monetary Fund (IMF). Fiscal monitor: how to mitigate climate change. 2019. Washington.
[57] The World Bank Group (WBG). Carbon pricing dashboard. Available: https://carbonpricingdashboard.worldbank.org/map_data; 2019.
[58] The European Environment Information and Observation Network (Eionet). Overview of electricity production and use in Europe. Available: https://www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricity-production-2/assessment-4; 2019.
[59] Eiffert P. Guidelines for the economic evaluation of building-integrated photovoltaic power systems. Golden, CO.(US): National Renewable Energy Lab.; 2003.
[60] Eicker U, Demir E, Gürlich D. Strategies for cost efficient refurbishment and solar energy integration in European Case Study buildings. Energy and Buildings 2015;102:237–49.
[61] The Norwegian water resources and energy directorate (NVE). Electricity disclosure 2018. Available: https://www.nve.no/energy-market-and-regulation/retail-market/electricity-disclosure-2018/?ref=mainmenu; 2019.
[62] Larsen H. Klimafotavstrykket av offentlige anskaffelser. Beregning av klimafotavtrykket av offentlige anskaffelser for årene 2008 til 2017. In: Direktoratet for forvaltning og IKT (difi); 2019.

II. Dataset for the solar incident radiation and electricity production of building integrated photovoltaics (BIPV) system on the northern\southern façade in dense urban areas

Hassan Gholami [1], Harald Nils Røstvik [2]

Department of Safety, Economics and Planning, University of Stavanger, Stavanger, Norway

[1] *PhD Researcher, hassan.gholami@uis.no*
[2] *Professor, harald.n.rostvik@uis.no*

Data
Volume 6, Issue 6, No. 57, 26 May 2021

https://doi.org/10.3390/data6060057

data

MDPI

Data Descriptor

Dataset for the Solar Incident Radiation and Electricity Production BIPV/BAPV System on the Northern/Southern Façade in Dense Urban Areas

Hassan Gholami * and **Harald Nils Røstvik**

City and Regional Planning Group, Institute of Safety, Economics and Planning (ISØP), Faculty of Science and Technology, University of Stavanger, 4021 Stavanger, Norway; harald.n.rostvik@uis.no
* Correspondence: hassan.gholami@uis.no; Tel.: +47-969-57295

Abstract: The prosperous implementation of Building Integrated Photovoltaics (BIPV), as well as Building Attached Photovoltaics (BAPV), needs an accurate and detailed assessment of the potential of solar irradiation and electricity production of various commercialised technologies in different orientations on the outer skins of the building. This article presents a dataset for the solar incident radiation and electricity production of PV systems in the north and south orientations in a dense urban area (in the northern hemisphere). The solar incident radiation and the electricity production of two back-to-back PV panels with a ten-centimetre gap for one year are monitored and logged as primary data sources. Using Microsoft Excel, both panels' efficiency is also presented as a secondary source of data. The implemented PV panels are composed of polycrystalline silicon cells with an efficiency of 16.9%. The results depicted that the actual efficiency of the south-facing panel (13–15%) is always closer to the standard efficiency of the panel compared to the actual efficiency of the north-facing panel (8–12%). Moreover, although the efficiency of the south-facing panel on sunny days of the year is almost constant, the efficiency of the north-facing panel decreases significantly in winter. This phenomenon might be linked to the spectral response of the polycrystalline silicon cells and different incident solar radiation spectrum on the panels. While the monitored data cover the radiation and system electricity production in various air conditions, the analysis is mainly conducted for sunny days, and more investigation is needed to analyse the system performance in other weather conditions (like cloudy and overcast skies). The presented database could be used to analyse the performance of polycrystalline silicon PV panels and their operational efficiency in a dense urban area and for different orientations.

Dataset: https://doi.org/10.5281/zenodo.4804993

Dataset License: Creative Commons Attribution 4.0 International

Keywords: solar radiation; reflected radiation; compact urban areas; PV power generation; building integrated photovoltaics (BIPV); building attached photovoltaics (BAPV)

Citation: Gholami, H.; Nils Røstvik, H. Dataset for the Solar Incident Radiation and Electricity Production BIPV/BAPV System on the Northern/ Southern Façade in Dense Urban Areas. *Data* **2021**, *6*, 57. https://doi.org/10.3390/data6060057

Academic Editors: Vladimir Sreckovic and Jamal Jokar Arsanjani

Received: 26 March 2021
Accepted: 25 May 2021
Published: 26 May 2021

1. Summary

While electricity plays an essential role in the modern world, 13% of the world's population, equal to 940 million people, are deprived of electricity [1]. This fact can lead us toward the importance of renewable energy resources, especially solar energy, which can be harnessed everywhere globally.

Photovoltaic systems deployed in buildings are divided into two main types [2–8]:

BAPV or Building Attached PV;

BAPV are added to the building without directly affecting the structure's function. Roof-mounted PV systems in buildings are generally placed in this category.

BIPV or Building Integrated PV;

BIPV are photovoltaic modules which can be integrated into the building skin, such as the façade or roof, to generate electricity out of solar irradiation [9,10]. They are increasingly being incorporated into new buildings as a principal or ancillary source of electrical power [11,12]. However, existing buildings may be retrofitted with similar technology. The climate also plays a key role in the performance of such a system [13] and it can also be used in other industries, such as the ship manufacturing industry [14].

Researchers have recently sought to determine the feasibility of southern, eastern and western façades for BIPV and BAPV applications [15–17], while they have not treated northern façades in much detail. It seems there has been an assumption that the north façades (in the northern hemisphere) are unfeasible economically because the radiation there is low [11,18].

Therefore, the authors designed an experimental study to investigate the northern façade's potential and compare it with the southern façade. The aim was to collect solar incident radiation and PV electricity production data on the north façade and evaluate the south façade materials' effect as a reflector to the opposite north-facing façade of the neighbouring building.

2. Value of the Data and Data Specification

The value of the presented data in this paper can briefly be described as follows:

- The data depict the effect of dense urban areas on the solar incident radiation of the different orientations of building skins and BAPV/BIPV systems' efficiencies with different orientations on building skins in the northern hemisphere.
- The monitored data help to identify the suitable locations for BAPV/BIPV on building skins and assess the feasibility of using the BAPV/BIPV system as a building envelope material for the entire building skins.
- The dataset collected polycrystalline silicon-based BAPV/BIPV panels' performance, and it can be used to compare the results with other technologies, such as perovskite or organic solar cells.
- The reflected radiation in dense urban areas can boost the potential of untraditional façades in the northern hemisphere.
- Using different façades result in more homogenous electricity production. It also could lead to matching of demand and supply.

The specifications of the data are also presented in Table 1.

Table 1. Specifications table of the data.

Subject	**Renewable Energy, Sustainability and the Environment**
Specific subject area	BAPV/BIPV potential in urban areas Solar energy in compact urban blocks BAPV/BIPV efficiency in different orientations of building skin BAPV/BIPV panels' performance on north/south façades
Type of data	Table Image Figure
How data were acquired	Data are measured, monitored and logged by the equipment as follows: Two sets of SR30 sun[e] Pyranometer "ISO Secondary Standard"+ met[log] data logger Two sets of EVT300 microinverters with an EVB202 data logger
Data format	Raw time series data in csv format. The data are available with a sample resolution of a minute.
Parameters for data collection	Incident solar radiation and BIPV electricity production were collected at the site.
Description of data collection	Incident solar radiation data are logged with a minute sample resolution as raw data. PV electricity production and temperature data are logged with a sample resolution of three minutes as raw data. System efficiency is calculated, and the data are processed using Microsoft Excel as secondary data.
Data source location	Institution: University of Stavanger City/Town/Region: Stavanger Country: Norway Latitude and longitude for collected data: 58.9380454722466° N, 5.692057201993845° E
Data accessibility	With the article

3. Methods

3.1. Site

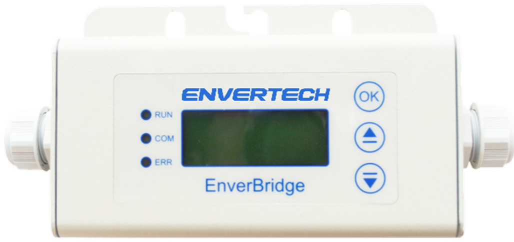
Figure 1 shows a picture of the site with all components and the location of the site. A 3D model of the site is also available as a supplement to this paper. The 3D model is a useful tool to investigate the boundary conditions (reflectance of ground surface/walls etc., the geometry of the complete building and the shading by neighbouring buildings) and the measurement results can therefore be used for the validation of simulations or for comparison with other measurements.

Figure 1. A picture of the site with components.

3.2. *System Components*

Table 2 indicates the components of the system and the implemented items. The datasheet and catalogue of the equipment as well as the 3D model of the site are available as Supplementary Materials, uploaded to Zenodo and is accessible by the following link: https://doi.org/10.5281/zenodo.4804993, accessed on 26 May 2021.

Table 2. List of system components.

Item	Schematic
TP660P Talesun 275 Wp panel Quantity: 2	
EVT300 Microinverters Quantity: 2	
EVB202 Data logger Quantity: 1	
SR30 Sun[e] Pyranometer Quantity: 2	
Met[log] data logger Quantity: 2	
Power[cube] 150W Quantity: 2	

3.3. System Implementation

The timeline of the system configuration is as follows.

In December 2019, the PV system and microinverters and electricity monitoring equipment were implemented in front of a glass façade, as shown in Figure 2. Therefore, the electricity production data are available from the first day of January 2020, as presented in the dataset.

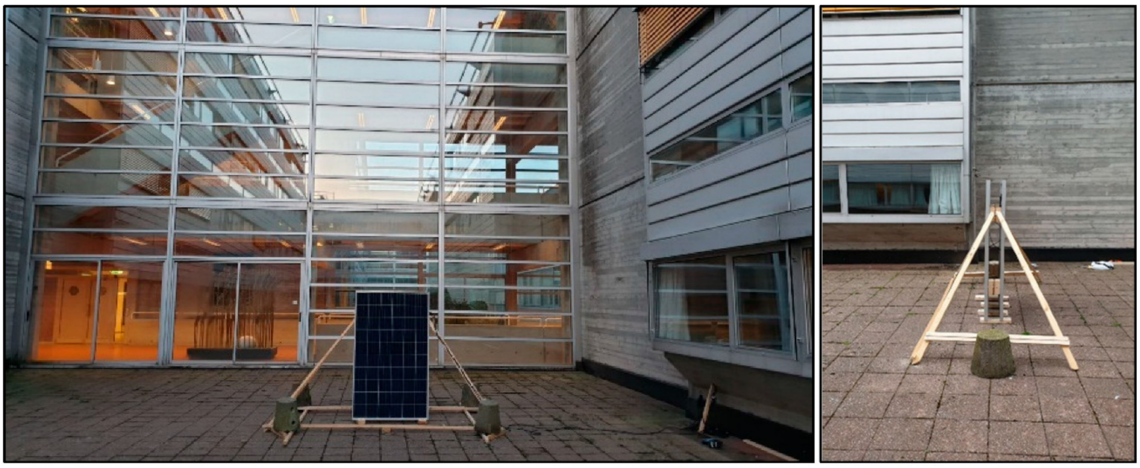


Figure 2. The implementation phase of PV panels in front of glass cladding.

On 1 May 2020, a 3 × 3 square meter white panel cladding implemented in front of the PV panel to monitor the effect of the reflected radiation of the white façade on the solar incident radiation and, consequently, the electricity production of the north-facing PV panel (Figure 3).

Figure 3. The panel cladding installation phase.

On 26 June 2020, two sets of solar incident radiation measuring equipment and logging equipment were implemented to calculate the PV system operational efficiency. Figure 4 shows two sets of pyranometers after installation at the site.

Figure 4. Implementation of irradiation measuring equipment.

4. Data Description (Raw Data)

All the described data in this section are available as a supplement to this paper. The electricity production is presented based on produced power per panel. The incident solar radiation is presented based on solar irradiance (power) per square meter (and not per total area of the panel).

4.1. Electricity Production

The electricity production of the system is available in the dataset as raw data. EN2020 and ES2020 tabs represent the PV panel's electricity production in the north and south direction, respectively. Figure 5 illustrates each PV panel's electricity production during a sunny day of each month from February 2020 to November 2020. The presented data in this figure can also be found in the dataset. The associated data of each day is available in the tab entitled to the investigated date. The selected days of each month are chosen to illustrate the system's performance and irradiation on the system in different months of the year. When it comes to the ground reflection, it is worth mentioning that there was not any snowfall during the monitoring period. Therefore, the ground reflection was always from a grey cement floor.

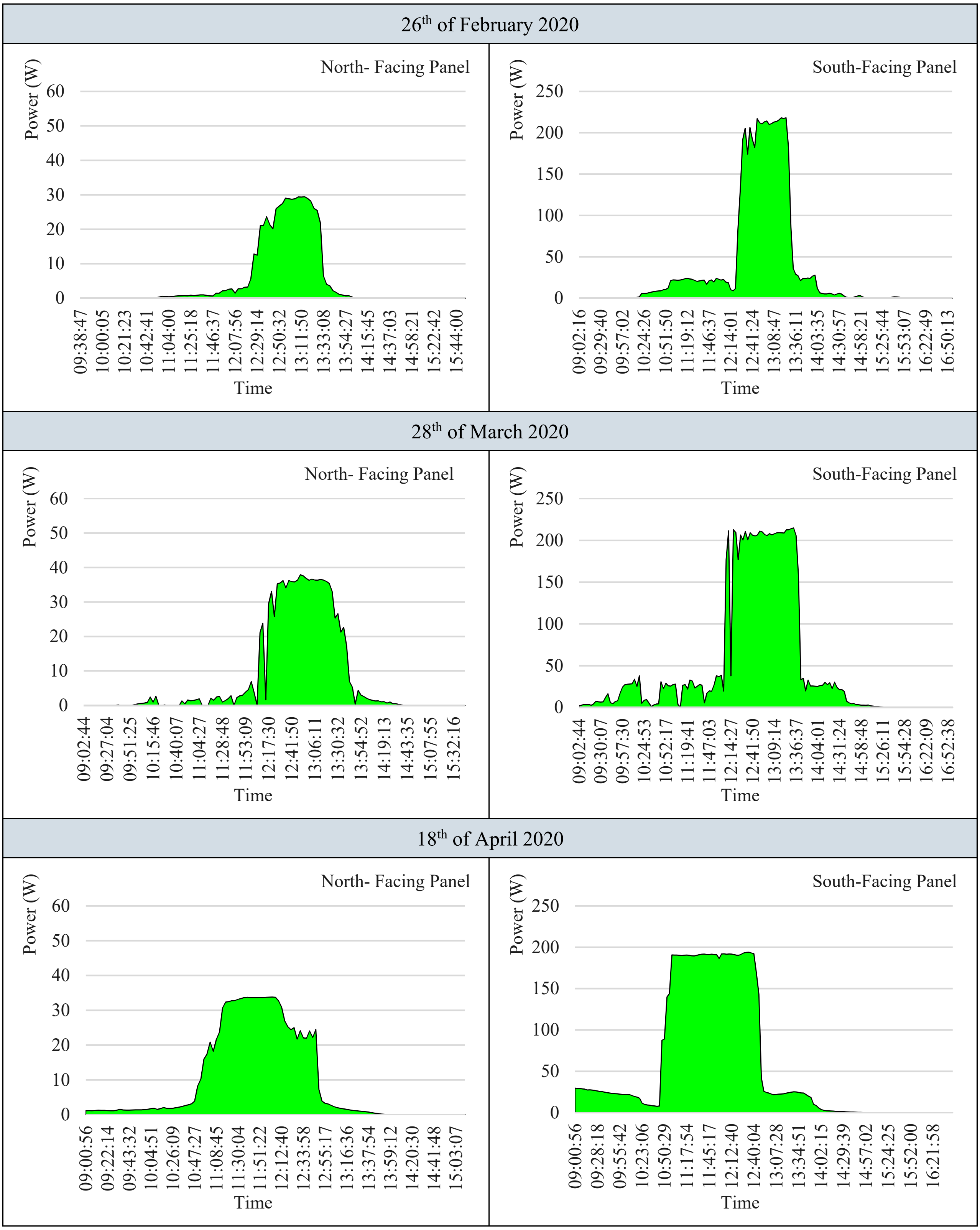


Figure 5. *Cont.*

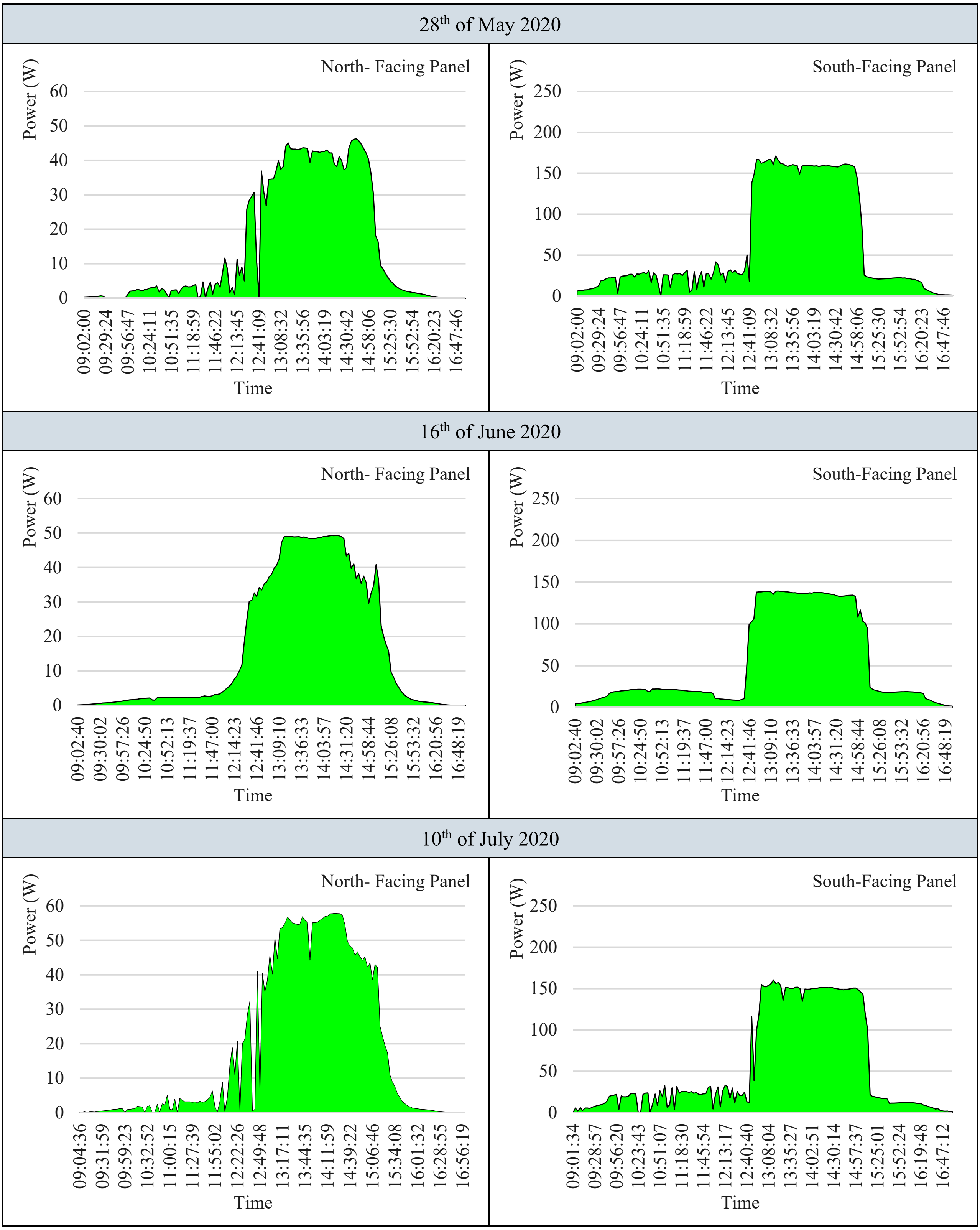


Figure 5. *Cont.*

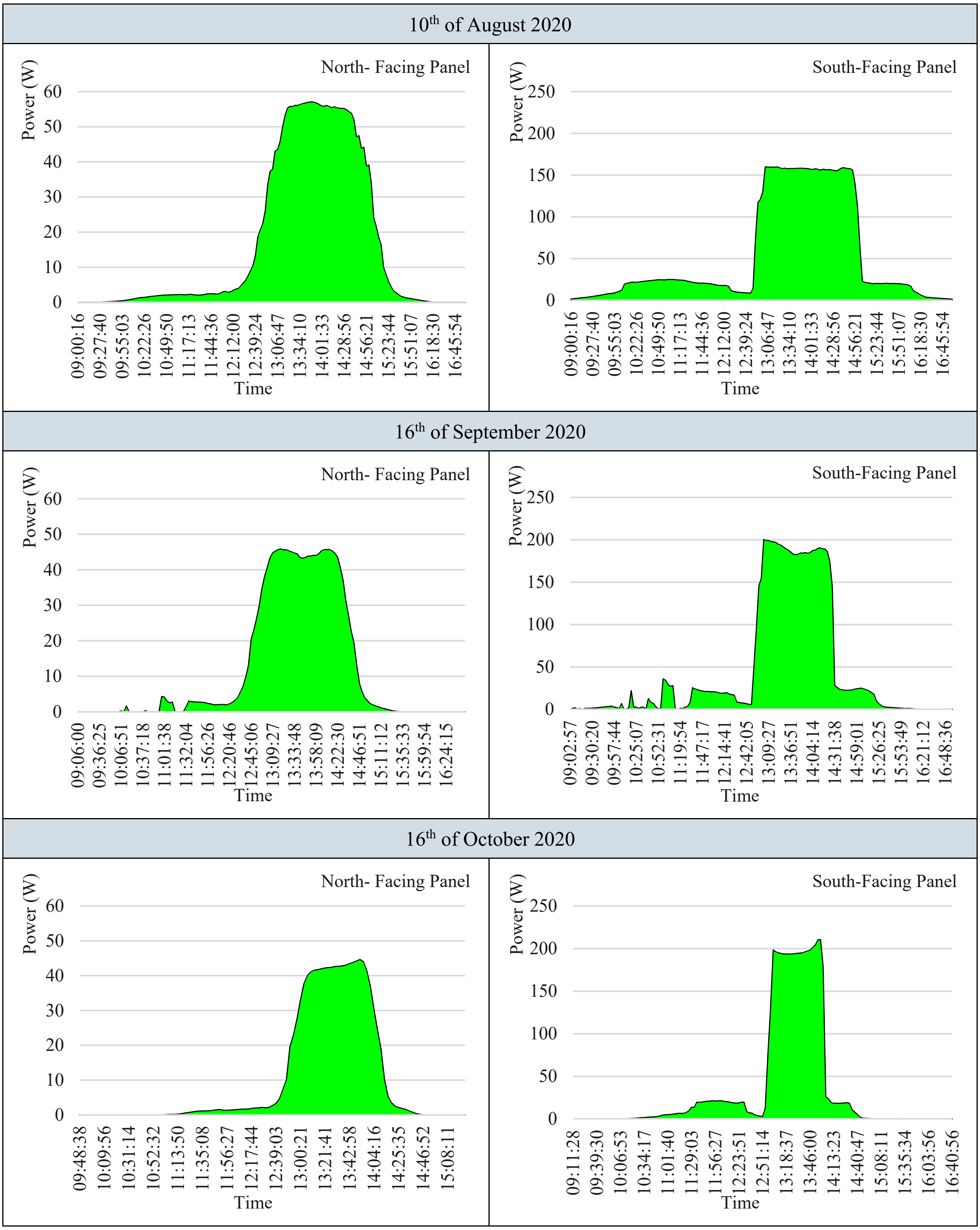


Figure 5. *Cont.*

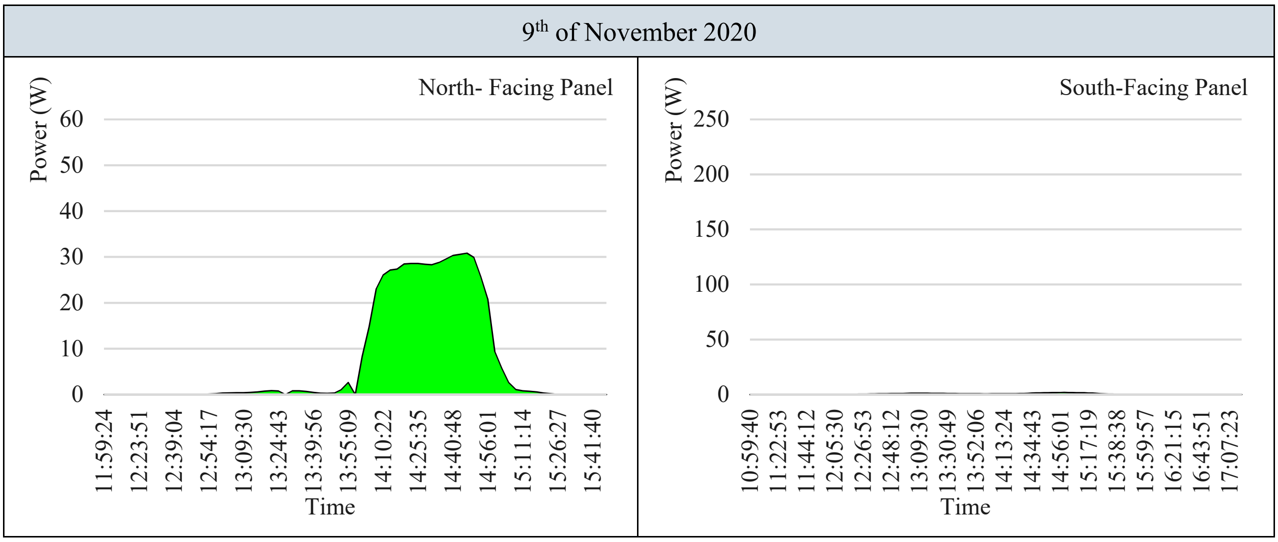


Figure 5. Electricity production of each PV panel on a sunny day of each month (February–November).

The geometry of the location, building and walls around the site resulted in cuts in irradiation and electricity production figures. That is why a 3D model is presented to comprehend the system performance and investigate the boundary conditions better.

As can be seen from the dataset, the total electricity production of the south-facing panel and the north-facing panel is equal to 51.78 and 10.51 kWh, respectively.

4.2. Solar Radiation

The solar incident radiation on the panels is available in the dataset as well as raw data. GN2020 and GS2020 tabs describe the solar incident radiation on the PV panel in the north and south direction, respectively. Figure 6 shows the solar incident radiation on the PV panels during a sunny day of each month from June 2020 to November 2020. The presented data in this figure can also be found in the dataset. The associated data of each day is available in the tab entitled to the investigated date.

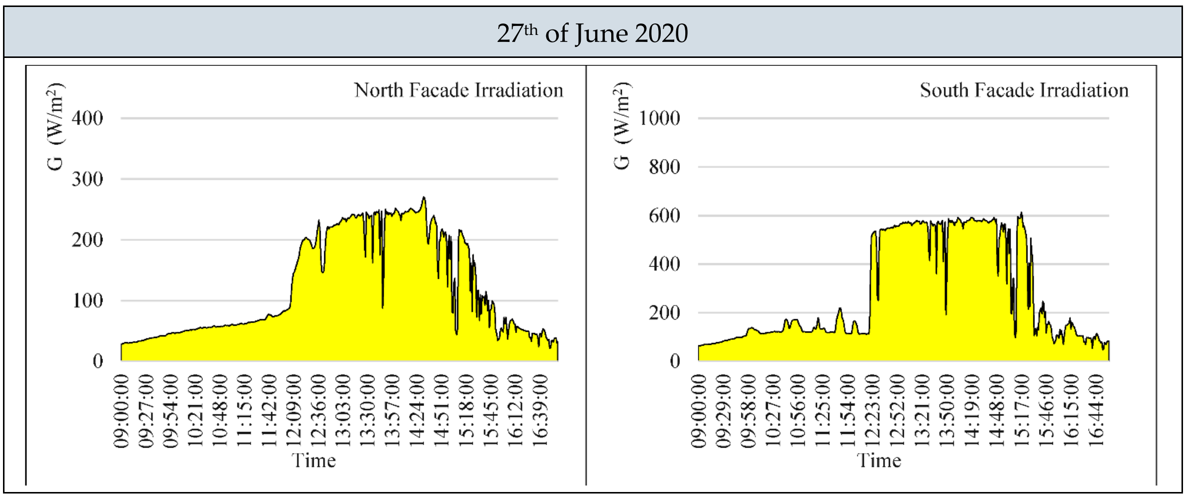


Figure 6. *Cont.*

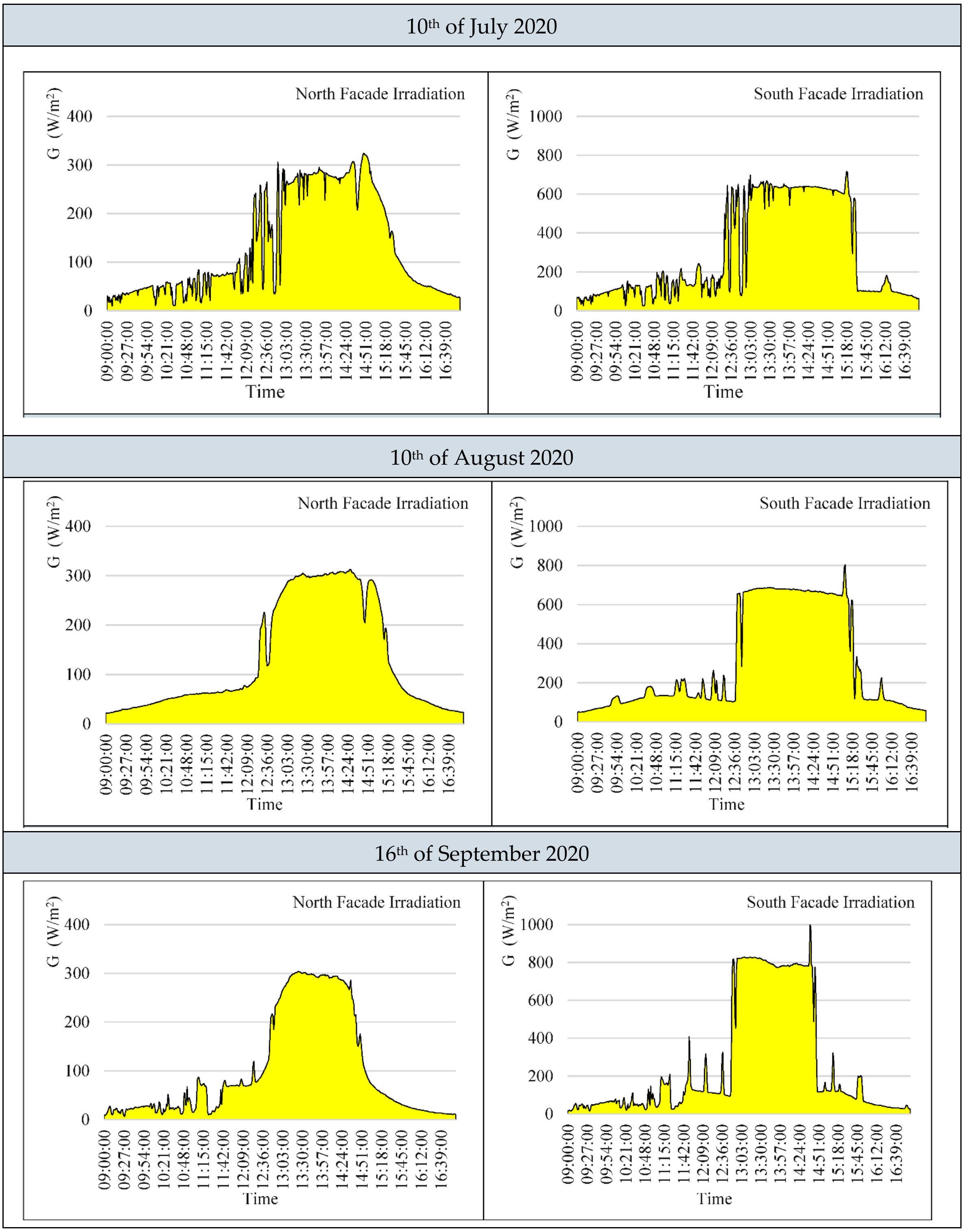


Figure 6. *Cont.*

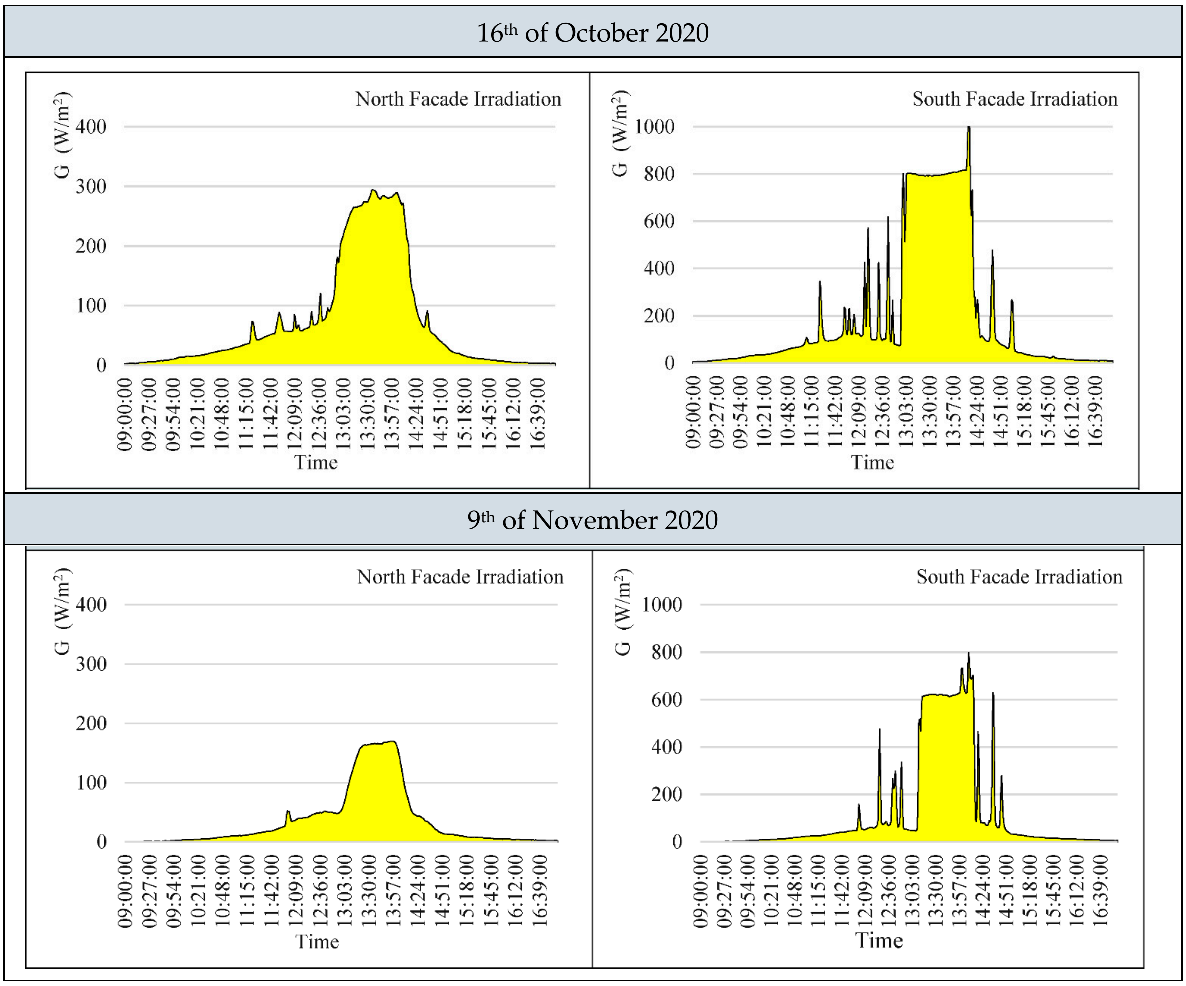


Figure 6. Solar incident radiation on each PV panel on a sunny day of each month (June–November).

As can be seen from Figures 5 and 6, on 9 November 2020, the generated power for the south-facing panel was zero even though solar incident radiation of over 600 W/m^2 was recorded. The reason lies behind the geometry of the site and surrounded objectives. The incident solar radiation hits the very upper part of the south-facing panel, where the pyranometer is installed (because of a very low solar altitude). Since there is no radiation on the remaining area of the south-facing panel (because of shading), the electricity production was zero.

On the other hand, since there was reflected radiation on the entire area of the north-facing panel, it produced electricity.

5. Discussion (Secondary Data)

Figure 7 illustrates the PV panels' average operational efficiency as a secondary source of data on discussed days and while there is no shading on the south-facing panel.

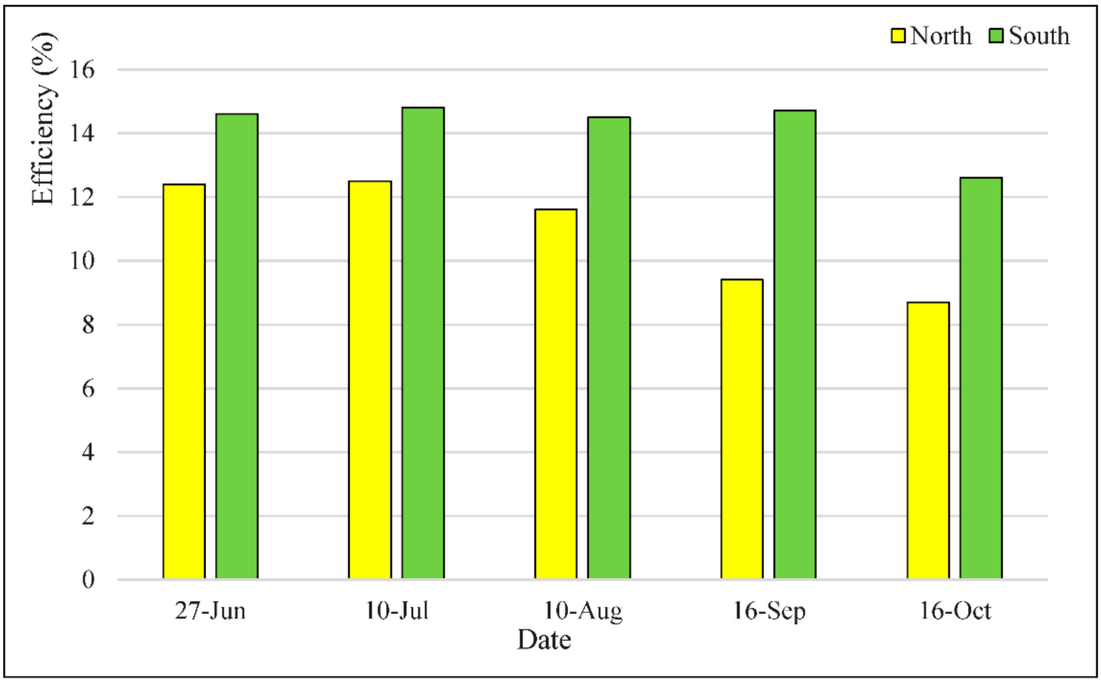


Figure 7. The average efficiency of the PV panels in a clear sky condition.

As can be seen from Figure 7, the efficiency of the north façade panel is always more than 2% less than the efficiency of the south façade panel on sunny days. The efficiency of the south-facing panel is between 13% to 15%. However, the efficiency of the north-facing panel is between 8% to 12% (on sunny days of the year). This gap becomes even more significant on cloudy days or overcast days.

The gap can be explained by the spectral response of the silicon-based PV cells to the incident solar radiation and the fact that the main radiation on the south-facing panel is direct radiation. In contrast, the main radiation on the north-facing panel is the reflected and diffuse radiation. That is why the south-facing panel's efficiency is closer to the standard efficiency of the panel compared to the north-facing panel.

Figure 8 depicts the peak production of each month of panels.

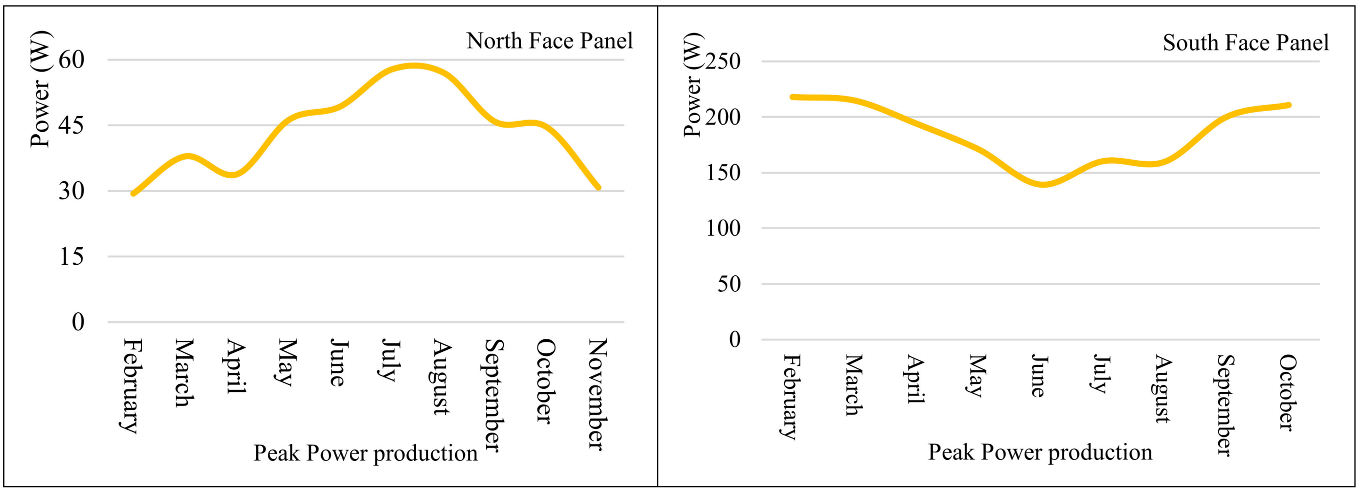


Figure 8. Recorded peak power production of each panel during the monitoring time.

The most interesting observation to emerge from the data comparison in Figure 8 is that the peak power production of the south-facing panel on sunny days in winter is more than its production on sunny days in summer, which is because of two reasons.

The first reason is the angle of solar radiation. In winter, the sun is more inclined towards the horizon and therefore, the solar altitude is smaller. Therefore, the incident radiation to a vertical south-faced panel is close to perpendicular, resulting in higher efficiency.

The second reason is the effect of temperature. The cold weather in winter contributes to a better performance of PV panels.

This also leads to a helpful match between electricity production and consumption in Scandinavian countries. Clear sky days in winter are generally the coldest days in these countries. Therefore, the energy consumption is high exactly when the PV system is producing at maximum power.

From the data in Figure 8, it is also apparent that the production of the north-facing panel follows the opposite trend of the south-facing panel, and its peak power production in summer is more than its peak power production in winter. The reason is the reflected radiation. In summer and because of higher solar altitude, the reflected radiation from the south façade on the north-facing panel is greater. However, in winter and because of the lower solar altitude and boundary condition of the site, the contribution of reflected radiation is less.

6. Conclusions

This project provided an important opportunity to advance the understanding of the performance of vertical BIPV/BAPV panels in urban areas of Scandinavian countries by presenting the performance of polycrystalline silicon PV panels in a dense urban area with the north- and south-facing orientations.

The results showed that the south-facing panel has its best performance in winter, while the north-facing panel presents its best performance in summer. Moreover, the efficiency of the south-facing panel is always more than the efficiency of the north-facing panel (at least 2%).

The findings observed in this study mirror those of our previous study [13] that have examined the effect of climate on the performance of different BIPV materials and technologies. Therefore, the data are a suitable source to compare this technology's performance with other emerging technologies, such as perovskite and organic solar cells as a building envelope material in cities, and investigate the impact of quality and quantity of solar radiation components on the performance and efficiency of PV panels with different orientations.

Finally, when it comes to the performance of PV systems in urban areas, more analytical work should be conducted to investigate it more in detail in various weather conditions, such as cloudy and overcast skies.

Supplementary Materials: All attached to this paper and described in the paper and available at: https://www.mdpi.com/article/10.3390/data6060057/s1.

Author Contributions: Conceptualisation, H.G. and H.N.R.; Data curation, H.G.; Formal analysis, H.G.; Funding acquisition, H.G. and H.N.R.; Investigation, H.G.; Methodology, H.G. and H.N.R.; Project administration, H.G.; Resources, H.G. and H.N.R.; Software, H.G.; Supervision, H.N.R.; Validation, H.G.; Visualisation, H.G.; Writing—original draft, H.G.; Writing—review and editing, H.N.R. All authors have read and agreed to the published version of the manuscript.

Funding: The work reported in this paper was supported by the Department of Safety, Economics, and Planning of the University of Stavanger (Project name: Building Integrated photovoltaic (BIPV) in dense urban areas, Project number: IN-12011).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Available at https://doi.org/10.5281/zenodo.4804993, accessed on 26 May 2021.

Acknowledgments: Special thanks goes to the Smart City Group and Future Energy Hub at the University of Stavanger for their support. The auhors would like to offer their gratitude to Steni AS and its Product Director, Ola Harildstad Olsen, for supporting and financing part of the equipment. The authors would also like to thank Trond-Ola Hågbo from the University of Stavanger for providing the 3D model of the site.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships which have or could be perceived to have influenced the work reported in this article. The funders had no role in the design of the study; in the collection, analyses or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Ritchie, H.; Roser, M.; Access to Energy. Our World Data 2019. Available online: https://ourworldindata.org/energy-access (accessed on 26 May 2021).
2. Barkaszi, S.; Dunlop, J. Discussion of strategies for mounting photovoltaic arrays on rooftops. *Sol. Eng.* **2001**, 333–338. [CrossRef]
3. Reddy, K.P.; Gupta, M.; Nundy, S.; Karthick, A.; Ghosh, A. Status of BIPV and BAPV System for Less Energy-Hungry Building in India—A Review. *Appl. Sci.* **2020**, *10*, 2337. [CrossRef]
4. Ghosh, A. Potential of building integrated and attached/applied photovoltaic (BIPV/BAPV) for adaptive less energy-hungry building's skin: A comprehensive review. *J. Clean. Prod.* **2020**, *276*, 123343. [CrossRef]
5. Kumar, N.M.; Sudhakar, K.; Samykano, M. Performance comparison of BAPV and BIPV systems with c-Si, CIS and CdTe photovoltaic technologies under tropical weather conditions. *Case Stud. Therm. Eng.* **2019**, *13*, 100374. [CrossRef]
6. Imenes, A.G. Performance of BIPV and BAPV installations in Norway. In Proceedings of the 2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC), Portland, OR, USA, 5–10 June 2016; pp. 3147–3152.
7. Wang, W.; Liu, Y.; Wu, X.; Xu, Y.; Yu, W.; Zhao, C.; Zhong, Y. Environmental assessments and economic performance of BAPV and BIPV systems in Shanghai. *Energy Build.* **2016**, *130*, 98–106. [CrossRef]
8. Desi Luvita, N.R.; Mohammad Kholid, R.; Budiarto, R.O. A scenario of BAPV and BIPV system for long-term projection energy demand in YogyakartaProceedings of the American Institute of Physics Conference Series. *AIP Conf. Proc.* **2019**, *2097*, 030090.
9. Gholami, H.; Nils Røstvik, H.; Manoj Kumar, N.; Chopra, S.S. Lifecycle cost analysis (LCCA) of tailor-made building integrated photovoltaics (BIPV) façade: Solsmaragden case study in Norway. *Sol. Energy* **2020**, *211*, 488–502. [CrossRef]
10. Gholami, H.; Røstvik, H.N. Economic analysis of BIPV systems as a building envelope material for building skins in Europe. *Energy* **2020**, *204*, 117931. [CrossRef]
11. Gholami, H.; Røstvik, H.N.; Müller-Eie, D. Holistic economic analysis of building integrated photovoltaics (BIPV) system: Case studies evaluation. *Energy Build.* **2019**, *203*, 109461. [CrossRef]
12. Gholami, H.; Nils Røstvik, H. Levelised Cost of Electricity (LCOE) of Building Integrated Photovoltaics (BIPV) in Europe, Rational Feed-In Tariffs and Subsidies. *Energies* **2021**, *14*, 2531. [CrossRef]
13. Gholami, H.; Nils Røstvik, H. The Effect of Climate on the Solar Radiation Components on Building Skins and Building Integrated Photovoltaics (BIPV) Materials. *Energies* **2021**, *14*, 1847. [CrossRef]
14. Esmailian, E.; Gholami, H.; Røstvik, H.N.; Menhaj, M.B. A novel method for optimal performance of ships by simultaneous optimisation of hull-propulsion-BIPV systems. *Energy Convers. Manag.* **2019**, *197*, 111879. [CrossRef]
15. Saretta, E.; Caputo, P.; Frontini, F. A review study about energy renovation of building facades with BIPV in urban environment. *Sustain. Cities Soc.* **2018**, *44*, 343–355. [CrossRef]
16. Biyik, E.; Araz, M.; Hepbasli, A.; Shahrestani, M.; Yao, R.; Shao, L.; Essah, E.; Oliveira, A.C.; del Caño, T.; Rico, E. A key review of building integrated photovoltaic (BIPV) systems. *Eng. Sci. Technol. Int. J.* **2017**, *20*, 833–858. [CrossRef]
17. Groppi, D.; de Santoli, L.; Cumo, F.; Garcia, D.A. A GIS-based model to assess buildings energy consumption and usable solar energy potential in urban areas. *Sustain. Cities Soc.* **2018**, *40*, 546–558. [CrossRef]
18. Gholami, H.H.N.; Røstvik Müller-Eie, D. Analysis of solar radiation components on building skins for selected cities. In Proceedings of the 14th Conference on Advanced Building Skins, Bern, Switzerland, 28–29 October 2019; pp. 541–549.

III. A novel method for optimal performance of ships by simultaneous optimisation of hull-propulsion-BIPV systems

Ehsan Esmailian [1,a] , Hassan Gholami[2,b], Harald Nils Røstvik[3,b], Mohammad Bagher Menhaj[4,c]

[a] Department of Maritime Engineering, Amirkabir University of Technology, PO Box 15875-4413, 424 Hafez Ave., Tehran, Iran
[b] Department of Safety, Economics and Planning, University of Stavanger, Kjell Arholmsgate 41, 4036 Stavanger, Norway
[c]Department of Electronic Engineering, Amirkabir University of Technology, PO Box 15875-4413, 424 Hafez Ave., Tehran, Iran

[1] Graduated MSc Students, eh.esmailian@gmail.com
[2] PhD Researcher, + 47 96 95 72 95, hassan.gholami@uis.no
[3] Professor, + 47 92 22 67 10, harald.n.rostvik@uis.no
[4] Professor, Menhaj@aut.ac.ir

Energy Conversion and Management
Volume 197, 1 October 2019, 111879

https://doi.org/10.1016/j.enconman.2019.111879

This paper is not included in the thesis for copyright reasons.

IV. The Effect of Climate on the Solar Radiation Components on Building Skins and Building Integrated Photovoltaics (BIPV) Materials

Hassan Gholami [1], Harald Nils Røstvik [2]

Department of Safety, Economics and Planning, University of Stavanger, Stavanger, Norway

[1] PhD Researcher, hassan.gholami@uis.no
[2] Professor, harald.n.rostvik@uis.no

Energies
Volume 14, Issue 7, No 1847, 26 March 2021, 2531

https://doi.org/10.3390/en14071847

energies

Article

The Effect of Climate on the Solar Radiation Components on Building Skins and Building Integrated Photovoltaics (BIPV) Materials

Hassan Gholami * and Harald Nils Røstvik

City- and Regional Planning, Institute of Safety, Economics and Planning (ISØP), Faculty of Science and Technology, University of Stavanger, 4021 Stavanger, Norway; harald.n.rostvik@uis.no
* Correspondence: hassan.gholami@uis.no or gholami.hassan.kh@gmail.com; Tel.: +47-51833037

Abstract: The business model of building-integrated photovoltaics (BIPV) is developing expeditiously and BIPV will soon be recognised as a building envelope material for the entire building skins, among other alternatives such as brick, wood, stone, metals, etc. This paper investigates the effect of climate on the solar radiation components on building skins and BIPV materials in the northern hemisphere. The selected cities are Stavanger in Norway, Bern in Switzerland, Rome in Italy, and Dubai in the UAE. The study showed that for all the studied climates, the average incident radiation on the entire building skins is slightly more than the average incident radiation on the east or west facades, regardless of the orientations of the building facades. Furthermore, the correlation between solar radiation components and different BIPV technologies is discussed in this paper. It is also found that when it comes to the efficiency of different BIPV cells, the impact of the climate on some of the BIPV technologies (such as DSC and OSC) is much more significant than others (such as c-Si, mc-Si and CIGS). The evidence from this study suggests that in climates with higher diffuse radiation-or with more overcast days per year-the contribution of IR radiation decreases. Therefore, the efficiency of BIPV materials that their spectral responses are dependent on the IR radiation (like Si and CIGS) in such a climate would drop down meaningfully. On the other hand, the DSC and OSC solar cells could be a good option for cloudy climates since they have more stable performance, even in such a climate. Although, their efficiency compared to other BIPV materials such as Si-based BIPV solar cells is still significantly less thus far.

Keywords: building skin; building envelope materials; climate change; solar radiation components; building-integrated photovoltaics (BIPV)

check for updates

Citation: Gholami, H.; Nils Røstvik, H. The Effect of Climate on the Solar Radiation Components on Building Skins and Building Integrated Photovoltaics (BIPV) Materials. *Energies* **2021**, *14*, 1847. https://doi.org/10.3390/en14071847

Academic Editor: Luisa F. Cabeza

Received: 1 March 2021
Accepted: 23 March 2021
Published: 26 March 2021

1. Introduction

Renewable energy technologies in urban areas have been at the forefront of research and development due to concerns related to the environment as well as energy independence and high fossil fuel costs. Among the options, building-integrated photovoltaics (BIPV) has attracted increasing interest in the past decade. BIPV refers to photovoltaic materials that are used to substitute traditional building materials in parts of the building skins, such as the facades, roofs, or skylights, to generate clean energy from sunshine [1]. Therefore, it must play a role in the building envelope that contains at least one additional function in addition to electricity generation. The BIPV secondary function could be as insulation or an exterior weather barrier [2,3]. The photovoltaic cells in the BIPV system can be ventilated with active or passive ventilation [4–8], and the system can be in the forms of tiles, foils, modules, or glazing [9,10].

During the past ten years, much more information has become available on the feasibility of the BIPV roof as well as BIPV on the south, east, and west façade. Along with this growth in the valuable insights into the feasibility of the BIPV system on building skins, however, there is an increasing concern over the feasibility of the BIPV on the untraditional orientations of building skins for BIPV applications. It looks that there seems to have been an assumption in which the northern façades (in the northern hemisphere) are economically unfeasible because the radiation there is low [11–22].

On the other hand, recent studies depict that different BIPV technologies have a different spectral response to the incident solar radiation and its components [23–25], and therefore the climate plays a key role in the performance of BIPV systems. However, there is a lack of studies investigating the effect of climates with different solar radiation spectrums and components in the literature.

Therefore, this study set out with four aims:

First, assessing the incident solar radiation components on building skins considering different climates;

Second, analysing the solar radiation potential of the entire building skins for the BIPV application (if BIPV is seen as a building envelope material for the entire building skin);

Third, evaluating the effect of climates on the overall efficiencies of different BIPV technologies and materials which are currently available in the market;

Fourth, investigating the effect of building orientation on the irradiance values of the building skins and the contribution of each solar radiation component.

The selected cities for this study are Stavanger, Bern, Rome, and Dubai.

In Section 2, a brief introduction of solar radiation and the available measuring methods, as well as the location of the case studies, are presented. The analysis of radiation on the building skins is discussed in Section 3. A correlation analysis between climate/radiation and climate/technology is accomplished in detail in Sections 4 and 5. A sensitivity analysis is accomplished in Section 6 in order to see the effect of orientations on incident solar radiation on building skins. Finally, in Section 7, the conclusion is presented.

2. Materials and Methods

In this section, solar radiation components and spectrum are discussed. Then, different methods of incident solar radiation measurement at the earth's surface are introduced and reviewed thoroughly. The selected city and their climates are briefly presented as well.

2.1. Solar Radiation Components

The incident radiation to a surface on earth has three components which are direct radiation, diffuse radiation, and reflected radiation.

- Direct radiation is also called, "beam radiation" or "direct beam radiation". It is used to describe solar radiation coming on a straight line from the sun, down to the surface of the earth. For sunny days with a clear sky, most of the solar radiation is direct radiation. On overcast days, the sun is shadowed by clouds, and the beam radiation is zero.
- Diffuse radiation is sunlight that has been dispersed or scattered by particles and molecules in the atmosphere and still made its way down to the surface. Diffuse radiation is commonly referred to as sky radiation because it comes from all regions of the sky. The amount of diffuse radiation is up to 100% of the total radiation for cloudy skies and 10% to 20% of the total radiation for clear skies.
- Reflected radiation is the reflection of direct and diffuse radiation on the ground. This contribution is small unless the collector is tilted at a steep angle from the horizontal, like a building façade.

2.2. Solar Radiation Spectrum

The radiation spectrum coming from the sun to the earth is subdivided into three main groups of ultraviolet, visible light, and infrared.

- Ultraviolet (UV) is wavelengths from 250 nm to 380 nm. UV rays are invisible to the human eyes and may be dangerous in the case of overexposure because they damage surfaces, colours and age materials.

- Visible light is wavelengths from 380 nm (violet) to 740 nm (red). Visible light rays are detectable by the human eyes and enable the sight of shapes, relief and colours.
- Short wave infrared (IR) constitutes wavelengths from 740 nm to 2500 nm. IR is invisible and is felt as heat. It constitutes most of the sun's energy that hits the earth.

Figure 1 shows the solar irradiance outside (Airmass equal to 0) and inside (Airmass equal to 1.5) of the atmosphere (Standard number ASTM G-173-03). The letters T and D stand for total and direct incident radiation. In terms of solar radiation inside of the atmosphere and at sea level, around 3% of solar radiation on earth is UV, around 42% is visible light, and the rest (55%) is IR.

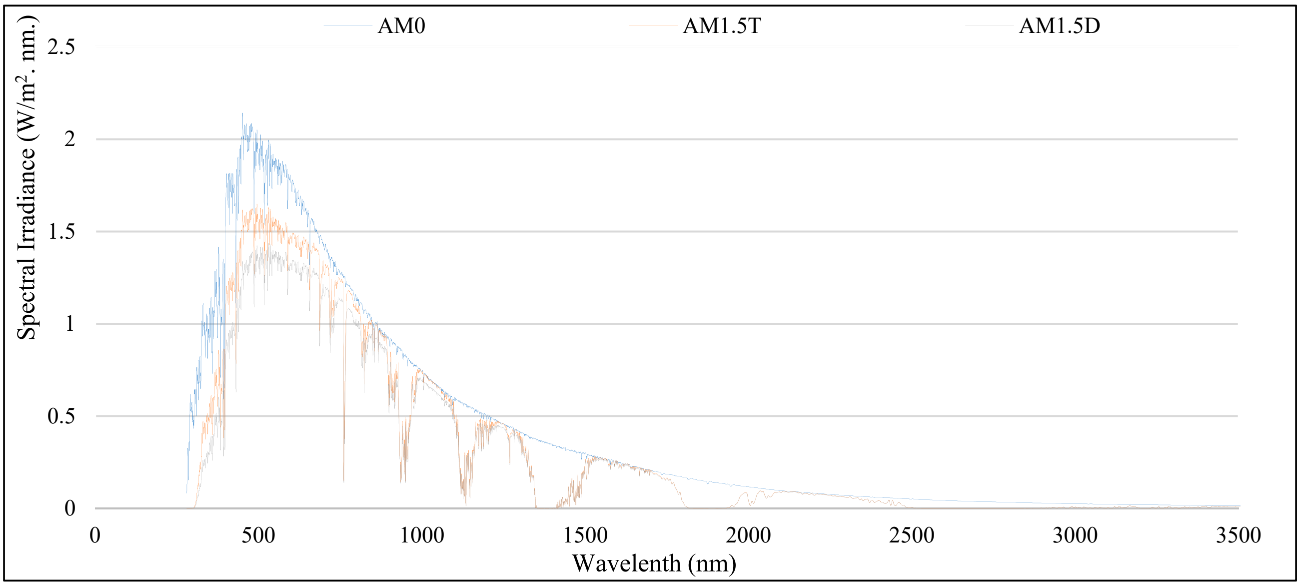


Figure 1. The solar spectral irradiance outside and inside of the atmosphere.

2.3. *Solar Radiation Measurement Methods at the Earth's Surface*

There are three methods to either measure or calculate the incident solar radiation on a surface at the earth, which are as follows:

2.3.1. Radiation Measuring Devices

In this method, the incident radiation is measured by a high-quality sensor which, thanks to the technology, is gaining greater accuracy nowadays. There are many sensors available on the market for this purpose and, based on the type of measured radiation, they fall into two subcategories of pyranometer and pyrheliometer. Sensor measurements should fulfill some conditions to be useful, such as [26]:

- Only high-quality measurement sensors should be used.
- Measurements should be performed at a reasonable interval (at least every hour).
- Sensors should be calibrated and cleaned regularly.
- Data should be available for a long period.

Currently, the number of radiation measurement stations that fulfill all these criteria is relatively low, and the stations are often spaced far apart. Therefore, this method is not a suitable way to measure incident solar radiation globally.

2.3.2. Satellite-Based Irradiation Data

Calculating irradiation data on a surface at the earth using satellite data has become more and more common currently. This method mostly uses data from geostationary meteorological satellites. In this method, the incident radiation data is available for the whole area covered by the satellite. For instance, the METEOSAT satellites cover Europe, Africa, and most of Asia up to 60° N, with a resolution of a few kilometers [27]. The satellite data is usually available for a long time as well. The issue with this method is that the solar radiation at ground level must be calculated using complicated mathematical algorithms that use satellite data as well as data on aerosols (dust, particles), atmospheric water vapor, and ozone. Some conditions (such as snow, which can be mistaken for clouds or dust storms, which can be challenging to detect in the satellite images) can cause the calculations to lose accuracy. Moreover, despite the perfect accuracy of satellite-based solar radiation data, this method also does not cover the polar area. This method has been described in some papers [27–29]. An example of satellite-based irradiation data is PVGIS-SARAH. This data set has been calculated by the Satellite Application Facility on Climate Monitoring (CM SAF) and the Photovoltaic Geographical Information System (PVGIS) team with a spatial resolution of 31 km [26].

2.3.3. Climate Reanalysis Data

Another type of solar radiation estimate is from climate reanalysis data. Reanalysis data are calculated by employing numerical weather forecast models, re-running the models for the past, and making corrections by the known meteorological measurements. The output is a large number of meteorological quantities, usually including incident solar radiation at ground level. These data sets generally have global coverage (including the polar areas) while the satellite methods do not. However, there are certain drawbacks associated with the use of this method such as its low spatial resolution and low accuracy, etc. The resolution of this method usually is one value every 30km or more and the accuracy of the incident solar radiation is not as precise as the satellite-based solar irradiance data over the areas covered by both data sets [30]. In this study, two reanalysis-based solar radiation data sets have been employed, which are ECMWF ERA-5 [31] and COSMO-REA [30].

2.4. Locations

Three locations within Europe are selected to analyse the satellite-based and climate reanalysis-based irradiation data. The radiation status of Dubai in the UAE is analysed as well because of its climate and perfect solar energy potential compared with other locations. Therefore, the selected cities are Stavanger in Norway, Bern in Switzerland, Rome in Italy, and Dubai in the UAE. Table 1 shows geographical information about the locations.

Table 1. The Geographical information of the selected cities.

City	Country	Latitude (Degree)	Longitude (Degree)	Altitude (Degree)
Stavanger	Norway	58.96	5.73	15
Bern	Switzerland	46.94	7.45	542
Rome	Italy	41.90	12.49	32
Dubai	UAE	25.27	55.29	0

2.4.1. Stavanger

Stavanger is a city located on a peninsula on the southwest coast of Norway. Due to the warmer temperature created by the gulf stream, the climate (warm and temperate) is more pleasant compared to other cities at similar latitudes [32]. The city experiences an oceanic climate with five months above 10 °C mean temperature and an annual average of 1428 mm of precipitation, which makes the city relatively wet. The city also has a small continental climate influence, which creates subzero lows during winter [33].

2.4.2. Bern

Bern is the capital of Switzerland with a marine west coast climate. The climate is mild, warm, and temperate with no dry season. The average temperature in Bern is 8.8 °C, and the annual precipitation is 911 mm [34]. The city has 103.7 days of air frost, 22.3 ice days, 14.1 days of snowfall, 36.7 days of snow cover and the average amount of snow measured per year is 52.6 cm for the period of 1981–2010 [32,35].

2.4.3. Rome

Rome is the capital city of Italy, with an annual average temperature of 16.7 °C. According to Köppen and Geiger, its climate is classified as a Mediterranean climate with cool, humid winters and warm, dry summers. The temperature in July averages 24.4 °C, which is the warmest month of the year. In January, the average temperature is 7.7 °C, which is the lowest average temperature of the whole year [32,36].

2.4.4. Dubai

Dubai is a city in the UAE with a desert climate, according to Köppen climate classification. There is almost no rainfall during the year in Dubai. The temperature there averages 26.7 °C with annual precipitation of about 87 mm. The month of August has an average temperature of 34.2 °C and January has an average temperature of 18.6 °C, they are the warmest and coldest months of the whole year. [32,37].

3. Solar Radiation Analysis on Building Skins

In order to be able to compare the outcome of the databases, the year 2015 has been selected, which is the most recent year that the incident radiation data for all selected European cities are available.

Figure 2 shows the total annual radiation on one square meter of a flat roof of the cities based on investigated databases. As can be seen from the figure, among the three databases, the only available database for Dubai is the SARAH database. Moreover, there is an insignificant variation between databases and, as mentioned earlier, the most accurate database currently is the SARAH database, which is a satellite-based database. Therefore, in order to elaborate solar radiation components on building skins of the cities, the SARAH database is selected, and this study investigated the data belonging to this database for more precise analysis.

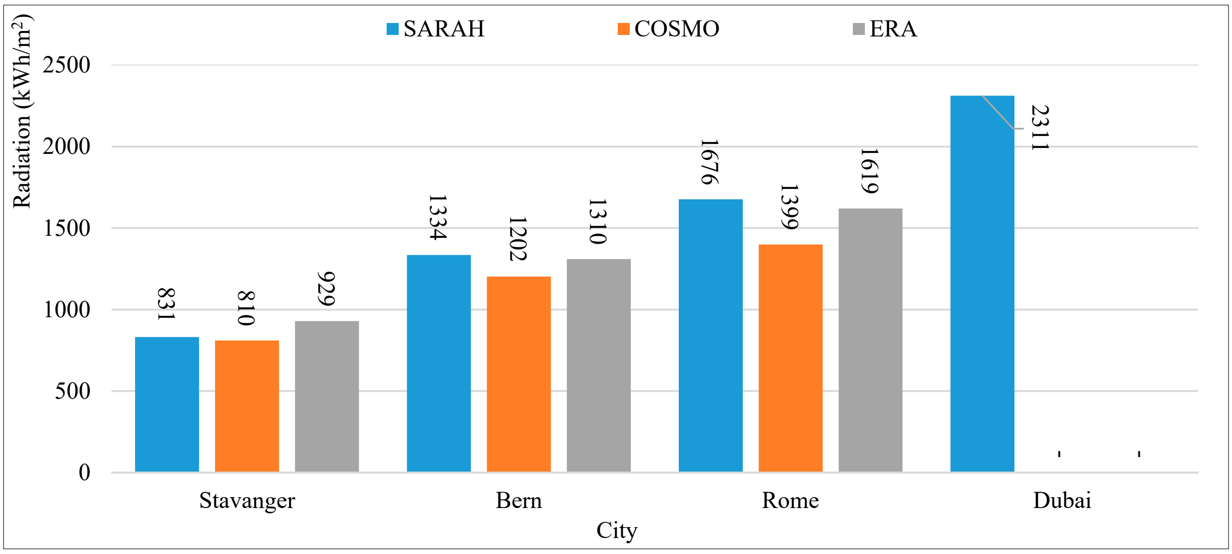


Figure 2. Annual incident solar radiation on a flat roof in the selected cities as per the databases.

The business model of BIPV is transitioning to a new business model with three players, which are BIPV manufacturers, installers and the main contractors [2]. Therefore, the BIPV is going towards the direction that soon it will be seen as a building envelope material option for building skins among other options like brick, wood, aluminum, etc. To see the annual solar irradiance on the building skins, incident solar radiation on building skins (BS) has been introduced. The annual solar irradiance on BS is calculated by the average of incident radiation on different orientations of the building envelope, which here is south, east, west, north façade, and roof area. This parameter could be used to evaluate the feasibility of the BIPV as a building envelope material for building skins.

Figure 3 depicts the annual incident solar radiation on one square meter of different orientations of building skins, and also BS for the selected cities as well as their components. The data illustrates that the difference between radiation on the south façade and the roof in the urban area becomes more and more significant when moving from cities with higher latitudes to lower latitudes. The northern façade has the lowest incident radiation while, in terms of Stavanger, the radiation there is significant when comparing western or eastern façade. The radiation on the eastern and western façade, which is sometimes also called morning and evening façade, is also quite the same for all cities. As can be predicted from the climate and latitude, the incident solar radiation on building skins in Dubai is significantly higher than in other European cities. The values of BS vary from 570 kWh/m^2 in Stavanger to 1280 kWh/m^2 in Dubai. There is also a clear correlation between solar irradiance on the east/west façade and BS, regardless of climate. As a general conclusion, it can be said that the average radiation on the building skins with the defined configuration in this study is always a little more than the incident solar radiation on the east/west skin of the building.

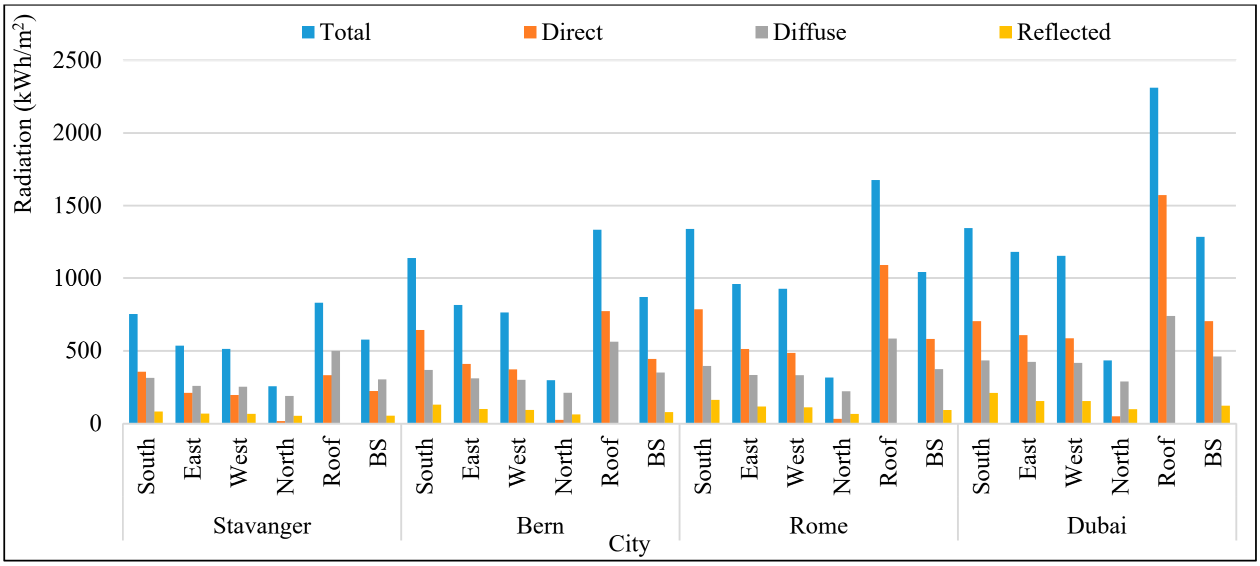


Figure 3. Incident solar radiation components on building skins of the cities.

In order to investigate the data in more detail, the contribution of each component together with the total radiation of each orientation is mentioned in Table 2. Except for the north façade, the major component of radiation on building skins for Bern, Rome and Dubai is direct radiation, which is because of the climate condition there.

Table 2. Annual incident solar radiation on building skins with the contribution of each component.

City	Orientation	Total Radiation (kWh/m^2)	Direct Radiation Contribution (%)	Diffuse Radiation Contribution (%)	Reflected Radiation Contribution (%)
Stavanger	South	751	47%	42%	11%
	East	535	39%	48%	13%
	West	513	38%	49%	13%
	North	254	6%	74%	21%
	Roof	831	40%	60%	0%
	BS	577	38%	52%	9%
Bern	South	1138	56%	32%	11%
	East	816	50%	38%	12%
	West	763	49%	39%	12%
	North	296	8%	71%	21%
	Roof	1334	58%	42%	0%
	BS	869	51%	40%	9%
Rome	South	1340	59%	29%	12%
	East	959	53%	35%	12%
	West	927	52%	36%	12%
	North	315	10%	70%	20%
	Roof	1676	65%	35%	0%
	BS	1043	56%	36%	9%
Dubai	South	1344	52%	32%	16%
	East	1182	51%	36%	13%
	West	1154	51%	36%	13%
	North	433	11%	67%	22%
	Roof	2311	68%	32%	0%
	BS	1285	55%	36%	9%

The average number of sunny hours in the cities is mentioned in Table 3 [38,39]. As the table shows, Stavanger has the least average annual hours of sunshine among the cases. Hence, the contribution of diffuse radiation on building skins for Stavanger is significantly higher and even more than the direct radiation in some facades. The incident radiation on the northern façade is different from other areas of the building. As can be seen from Table 2, the contribution of direct radiation in the northern façade is significantly low and, instead of direct radiation, diffuse radiation plays an important role in this orientation. Diffuse radiation constitutes around 70% of the total radiation of the northern façade.

Table 3. Average annual hours of sunshine [38,39].

City	Number of Hours
Stavanger	1538
Bern	1639
Rome	2516
Dubai	3570

By moving from higher latitudes to lower latitudes, the contribution of the south façade is becoming less while the contribution of the roof is becoming bigger, which makes sense when considering the location of the sun in the sky as depicted in Figure 4. Moreover, the contributions of the morning and evening façades are around 36% no matter which climate or latitude the building is in. The contribution of the northern façade is also around 6%, except Stavanger because of higher diffuse radiation on building skins, the incident radiation there is around 9%.

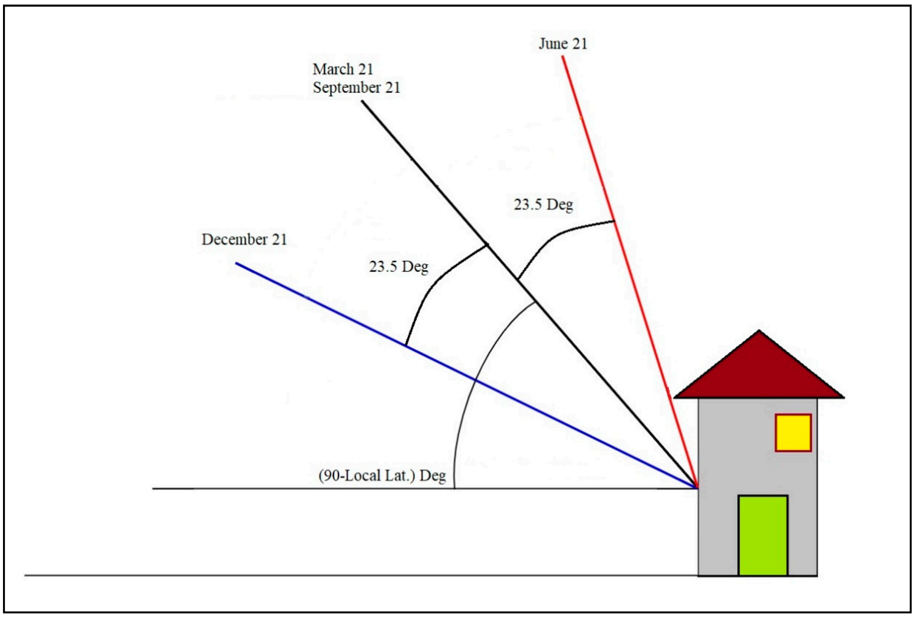


Figure 4. The seasonal declination differences of the sun, viewed from a building in the northern hemisphere.

4. Climate and Radiation

On a sunny day, the solar spectral irradiance of different hours of a day is as shown in Figure 5. (Standard number ASTM G-173-03).

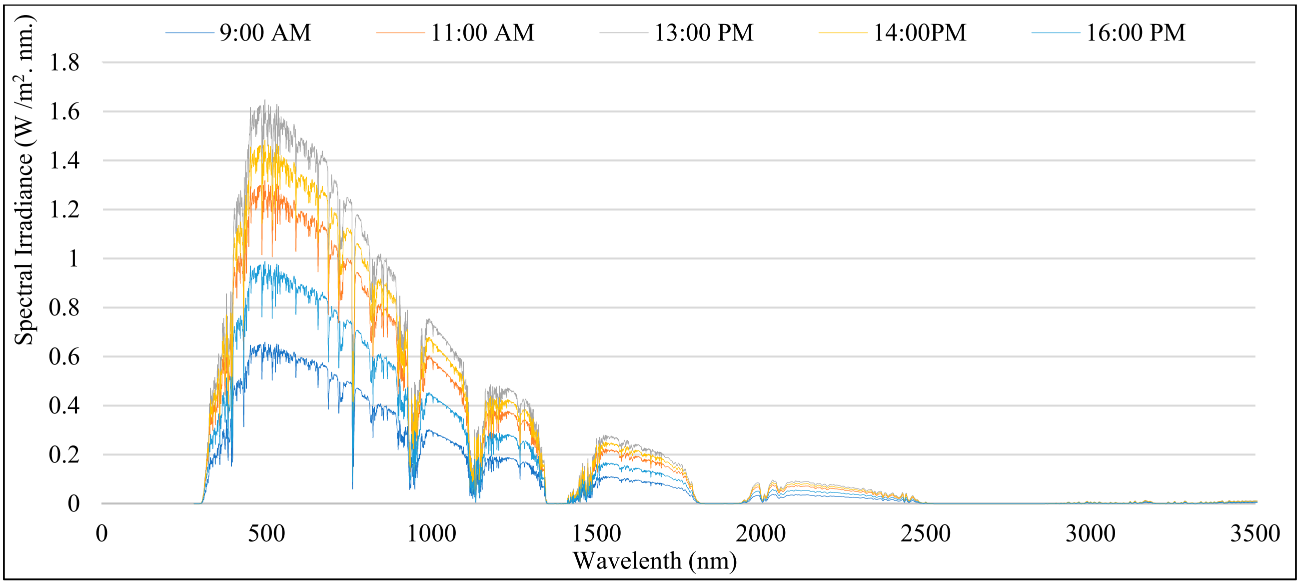


Figure 5. Solar spectral irradiance of different hours of a clear day.

What is interesting in this data is that it seems what changes in daytime hours is the power of the wavelengths with a specific ratio or proportion. For example, it appears that the values of spectral irradiance at 11:00 are twice as big as the spectral irradiance at 09:00 on every wavelength.

A normalisation procedure would be a useful asset to evaluate the spectral characteristics of the solar spectra measured at various times and climates. The spectral irradiance has been normalised with respect to the intensity value measured at 560 nm at the same location and in the same spectrum (because environmental conditions have the least effect on the intensity at this wavelength). The normalised spectra during the day, during the year, and for an overcast day have been presented in Figure 6 [40].

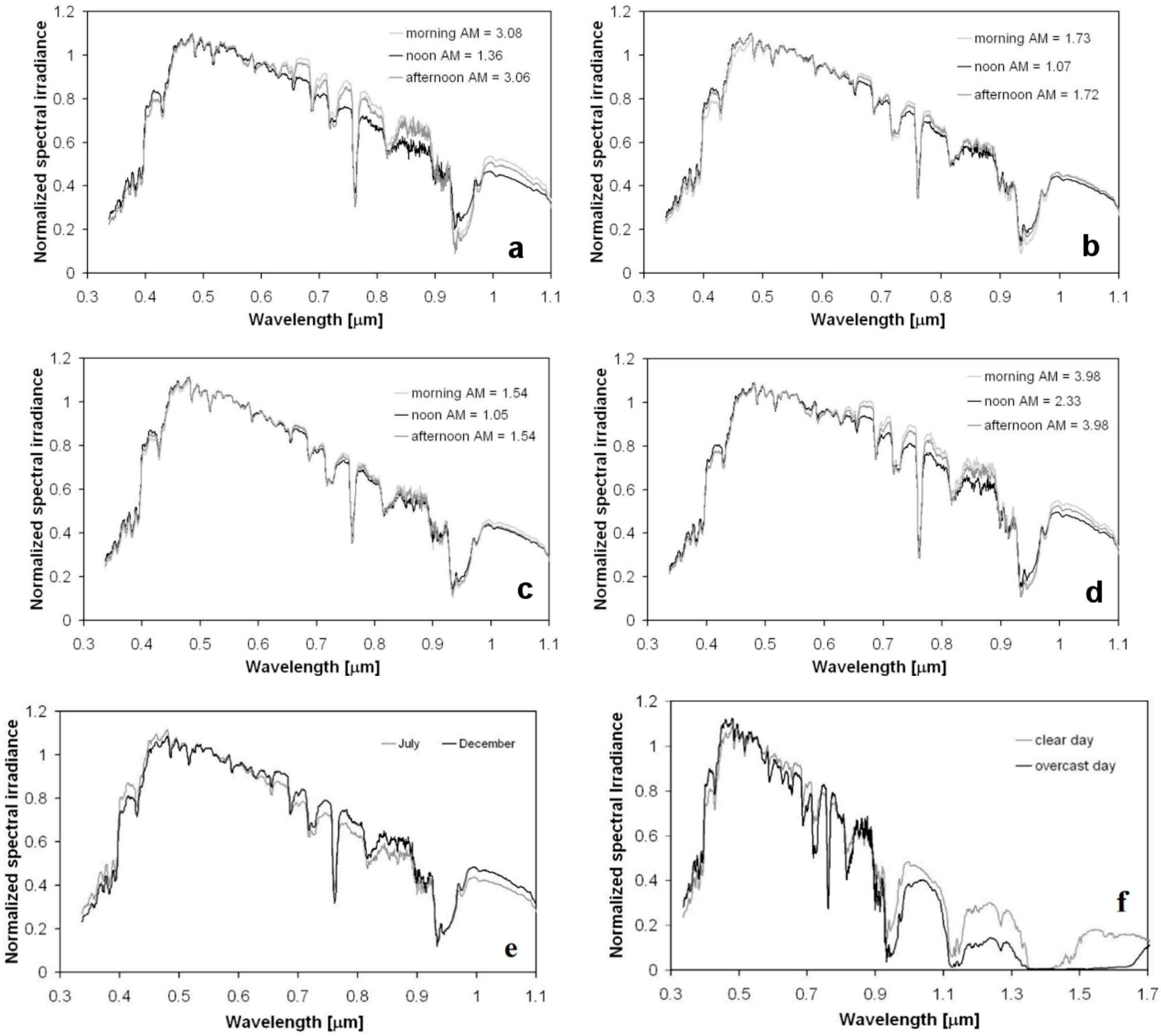


Figure 6. (**a**) Daily spectra variation of a clear day in March; (**b**) daily spectra variation of a clear day in May; (**c**) daily spectra variation of a clear day in July; (**d**) daily spectra variation of a clear day in December; (**e**) Normalised spectra for July and December; (**f**) irradiance spectra taken on the 5th (clear day) and 8th (overcast day) of December. [40].

The most striking result to emerge from Figure 6 is that, in a cloudy sky or on an overcast day, a significant portion of IR radiation is absorbed by the clouds and the normalised amounts of UV and visible light spectrum during both weather conditions is almost the same. In other words, it could be perceived that the sky attempts to eliminate IR radiation in overcast days while the normalised spectral irradiance of the UV and visible light spectrum is following the same pattern.

The normalised spectral irradiance for different hours of a sunny day, regardless of the season, is following the same patterns. It means that the effect of solar altitude on the spectral irradiance of different wavelengths is uniform.

Interestingly, there are differences in the normalised spectral irradiance of UV and IR radiation during a sunny day in winter and summer while the normalised spectral irradiance of the visible light spectrum during the winter and summer is almost the same. Therefore, the effect of the seasonal declination on the spectral irradiance of different wavelengths is as follows: for the UV spectrum, the normalised spectral irradiance during a sunny day in summer is more than winter; in terms of IR radiation, the normalised spectral irradiance during a sunny day in winter is more than in summer; finally, in terms of the visible light spectrum, the normalised spectral irradiance is not dependent on seasonal declination.

The relation between solar spectral irradiance and climates is interesting and important because the intensity of solar radiation components and, more specifically, direct and diffuse radiations, is closely linked to the climate. In overcast days or a climate with several cloudy days, a significant portion of the incident solar radiation on building skins is diffuse radiation (Table 2) and the sky absorbs a significant portion of IR irradiance (Figure 6f). Therefore, it could be concluded that the contribution of the IR radiation to diffuse radiation is less than its contribution to beam radiation on building skins.

5. Climate and Technology

The energy of each photon is inversely proportional to the wavelength of the associated wave and the BIPV materials are ionised by photons with energies higher than their bandgap. In other words, the BIPV materials are ionised by wavelengths lower than the wavelength corresponding to their bandgap. Figure 7 shows the absorption wavelengths of crystalline Silicon and Germanium as an example on the solar spectrum.

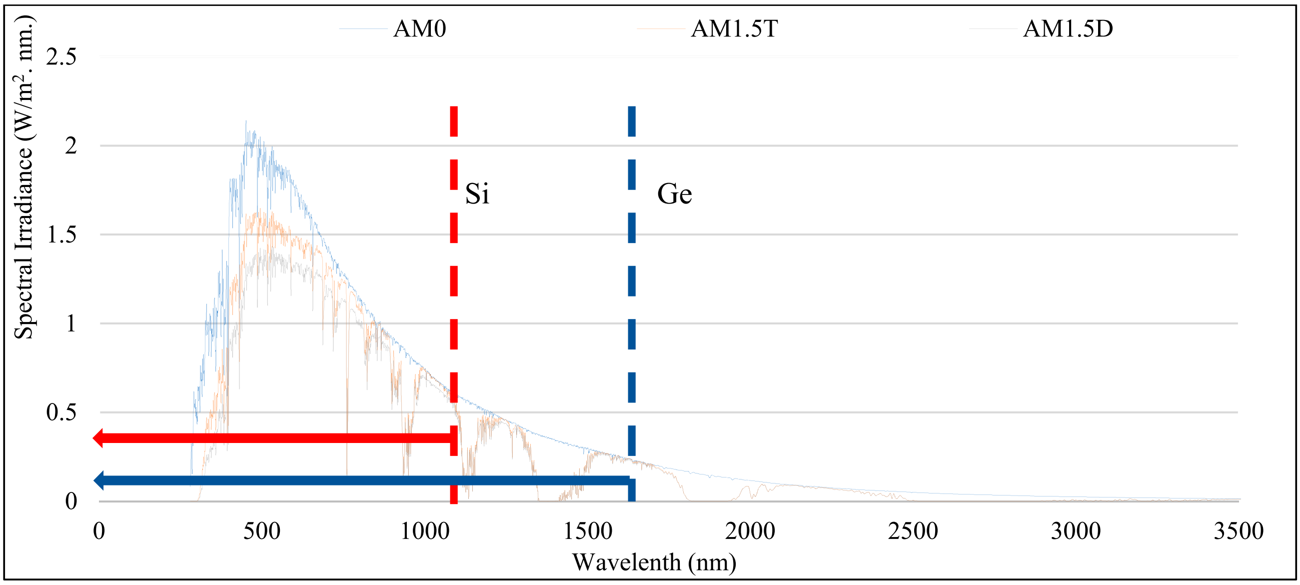


Figure 7. The absorption wavelengths of Si and Ge.

Since Ge can absorb most of the solar spectrum, it might lead to creating only Ge cells. However, what is essential in BIPV materials is their efficiency and not their ability to absorb a wider band. Ge cells produce much more current per square centimeters than Si cells do, but their generated voltage is much smaller. Therefore, the output power per area unit and the efficiency of Ge would be lower than Si. Figure 8 illustrates all these explanations by Si and Ge Current-Voltage and Power-Voltage curves.

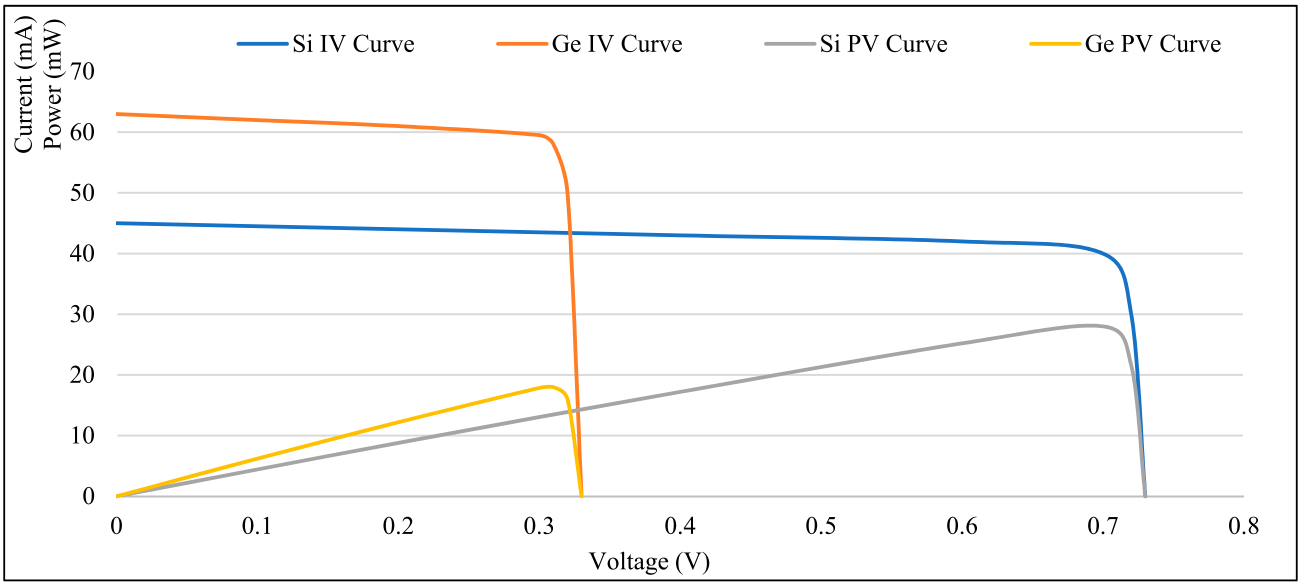


Figure 8. The I-V and P-V curves of Si and Ge BIPV cells.

Figure 9 represents the spectral responses of a variety of BIPV technologies. They can be divided into three categories based on their spectral responses.

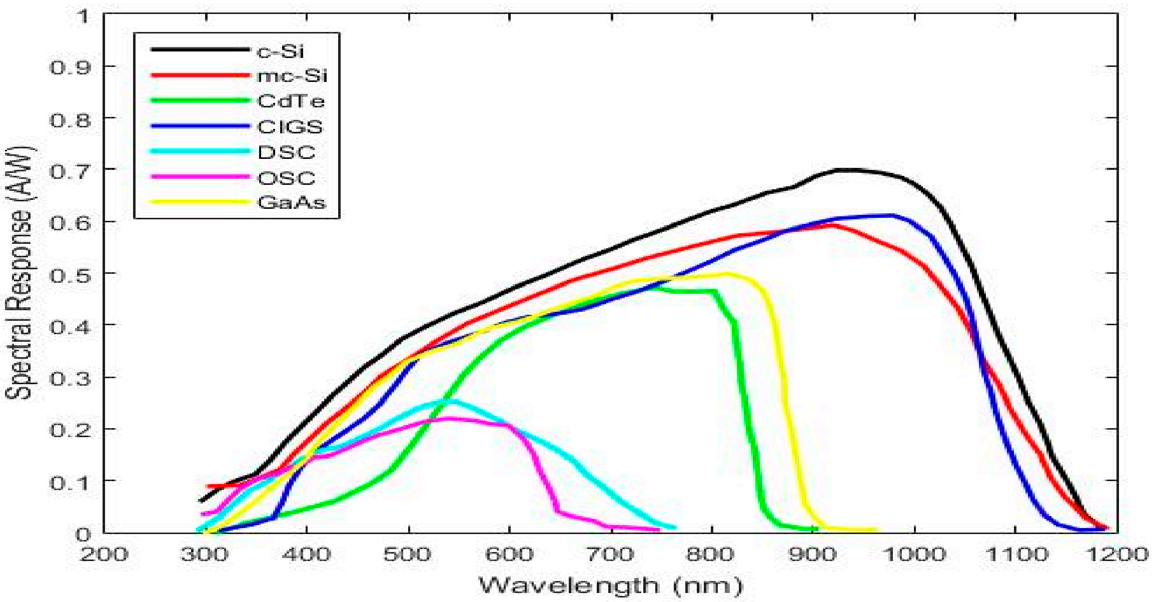


Figure 9. Spectral responses from a variety of BIPV cell technologies [41].

The dye-sensitised solar cell (DSC) and organic solar cell (OSC) are placed in the first group. The spectral responses of this group are almost adjusted to the visible light spectrum. It means that the efficiencies of these technologies are only correlated to the visible light spectrum. As mentioned earlier, the contribution of the visible light spectrum to the beam or diffuse radiation is almost the same. Therefore, it can be concluded that the efficiencies of DSC and OSC technologies are almost constant in different climates and radiation conditions, such as either low radiation or clear sky condition.

The second group includes Copper Indium Gallium Selenide (CIGS), monocrystalline Silicon (c-Si), and multi-crystalline Silicon (mc-Si). Their spectral responses cover wavelengths less than 1200 nm, but with different efficiencies. This means that the efficiencies of these technologies would drop down in a climate with several overcast days due to their significant dependency on IR radiation.

Two remaining technology, Gallium Arsenide (GaAs) and Cadmium Telluride (CdTe) constitute the third group. These materials are sensitive to UV, visible, and IR radiation of less than 900 nm. It means that their efficiency is neither completely dependent on the visible light (like the first group) nor that much dependent on the IR radiation (like the second group). The efficiency of this group will be degraded in a climate such as Stavanger but not as much as the second group.

All in all, it can be concluded that-in terms of efficiency-the performance of the first group would be the most stable option in different climates and radiation conditions. Furthermore, a significant reduction in the efficiency of the second group in a climate with a high contribution of beam radiation compared to a climate with a high contribution of diffuse radiation is predictable. It is worth mentioning also that, in terms of climates like the one in Dubai with several sunny days during the year, there is great potential of gaining solar energy using technologies that are based on concentration, like concentrated photovoltaics technology. On the other hand, for climates with several overcast sky days like Stavanger, solar technology based on the concentration idea is not a suitable choice because of low annual beam radiation in this climate.

6. Sensitivity Analysis of Solar Irradiance and Building Orientation

A sensitivity analysis is done for one of the case studies (Stavanger) in order to evaluate the effect of orientations of the building facades on the quantity of BS as well as the contribution of the solar radiation components. The building is rotated clockwise by the angle of rotations of 10, 20, 30, 40 and 45 degrees and the result is presented in Figure 10. The most interesting aspect of Figure 10 is that the values of BS are almost constant, regardless of the building orientation. Since the radiation on the roof is constant as well, it can be concluded that the total radiation on the building facades is always a constant value that is spread between different facades with different orientations.

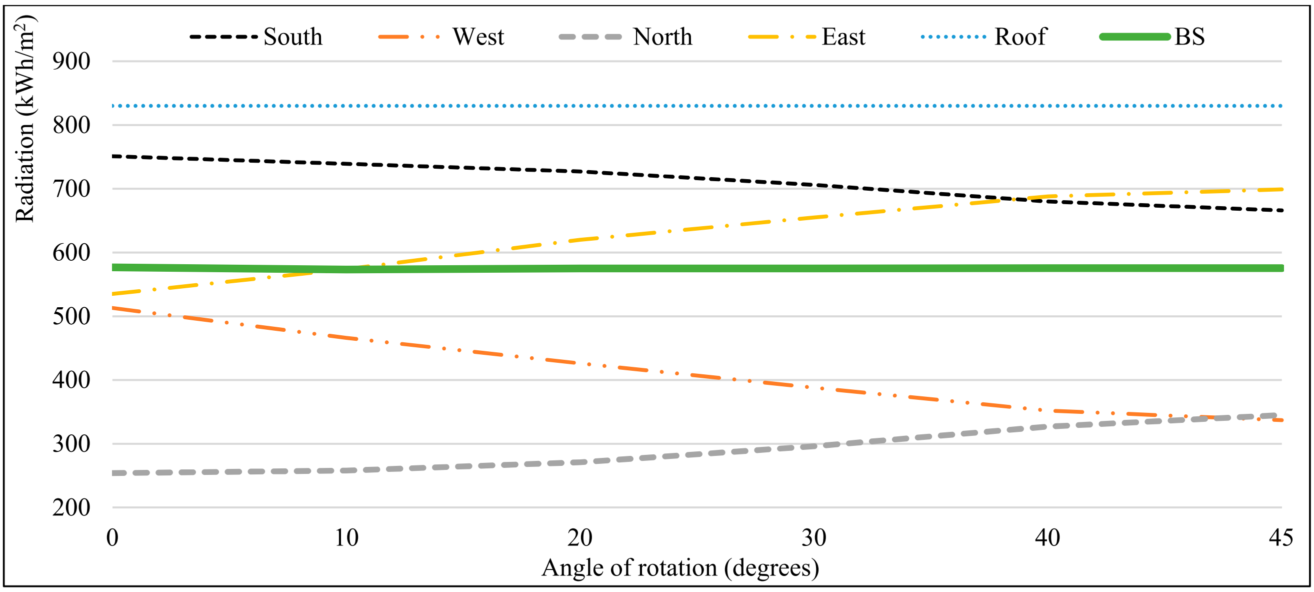


Figure 10. The correlation of radiation on the building skins and the building orientation in Stavanger.

The correlation between the contribution of the solar radiation components on building skins and building orientation is the same as the correlation of BS and the building orientation. The contribution of solar radiation components to the BS in Stavanger is always 38%, 53% and 9% for the beam, diffuse and reflected radiation, respectively, regardless of the building orientation. The results of this sensitivity analysis for Stavanger is consistent with other case studies.

7. Conclusions

This study has gone some way towards enhancing our understanding of solar radiation components on building skins with different orientations in different climates. Although the current study is based on four case studies, the findings suggest that the solar radiation potential of BIPV material as a building envelope material for the whole building skins is significant (576, 869, 1043, 1284 kWh per square meters for Stavanger, Bern, Rome, and Dubai). The BS values are slightly more than the morning and evening façade potentials of the case study.

It is also concluded that the climate is a significant factor when it comes to the contribution of incident solar radiation components on a surface. In other words, in order to choose the suitable solar technology to produce energy from incident solar radiation, the climate of the location needs to be studied precisely.

The evidence from this study suggests that in climates with higher diffuse radiation, the contribution of IR radiation decreases. Therefore, the efficiency of BIPV materials that their spectral responses are dependent on the IR radiation (like Si and CIGS) in such a climate would drop down meaningfully. On the other hand, organic and dye-sensitised solar cells could be a good option for a cloudy climate since they have a more stable performance even in such a climate. Although, their efficiency compared to other BIPV materials, such as Si-based BIPV solar cells, is still significantly less until now.

Finally, when it comes to the impact of the climate on the BIPV system, BIPV performance is also very much dependent on temperature and it should also be considered simultaneously with other factors mentioned in this study. In fact, the effect of some of the parameters being considered in this study (spectral response vs. type of solar radiation availability) may be of the same order of magnitude as those coming from temperature. Soiling and snowfall are, of course, other very important issues in some of the climates considered. These are important issues for future research and a further study with more focus on the mentioned parameters is therefore suggested.

Author Contributions: Conceptualization, Hassan Gholami; Data curation, Hassan Gholami; Formal analysis, Hassan Gholami; Funding acquisition, Harald Nils Røstvik; Investigation, Hassan Gholami; Methodology, Hassan Gholami; Project administration, Hassan Gholami and Harald Nils Røstvik; Software, Hassan Gholami; Supervision, Harald Nils Røstvik; Validation, Hassan Gholami; Visualization, Hassan Gholami; Writing–original draft, Hassan Gholami; Writing–review & editing, Harald Nils Røstvik. All authors have read and agreed to the published version of the manuscript.

Funding: The work reported in this paper was supported by the Department of Safety, Economics, and Planning of the University of Stavanger (Project name: Building Integrated Photovoltaic (BIPV) in dense urban areas, Project number: IN-12011).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: Special thanks also go to the Smart City Group and Future Energy Hub at the University of Stavanger for their support.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Abbreviations

°C	Degree Celsius	IV	Current-Voltage
AM	Air mass	kWh	Kilowatt hour
BIPV	Building integrated photovoltaics	LiDAR	Light detection and ranging
BS	Building skin	mc-Si	Multi-crystalline Silicon
CdTe	Cadmium Telluride	nm	Nano meter
CIGS	Copper Indium Gallium Selenide	OSC	Organic solar cell
CM SAF	Satellite application facility on climate monitoring	PVGIS	Photovoltaic geographical information system
c-Si	Monocrystalline Silicon	PV	Power-Voltage
D	Direct incident radiation	Si	Silicon
DSC	Dye-sensitized solar cell	m^2	Square meter
GaAs	Gallium Arsenide	T	Total incident radiation
Ge	Germanium	UAE	United Arab Emirates
GIS	Geographic information system	UV	Ultraviolet Radiation
IR	Short wave infrared radiation	W	Watt

References

1. Jing Yang, R.; Zou, P.X.W. Building integrated photovoltaics (BIPV): Costs, benefits, risks, barriers and improvement strategy. *Int. J. Constr. Manag.* **2015**, *16*, 39–53.
2. Osseweijer, F.J.; Van Den Hurk, L.B.; Teunissen, E.J.; Van Sark, W.G. A comparative review of building integrated photovoltaics ecosystems in selected European countries. *Renew. Sustain. Energy Rev.* **2018**, *90*, 1027–1040. [CrossRef]
3. Gholami, H.; Røstvik, H.N. Economic analysis of BIPV systems as a building envelope material for building skins in Europe. *Energy* **2020**, *204*, 117931. [CrossRef]
4. Gholami, H.; Sarwat, A.; Hosseinian, H.; Khalilnejad, A. Evaluation of optimal dual axis concentrated photovoltaic thermal system with active ventilation using Frog Leap algorithm. *Energy Convers. Manag.* **2015**, *105*, 782–790. [CrossRef]
5. Gholami, H.; Khalilnejad, A.; Gharehpetian, G. Electrothermal performance and environmental effects of optimal photovoltaic–thermal system. *Energy Convers. Manag.* **2015**, *95*, 326–333. [CrossRef]
6. Mohammadi, F.; Gholami, H.; Menhaj, M.B. Effect of ventilation on yearly photovoltaic performance. In Proceedings of the 1st International Conference on New Research Achievements in Electrical and Computer Engineering, Tehran, Iran, 13 May 2016.
7. Ibrahim, A.; Fudholi, A.; Sopian, K.; Othman, M.Y.; Ruslan, M.H. Efficiencies and improvement potential of building integrated photovoltaic thermal (BIPVT) system. *Energy Convers. Manag.* **2014**, *77*, 527–534. [CrossRef]
8. Agrawal, B.; Tiwari, G. Life cycle cost assessment of building integrated photovoltaic thermal (BIPVT) systems. *Energy Build.* **2010**, *42*, 1472–1481. [CrossRef]
9. Shukla, A.K.; Sudhakar, K.; Baredar, P. A comprehensive review on design of building integrated photovoltaic system. *Energy Build.* **2016**, *128*, 99–110. [CrossRef]
10. Esmailian, E.; Gholami, H.; Røstvik, H.N.; Menhaj, M.B. A novel method for optimal performance of ships by simultaneous optimisation of hull-propulsion-BIPV systems. *Energy Convers. Manag.* **2019**, *197*, 111879. [CrossRef]
11. Biyik, E.; Araz, M.; Hepbasli, A.; Shahrestani, M.; Yao, R.; Shao, L.; Essah, E.; Oliveira, A.C.; del Caño, T.; Rico, E.; et al. A key review of building integrated photovoltaic (BIPV) systems. *Eng. Sci. Technol. Int. J.* **2017**, *20*, 833–858. [CrossRef]
12. Jelle, B.P.; Breivik, C.; Røkenes, H.D. Building integrated photovoltaic products: A state-of-the-art review and future research opportunities. *Sol. Energy Mater. Sol. Cells* **2012**, *100*, 69–96. [CrossRef]
13. Brito, M.; Freitas, S.; Guimarães, S.; Catita, C.; Redweik, P. The importance of facades for the solar PV potential of a Mediterranean city using LiDAR data. *Renew. Energy* **2017**, *111*, 85–94. [CrossRef]
14. Saretta, E.; Caputo, P.; Frontini, F. A review study about energy renovation of building facades with BIPV in urban environment. *Sustain. Cities Soc.* **2019**, *44*, 343–355. [CrossRef]
15. Groppi, D.; De Santoli, L.; Cumo, F.; Garcia, D.A. A GIS-based model to assess buildings energy consumption and usable solar energy potential in urban areas. *Sustain. Cities Soc.* **2018**, *40*, 546–558. [CrossRef]
16. Vulkan, A.; Kloog, I.; Dorman, M.; Erell, E. Modeling the potential for PV installation in residential buildings in dense urban areas. *Energy Build.* **2018**, *169*, 97–109. [CrossRef]
17. Urbanetz, J.; Zomer, C.D.; Rüther, R. Compromises between form and function in grid-connected, building-integrated photovoltaics (BIPV) at low-latitude sites. *Build. Environ.* **2011**, *46*, 2107–2113. [CrossRef]
18. Yoon, S.; Tak, S.; Kim, J.; Jun, Y.; Kang, K.; Park, J. Application of transparent dye-sensitised solar cells to building integrated photovoltaic systems. *Build. Environ.* **2011**, *46*, 1899–1904. [CrossRef]
19. Domjan, S.; Arkar, C.; Begelj, Ž.; Medved, S. Evolution of all-glass nearly Zero Energy Buildings with respect to the local climate and free-cooling techniques. *Build. Environ.* **2019**, *160*, 106183. [CrossRef]
20. Gholami, H.; Røstvik, H.N.; Müller-Eie, D. Holistic economic analysis of building integrated photovoltaics (BIPV) system: Case studies evaluation. *Energy Build.* **2019**, *203*, 109461. [CrossRef]

21. Gholami, H.; Røstvik, H.N.; Müller-Eie, D. Analysis of solar radiation components on building skins for selected cities. In Proceedings of the 14th Conference on Advanced Building Skins, Bern, Switzerland, 28–29 October 2019; pp. 541–549.
22. Gholami, H.; Røstvik, H.N.; Kumar, N.M.; Chopra, S.S. Lifecycle cost analysis (LCCA) of tailor-made building integrated photovoltaics (BIPV) façade: Solsmaragden case study in Norway. *Sol. Energy* **2020**, *211*, 488–502. [CrossRef]
23. Nofuentes, G.; García-Domingo, B.; Muñoz, J.; Chenlo, F. Analysis of the dependence of the spectral factor of some PV technologies on the solar spectrum distribution. *Appl. Energy* **2014**, *113*, 302–309. [CrossRef]
24. Brennan, M.; Abramase, A.; Andrews, R.; Pearce, J. Effects of spectral albedo on solar photovoltaic devices. *Sol. Energy Mater. Sol. Cells* **2014**, *124*, 111–116. [CrossRef]
25. Nofuentes, G.; De La Casa, J.; Solís-Alemán, E.M.; Fernández, E.F. Spectral impact on PV performance in mid-latitude sunny inland sites: Experimental vs. modelled results. *Energy* **2017**, *141*, 1857–1868. [CrossRef]
26. Photovoltaic Geographical Information System (PVGIS). Overview of PVGIS Data Sources and Calculation Methods. Available online: https://ec.europa.eu/jrc/en/PVGIS/docs/methods (accessed on 1 January 2021).
27. Amillo, A.G.; Huld, T.; Müller, R. A new database of global and direct solar radiation using the eastern meteosat satellite, models and validation. *Remote Sens.* **2014**, *6*, 8165–8189. [CrossRef]
28. Mueller, R.; Behrendt, T.; Hammer, A.; Kemper, A. A New Algorithm for the Satellite-Based Retrieval of Solar Surface Irradiance in Spectral Bands. *Remote Sens.* **2012**, *4*, 622–647. [CrossRef]
29. Mueller, R.; Matsoukas, C.; Gratzki, A.; Behr, H.; Hollmann, R. The CM-SAF operational scheme for the satellite based retrieval of solar surface irradiance—A LUT based eigenvector hybrid approach. *Remote Sens. Environ.* **2009**, *113*, 1012–1024. [CrossRef]
30. Bollmeyer, C.; Keller, J.D.; Ohlwein, C.; Wahl, S.; Crewell, S.; Friederichs, P.; Hense, A.; Keune, J.; Kneifel, S.; Pscheidt, I.; et al. Towards a high-resolution regional reanalysis for the European CORDEX domain. *Q. J. R. Meteorol. Soc.* **2015**, *141*, 1–15. [CrossRef]
31. Hennermann, K.; Berrisford, P. ERA5 Data Documentation. Copernicus Knowledge Base. 2017. Available online: https://confluence-test.ecmwf.int/display/CKB/ERA5%3A+data+documentation (accessed on 1 January 2021).
32. Peel, M.C.; Finlayson, B.L.; McMahon, T.A. Updated world map of the Köppen-Geiger climate classification. *Hydrol. Earth Syst. Sci. Discuss.* **2007**, 439–473.
33. Climate-Data.org. Climate Stavanger. 2018. Available online: https://en.climate-data.org/europe/norway/rogaland/stavanger-647/ (accessed on 1 January 2021).
34. Climate-Data.org. Climate Bern. 2018. Available online: https://en.climate-data.org/europe/switzerland/bern/bern-55/ (accessed on 1 January 2021).
35. MeteoSwiss. Climate Normals Bern/Zollikofen Reference Period 1981−2010. Available online: https://www.meteoswiss.admin.ch/product/output/climate-data/climate-diagrams-normal-values-station-processing/BER/climsheet_BER_np8110_e.pdf (accessed on 1 January 2021).
36. Climate-Data.org. Climate Rome. 2018. Available online: https://en.climate-data.org/europe/italy/lazio/rome-1185/ (accessed on 1 January 2021).
37. Climate-Data.org. Climate Dubai. 2018. Available online: https://en.climate-data.org/asia/united-arab-emirates/dubai/dubai-705/ (accessed on 1 January 2021).
38. Data, C. Climate of European Cities. Available online: https://www.climatedata.eu/climate.php?loc=itxx0067&lang=en (accessed on 1 January 2021).
39. World Weather & Climate Information. Average Monthly Hours of Sunshine in Dubai. Available online: https://weather-and-climate.com/average-monthly-hours-Sunshine,dubai-ae,United-Arab-Emirates (accessed on 1 January 2021).
40. Cornaro, C.; Andreotti, A. Solar spectral irradiance measurements relevant to photovoltaic applications. In Proceedings of the International Conference on Applied Energy (ICAE 2011), Perugia, Italy, 16 May 2011.
41. National Technology and Engineering Solutions of Sandia. Spectral Response. Available online: https://pvpmc.sandia.gov/modeling-steps/2-dc-module-iv/effective-irradiance/spectral-response/ (accessed on 1 January 2021).

V. Holistic economic analysis of building integrated photovoltaics (BIPV) system: case studies evaluation

Hassan Gholami [1], Harald Nils Røstvik [2], Daniela Müller-Eie [3]

Department of Safety, Economics and Planning, University of Stavanger, Kjell Arholmsgate 41, 4036 Stavanger, Norway

[1] PhD Researcher, + 47 96 95 72 95, hassan.gholami@uis.no
[2] Professor, + 47 92 22 67 10, harald.n.rostvik@uis.no
[3] Associate Professor, +47 51 83 19 15, daniela.mueller-eie@uis.no

Energy and Buildings
Volume 203, 15 November 2019, 109461

https://doi.org/10.1016/j.enbuild.2019.109461

Energy & Buildings 203 (2019) 109461

Contents lists available at ScienceDirect

Energy & Buildings

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

Holistic economic analysis of building integrated photovoltaics (BIPV) system: Case studies evaluation

Hassan Gholami*, Harald Nils Røstvik, Daniela Müller-Eie

Department of Safety, Economics and Planning, University of Stavanger, Kjell Arholmsgate 41, 4036 Stavanger, Norway

ARTICLE INFO

Article history:
Received 23 May 2019
Revised 16 September 2019
Accepted 22 September 2019
Available online 24 September 2019

Keywords:
Building integrated photovoltaics (BIPV)
Net present value (NPV)
Discounted payback period (DPP)
Cost-benefit analysis
Lifecycle cost analysis (LCCA)

ABSTRACT

Recent trends and future objectives in sustainable buildings are to reduce energy consumption, and simultaneously try to supply their energy demand within the building employing an environmentally friendly energy resource which leads to a nearly zero energy building (nZEB). Building integrated photovoltaics (BIPV), which is one of the fastest growing industries worldwide currently, refers to photovoltaic cells that are integrated into the building envelope such as facade or roof to generate clean energy from sunshine and is the most remarkable technology to contribute to nZEB purposes. In this paper, an innovative approach of BIPV economic analysis is presented. The proposed method is to quantify the societal and environmental advantages of a BIPV system as much as possible and import these values to the economic analysis in order to see their effects in a lifecycle cost analysis (LCCA). In order to compare the results with the current LCCA, four case studies from Brazil, Italy, China, and Bahrain were chosen, because they were the most recent BIPV system LCCA, and the suggested method was applied on them. The economic analysis showed that with the societal and environmental benefits of the implemented system, replacing conventional façades and roof building materials with BIPV modules will become economically more feasible. As a result, the presented strategy could not only expectantly guide the end user to decide more conscious about the implementation of BIPV systems but also steer governments or decision-makers to support the technology by rational subsidies and incentives.

1. Introduction

The energy demand of the world is increasing and the building sector, which includes residential, commercial and public buildings, is currently responsible for%31 of the world's energy demand [1]. On the other hand, fossil fuels, which are currently used as the world's primary energy source, are encountering serious issues such as those of energy shortages, environmental damage, and climate change [2,3]. Therefore, the need for alternative energy resources, which are renewable and non-polluting, is increasing.

As the world's demand and focus on renewable and clean energy are escalating, zero energy, plus energy, and zero emission buildings are rapidly drawing attention, because such buildings conform to the earlier mentioned criteria. To become a zero energy or zero emission building, it needs to harvest energy from its surroundings, where solar energy is one of the obvious choices. In this regard, Building integrated photovoltaics (BIPV), which refer to photovoltaic cells that are integrated into the building envelope such as facade or roof, is a technology that generates electrical energy by exploiting the incident solar radiation to the building skin. In this technology, solar cells are considered as building envelope materials like tiles, foils, modules or windows. The system retains current building skin materials' specifications like weather protection, privacy, noise protection, heat insulation, and simultaneously generates electrical energy for the building [4]. The BIPV lifetime is currently estimated around 30 years [5], while new studies show it could be as long as 50 years [6,7]. BIPV can be employed to either new buildings or renovated ones [8]. The size of the BIPV system can vary from a few kilowatt (kW) for a residential building to several megawatt (MW) for a commercial application [9].

Based on the location of the installation in the building, it can be divided into two subgroups of BIPV roof and BIPV façade. Currently, BIPV rooftops are the most pleasant place for integrating solar PV modules [10]. Generally, there is less shading at a rooftop system than at a façade system. Rooftops regularly give a significant unused surface to BIPV application and the annual solar incident radiation per square meter on the rooftop area is usually more than facades. From the market point of view, more than 80% of the BIPV systems are rooftop mounted and the rest belong

* Corresponding author.
E-mail addresses: hassan.gholami@uis.no (H. Gholami), harald.n.rostvik@uis.no (H.N. Røstvik), daniela.mueller-eie@uis.no (D. Müller-Eie).

https://doi.org/10.1016/j.enbuild.2019.109461

Nomenclature

BAPV	Building attached photovoltaic
BIPV	Building integrated photovoltaics
$BIPV_{np}$	BIPV system nominal power
CdTe	Cadmium Telluride
CI	Bash inflows
C_N	Electricity tariff
CO	Cash outflows
C_{PD}	Power delivery cost
CSCCs	Country-level contributions to the SCC
DPP	Discounted payback period
DR	Discount rate
EEMC	Eequivalent envelope material cost
E_{grid}	Annual amount of inputting electricity to the grid
EPBT	Energy payback time
FiT	Feed-in tariff
GPBT	Greenhouse-gas payback
GSCC	Global societal cost of carbon
IC	Initial cost
IRC	Inverter replacement cost
kW	Kilowatt
kWh	Kilowatt-hour
kW_p	Peak power of BIPV system
LCCA	Lifecycle cost analysis
MW	Megawatt
NC_t	Net cash flow
NPV	Net present value
nZEB	Nearly zero energy building
O&M	Operation and maintenance
P	The lifespan of PV
PB	Projected benefit
PIC	Project investment cost
S	Initial investment
SCC	Societal cost of carbon
t	Number of the year
T_{LL}	Transmission line loss percentage
USD	US Dollar
ZEB	Zero energy buildings

to the façade mounted systems [11]. Moreover, most of the BIPV products for facades are less widespread [12]. Studying the scientific literature, BIPV facades are still a challenging option to employ in comparison to BIPV roofs because of several issues involved with this application [11]. Urban obstacles, shading from neighbouring buildings, openings and other architectural elements, are some of the issues which can significantly affect the BIPV facade potential [13]. However, the contribution of BIPV facades in retrofit intervention should not be neglected.

The possibility to achieve zero energy buildings (ZEB) or even plus energy building goals [14], using different facades and orientations of a building to spread the energy production throughout a day [15], and the contribution of the system to enhance energy performance of the envelopes [16] are some advantages of renovating the façades of an existing building with a multi-functional BIPV system. Moreover, a recent research study conducted by Sánchez-Pantoja et al. [17] reveals that photovoltaic integration in building facades are aesthetically accepted by society. BIPV technology is also valued more positively than building attached photovoltaic (BAPV), which are PV systems added on the building without a direct contact with the structure.

Research conducted by Azadian and Radzi [6] classified the barriers of using BIPV system in building industries into four main groups of institutional barriers, public acceptance, economic barriers and technical barrier. Concerning BIPV technical analysis, many studies have been carried out to illustrate the various types of technology as well as their specifications and applications [3,6,11,18–25]. It should be noted that by dealing with the economic barrier and solving this problem, we can easier tackle public acceptance issues. From recent studies and market surveys, it can be concluded that the high capital cost of the BIPV system is the most significant barrier to use this technology in the building sector [9]. Therefore, while photovoltaic integration in building facades are aesthetically accepted by the society, high capital cost and low electrical efficiency of the BIPV system are some of the barriers that need to be tackled in order to increase the public acceptance.

When it comes to the BIPV economic analysis, many studies have conducted an economic analysis of a BIPV system or the various policies which affect the analysis, but very few have quantified or monetised the impact of BIPV systems on the community (society) and environment. [3,5,9,12,26–28] In other words, there is a lack of knowledge of lifecycle cost related to BIPV systems to allow clients and end users to make more informed decisions on the use of BIPV products. Since this issue has not been addressed in recent research studies, our focus in this paper is on this challenge.

Lifecycle cost analysis (LCCA) is a technique that allows the assessment of BIPV alternatives for final selection, based on the two factors of initial costs and the monitoring of costs throughout the life of a project, to reach the minimum cost as well as highest profit. A Comprehensive analysis is an analysis that allows the end users to choose the source of energy for their building considering all consequences of their decision. This type of analysis should investigate various available options such as different BIPV systems considering their societal and environmental advantages, as well as their role in building material offset, because of their dual function as building envelope and power generator.

Sorgato et al. [14], in 2018 evaluated the feasibility of employing thin-film Cadmium telluride (CdTe) BIPV system technically and economically for the same building in six Brazilian cities. The results illustrated that it is feasible to meet the net annual energy consumption of the studied building with a BIPV system using building rooftops and façades. The research also confirmed that climate plays an essential role in the net annual energy consumption of the building, as well as the energy generated by BIPV systems. However, the study did not elaborate on the societal and environmental economic effects of the BIPV system. The economic evaluation of the system could have been more comprehensive if the study had considered the benefits of the BIPV system as quantifiable as possible.

Aste et al. [29] evaluated the first Italian BIPV project after 13 years of continuous operation to elaborate its technical and economic performances and, through this, predict its lifetime performance. They found that during the 13 years of operation, the system did not show a significant decrease in performance. The performance decay measured was equal to 0.37% per year, which is less than the usually considered degradation in multi-crystalline Silicon system which is approximately 0.5% per year [30]. Moreover, Infrared Spectroscopy and visual inspection revealed that no PV module was damaged. This could be because of skillful system design, rear side ventilation of the modules and also high-quality components. The results confirmed that BIPV systems can work productively during its lifetime, ensuring good energy and economic performances. Like the Sorgato et al. [14], this research did not take into account the societal and environmental benefits of the BIPV system in order to carry out the LCCA.

Wang et al. [31] carried out a study for environmental assessments and economic performance of BIPV system by analysing the net present values (NPV) and the payback period of the BIPV system of a building in Shanghai over its lifecycle. The payback time of the initial cost considering the feed-in tariff (FiT) of renewable energy in the residential sector was obtained in 6.52 years. Moreover, the energy payback time (EPBT) and the greenhouse-gas payback time (GPBT) of the BIPV system was calculated to be 3.1 and 0.4 years, respectively. However, by considering the societal and environmental benefits of the BIPV system the result might be more promising. These factors were not taken into consideration for this case study.

Alnaser [32] evaluated the performance of an 8.6 kW BIPV system with polycrystalline PV cells in Bahrain Petroleum Company at Awali Town, Kingdom of Bahrain. This is a country in an arid zone with high annual solar radiation. The results showed that the payback time of the system reached about 624 years, which is due to the low cost of the electricity in Bahrain (8 cent for consumption up to 3000 kWh per month). The electricity tariffs in Bahrain is subsidized while it is mainly produced by cheap oil. The research states that if the feed-in tariff were set to purchase each one kWh solar electricity for 1 US dollar, then the payback would be five years. By assuming the emission of one kg CO_2 per one kWh of electricity, the study concluded that the system decreased the CO_2 emission by nine tons, annually. However, the study did not quantify this carbon emission cost to see its effect on the payback time.

In this current paper, an innovative approach for LCCA of the BIPV systems is proposed. The suggested method is applied to the recent studies, which was economically analysed the system but without taking into consideration of societal and environmental consequences of BIPV technology. In other words, the recent case studies are re-analysed by the suggested LCCA. Therefore, the traditional LCCA and the suggested LCCA for the same case studies can be easily compared.

In section two, the methodology and assumption are discussed in details. Then, in section three, the societal and environmental advantages of BIPV systems are quantified as much as possible in order to see their effects on payback time as well as net present value. In section four, the results are depicted and discussed and finally, in section five, the conclusion is presented.

2. Methodology

2.1. Case studies

Four case studies are selected in order to apply the suggested method and evaluate the effect of societal and environmental factors on the economic feasibility of a system. The locations are Milan [29], six cities in Brazil [14], Shanghai [31], and Awali [32].

2.1.1. Milan [29]

The study evaluated the pilot BIPV plant at the Politecnico di Milano, which underwent 13 years of continuous operation. The results obtained indicated that the BIPV plant analysed did not show a significant decrease in long-term performance. The measured PR (performance ratio) decay is equal to 0.37%/year. In addition, visual inspection and IR analysis (infrared spectroscopy) showed that no BIPV modules are affected by serious damage. The paper claimed that this result was due to the good system design during the preliminary stage, high-quality components and also the rear ventilation of the modules, which avoids overheating in the warmer days of the year. Finally, an economic analysis was carried out and showed that the DPP time of the BIPV system is 13 years.

2.1.2. Six cities in Brazil [14]

The paper evaluated a technical and economic potential of integrating state-of-the-art, frameless, glass thin-film cadmium telluride (CdTe) BIPV modules on a commercial building façade and roof, and analyzed the economic feasibility of replacing conventional façade materials like aluminum composite and architectural glass material with BIPV modules in six Brazilian cities. The technical analysis consisted in assessing the energy performance of a four-storey office building for each of the six cities. The technical analysis indicated that it is possible to fully meet the energy demand of the office building with BIPV integration in six evaluated Brazilian cities. The study also showed that while the local climate has a remarkable impact on energy consumption, BIPV energy production follows the same trend. Moreover, the economic analysis indicated that with the declining costs of BIPV systems, replacing traditional façade building materials with BIPV modules is not only an innovative approach but also of economic benefit. The DPP of the BIPV system for six cities considering different inflation rates were calculated which was between six years to up to 16 years.

2.1.3. Shanghai [31]

This study evaluated two systems in Shanghai. A building attached photovoltaic (BAPV) system of 3 kW_p and a building integrated photovoltaic (BIPV) system of 10 kW. The monthly system efficiencies, output yields and monthly performance ratio (PR) of the two systems were recorded. In order to analyze the system benefits, NPV and DPP method were employed. PV SOL software was used to simulate these two systems. The simulation results including economic and performance states were illustrated in this study. Moreover, energy payback time (EPBT) and the greenhouse-gas payback time (GPBT) were employed to evaluate environmental impacts. EPBT of the two systems was 4.2 years and 3.1 years. The results for GPBT were 1.3 years and 0.4 years, respectively. The DPP of the BIPV system considering the government incentive was 11 years, which is because of the significant subsidy that China allocates to the owners of renewable energy systems.

2.1.4. Awali [32]

The study reported the performance of 1.5 years of 8.64 kW smart BIPV system integrated into a building at Awali, which is a town in the kingdom of Bahrain located in the middle of a desert area. The BIPV system covers a roof area of 59 m^2 (36 BIPV panels). The data showed that the annual produced solar electricity from the BIPV system was 8879 kWh while the expected energy set by the producer (Petra solar) was 11,990 kWh. The calculated DPP for the BIPV system was 624 years, which was because of the low electricity tariff for domestic use (in 2015). The electricity tariff for domestic use was only 3 fils (¢ 0.80) for the first 3000 kWh, 9 fils (¢2.34) for consumption from 3001 to 5000 kWh and 16 fils ¢4.16 for consumption from 5001 kWh and more.

2.2. Economic analysis tools

In order to compare the economic feasibility of the case studies after considering the societal and environmental factors, two financial tools which were used by the examined case studies have been employed, which are the Net present value (NPV) and discounted payback period (DPP). The NPV is a tool to show the net difference between the profits and costs of the system in present or annual values. It is calculated by the difference between the present value of profits and the present value of costs [33]. The DPP period is the minimum time it takes to recoup investment costs [33].

2.3. Input parameters

Several parameters and factors need to be taken into consideration in order to develop the economic analyses. The most important of them are;façade and roof material costs, PV system investment costs, electricity tariff, BIPV system lifecycle, BIPV electricity production during its lifetime, solar incident radiation of the location, operation and maintenance (O&M) costs, PV degradation rate,

Table 1
some of input data from the case studies.

City	Belem	Brasília	Curitiba	Florianopolis	Rio de Janeiro	Sao Paulo	Milan	Awali	Shanghai
Roof area (m2)	600	600	600	600	600	600	106	60	66
Façade area (m2)	607.6	607.6	607.6	607.6	607.6	607.6	0	0	0
$BIPV_{np}$ (kWp)	180	180	180	180	180	180	10.95	8.64	10
E_{grid} (MWh)	197.2	223.5	201.2	190.3	197.6	170.1	9.7	8.9	9.9
C_N ($)	0.22	0.17	0.19	0.19	0.24	0.17	0.22	0.06	0.082
Investment ($)	231,152						25,000	43,000	19,474
Application	Roof / Facade						Roof		
Technology	Thin-film CdTe						Poly Crystalline Si		Mono Crystalline Si

Table 2
Discount rate of each case study.

Country	DR (%)
Brazil	5.5 [14]
China	3 [31]
Italy	3 [29]
Bahrain	4 [36]

Table 4
The inflation rate of electricity tariff for each case study.

Country	Electricity tariff
Inflation Rate	
Brazil [14]	3
China [31]	2
Italy [29]	6
Bahrain [38]	3

inverter replacement cost over BIPV system lifetime and BIPV system type based on its connection to the system (on-grid, off-grid or hybrid). The electricity costs depend on each analysed country and city according to the energy tariff charged by the local power distribution company.

From the case studies, it can be found that the system type in all of them is the on-grid type which means they are directly connected to the network using a grid-connected inverter and the system is without any storage system.

The costs due to the replacement of inverters represent 17% of the whole BIPV system's initial cost [14]. Moreover, Grid-connected inverters usually have a ten to fifteen years warranty. Therefore, the replacement of the inverter was assumed to be required every ten years [34].

A study led by Jordan and Kurtz [30] 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. Therefore, this ratio of energy losses per annum has been adopted in this study.

Annual operation and maintenance (O&M) costs of a BIPV system is assumed to be 1% of the initial cost of BIPV system per year [35].

Table 1 represents a brief overview of the case studies and their properties.

In order to be able to calculate NPV and DPP, the discount rate (DR..) corresponding to each case study has to be defined. The discount rate is the rate of interest which a bank charges on its loans. The rate is a part of the calculation of NPV when doing a discounted cash flow analysis. This rate is different for each country. Table 2 shows the discount rate for each case study for 2018.

It is worth mentioning that the feed-in tariff for residential BIPV in China is 0.1498 US dollar [31], but the electricity tariff supplied by the network is 0.082 USD. In this paper, for electricity price, we always use the electricity price of the network without any subsidy or incentive in order to evaluate the real payback time of the BIPV systems. Moreover, the electricity tariff in Bahrain is extremely low, which results in unreasonable longer payback time if we do not consider any subsidy or incentive.

The BIPV system lifecycle is considered 30 years; however recent studies showed that their life could reach to 50 years [6,7].

The solar incident radiation of the case studies can be extracted from PVGIS-SARAH. The Satellite Application Facility on Climate Monitoring (CM SAF) and the Photovoltaic Geographical Information System (PVGIS) team with a spatial resolution of 31 km has calculated this data set [37]. Table 3 shows the average daily incident radiation of roof and different facades for the case studies from 2005 to 2016. It is worth mentioning that all six Brazilian cities in this study are located on the southern hemisphere and the rest of case studies are located on the northern hemisphere.

The electricity tariff inflation rate is different from country to country. These values have been extracted based on historical data of case studies and presented in Table 4.

The electricity inflation rate for Bahrain was not mentioned in their study. Up until recently, electricity tariffs in Bahrain were subsidized. Since 2016, new electricity tariffs have been applied to electricity consumers. The electricity tariffs will be gradually increased to meet the cost of power generation of 29 fils/kWh (0.08 USD) by 2019. For years after 2019, we consider the price increasing rate is the same as the inflation rate which is 3% [38].

Table 3
Average daily incident radiation of roof and different facades of each case study.

Country	City	Roof	South Facade	East Façade	West Façade	North facade
Brazil	Belem	5.51	1.97	2.96	2.33	2.13
	Brasilia	5.35	2.06	2.65	2.46	2.69
	Curitiba	4.22	2.59	2.13	2.11	2.62
	Florianopolis	4.25	2.78	2.13	2.06	2.70
	Rio de Janeiro	4.81	2.77	2.41	2.34	2.79
	Sao Paulo	5.27	2.89	2.69	2.56	3.10
China	Shanghai	3.72	2.44	1.79	1.98	1.03
Italy	Milan	3.93	3.18	2.16	2.36	0.82
Bahrain	Awali	6.16	3.61	3.16	3.20	1.19

Table 5
C_{TL}, T_{LL} and C_N value of the case studies.

Country	City	C_N (USD/kWh)	T_{LL} (%) [53]	C_{TL} (USD/kWh)
Brazil [14]	Belem	0.22	15.8	0.035
	Brasilia	0.17	15.8	0.027
	Curitiba	0.19	15.8	0.030
	Florianopolis	0.19	15.8	0.030
	Rio de Janeiro	0.24	15.8	0.038
	Sao Paulo	0.17	15.8	0.027
China [31]	Shanghai	0.082	5.5	0.005
Italy [29]	Milan	0.22	7	0.015
Bahrain [32]	Awali	0.06	4	0.001

2.4. Societal and environmental factors

While there are many research studies attempting to illustrate the societal and environmental effect of the renewable energies generally [2,39–44] and BIPV system specifically [3,5,9,31,45–49], few research studies focused on quantifying these benefits and there was no study that applied the monetised value of these benefits to the economic analysis of the BIPV system. As a result, the presented strategy could not only expectantly guide the end user to decide more conscious about the implementation of BIPV system but also steer governments or decision-makers to support the technology by rational subsidies and incentives. The most important societal and environmental factors which will be affected by using BIPV system are listed below.

2.4.1. Transmission line lost power

Power plants, which are typically located a long distance from the cities because of the security and environmental considerations, supply energy to urban areas. Such a configuration needs transmission and distribution lines to deliver the energy to the end users, which results in electricity loss in the power grid. For instance, this value for Norway was around 6% in 2014 [50]. Based on the electricity tariff of $0.18/kWh [51] and considering the total electricity production of 142TWh in 2014 for Norway [52], the value of the lost energy is 1.54 billion US dollar. The value is comparatively higher for countries such as the USA and Brazil, which have longer and larger power transmission lines compared to Norway. BIPV is a suitable solution to this problem because it removes the distance between the location of the electricity consumption and generation. The transmission and distribution lines loss value per each kWh for each country can be directly calculated as follows:

$$C_{TL} = T_{LL} \times C_N \quad (1)$$

Which C_{TL}, TLL, and C_N represent the cost of transmission line loss, transmission line loss percentage, and electricity tariff, respectively. Table 5 depicts these values for the studied cases.

2.4.2. Power delivery cost

BIPV is also a great asset to reduce or even omit the capital expenditure required to expand the network infrastructure or maintenance. On the contrary of the BIPV systems, some other forms of renewable energies like solar farms or wind farms might lead to the need of expanding the network infrastructure or even some slight changes in the climate of the exploited land. According to the International Energy Agency (IEA), World electricity demand increased by 4% in 2018 which is significantly higher than the total increase in energy demand [54]. There are two possible solutions to manage this demand growth; upgrading the transmission and distribution lines throughout the world or producing electrical energy nearer the end users. BIPV technology is an excellent response to remove this distance and omit or at least postpone the considerable investments required to extend the transmission and distribution lines. Moreover, according to the USA Energy Information Administration (EIA) report of September 2017, electricity prices reflect rising delivery costs while the electricity generation cost is declining [55]. In terms of USA, delivery costs are responsible for 36% of the total price of electricity for the end user. Many factors involved in the delivery cost such as transmission costs, expenses for distribution equipment which deals with lower voltages, charges for installing, operating, and maintaining meters and sensors [55]. Considering a depreciated estimate, generated electricity by a BIPV system can decrease the delivery cost of around 20% of the electricity t [56].

Table 6
CSCCs of each case study [61].

Country	CSCCs (USD/ton)
Brazil	41.217
China	50.019
Italy	4.751
Bahrain	85.667

2.4.3. The societal cost of carbon (SCC)

The societal cost of carbon (SCC) consists of the damage caused by carbon emission [57]. It is around $33 per ton for global effect and $2 per ton for domestic effect as per the US Department of Transport estimation [57]. However, the value calculated for SCC by organisations have a non-ignorable discrepancy, and most agencies decline to state a number as a line item on the cost-benefit balance sheet and leave it as “non-monetized” benefits in the final calculation. The average SCC value for the electricity generation is around $0.048–0.097 per kWh [58] which is a noticeable amount.

Some countries like Australia has started to enact national carbon emission charge ($25.4 per ton) to increase the cost of electricity generation with conventional methods and simultaneously give up subsidies for electrical energy produced by renewable sources, which are carbon-free [59,60]. However, a recent study led by Ricke et al. [61], found that the global societal cost of carbon (GSCC) is dramatically higher than previous estimates. In terms of USA as an example, it is probably between 177 USD and 805 USD per ton, most likely 418 USD. Table 6 shows the country-level contributions to the SCC (CSCCs) cost for the studied countries [61]. It should be noted again that since the global societal cost of carbon, which is the sum of all country-level societal costs of carbon, is around 418 USD per ton, efforts to reduce carbon emissions through the clean energy resources need to be accelerated.

2.4.4. Material cost

The conclusion of the previous research on this issue is not aligned. Some of them determined that the BIPV system imposes more cost on the building. For example, the research conducted by Hammond et al. [5], revealed that the initial cost of BIPV roof tile would be 2% more than regular concrete roof tiles. However, some other studies claim that the additional cost of BIPV is equivalent

Table 7
The cost of a general facade and roof of each case study per square meter.

Country	Location	Cost (USD/m^2)
Brazil	Roof [64]	45
	Facade [14]	21
China	Roof [65]	35
Italy	Roof [66]	45
Bahrain	Roof [67]	40

to or even lower than traditional materials. Research conducted by Koinegg et al. [62] contended that the cost of BIPV glazing system could even be 20% less than polished stone facades and lead to saving in installation cost due to the issue involved with the weight of the stones as well. It should be noted that these values are for the initial cost of the BIPV systems and its secondary function as an energy producer was not taken into consideration. In other words, the capital cost of a BIPV system should be split between its functions as a building envelope as well as electricity producer [63] which is what we took in consideration for this study.

In order to evaluate the BIPV system economically, for each case study depending on the location of the BIPV system which could be roof or façade, we considered the additional cost that the BIPV system resulted in because of its function as a power generator.

The average cost of an ordinary façade and roof for each case study is shown in Table 7.

It is worth mentioning that BIPV also results in a societal benefit through the reduction in land use required for the production of the electricity. This is because BIPV systems require no additional land in contrast with the traditional methods of electricity generation [27].

2.5. Lifecycle cost analysis (LCCA)

2.5.1. Methodology

The common framework of LCCA was established in 1997 under the guidelines set by the International Organization for Standardization [68,69].

LCCA is a process to determine the aggregate of all the costs associated with an asset, including acquisition, operation, installation, refurbishment, maintenance, and disposal. Accordingly, it is a key component of any asset management structure.

The four key components of life cycle costing are as follow:

- costs of owning and operating an asset
- the lifespan of the asset
- the discount and inflation rate
- the benefits (quantitative and qualitative) of the asset during its lifespan.

Decision making based on LCCA often involves a combination of both quantitative and qualitative assessments. The quantitative results provide a baseline, but many other factors relevant to a decision may not be quantifiable in terms of costs. These qualitative assessments support the results of the quantitative analysis and will be addressed in the development of a business. The focus of this study is to quantify all the advantages of using such a BIPV system as much as possible to see their effects in economic assessment.

The developed LCCA model for BIPV generation system distributed into two cost categories, which are cost and saving:

The cost category includes cost for purchasing BIPV Panels and electrical apparatus, mounting structure and civil works, spare parts, operation and maintenance, and disposal cost.

The saving category contains the saving in the transmission line loss, power delivery cost, societal cost of Carbon, and equivalent envelope material cost as well as the income from the electricity generation. Such a compehensive LCCA which quantify all these advantages has not been carried out as mentioned earlier.

2.5.2. Formulation

As mentioned earlier, an LCCA research that considers the multi-functional performance of BIPV system, as well as the societal and environmental factors (against traditional LCCA analysis) is lacking. Therefore, the following assessment is presented.

The basis of the suggested economic assessment model is NPV, which is used for financial appraisal [70], and can be expressed as follows [31]:

$$\mathrm{NPV} = \sum_{t=0}^{p} (CI - CO)(1 + DR)^{-t} \tag{2}$$

Where CI is cash inflows, CO is cash outflows, DR is the discount rate, p is the lifespan of PV (years) and t is the number of the year.

The initial investment S for PV systems is calculated by (3):

$$S = \mathrm{PIC} - \mathrm{EEMC} \tag{3}$$

Which PIC and $EEMC$ stand for project investment cost and equivalent envelope material cost, respectively.

The cash inflows of the connected grid system in year t can be shown as (4) :

$$CI = C_N \times E_{grid} + PB \tag{4}$$

Which C_N, E_{grid} and PB represent electricity tariff of the case study, the annual amount of inputting electricity to the grid and the projected benefit, respectively. The projected benefit can be calculated as follows:

$$\mathrm{PB} = C_{TL} + C_{PD} + SCC \tag{5}$$

Where C_{TL}, C_{PD}, and SCC are the cost of transmission line loss, power delivery cost, and societal cost of Carbon.

The cash outflows of the connected grid system in year t can be shown as (6) :

$$CO = O\&M + IRC(if\ t = 10, 20) \tag{6}$$

Which $O\&M$ and IRC stand for operation and maintenance and inverter replacement cost. It should be noted that as mentioned earlier, the replacement of the inverter is scheduled for once per ten years considering the manufacturers' warranty.

The net cash flow NC_t in year t can be expressed as the following:

$$NC_t = CI - CO \tag{7}$$

Finally,the NPV of the BIPV system can be expressed as the following formula:

$$\begin{aligned} \mathrm{NPV} &= -S + \frac{NC_1}{(1+DR)} + \frac{NC_2}{(1+DR)^2} + \ldots + \frac{NC_n}{(1+DR)^n} \\ &= -S + \sum_{t=1}^{p} \frac{NC_t}{(1+DR)^t} \end{aligned} \tag{8}$$

And the discounted payback period (DPP) can be calculated as follows:

$$-S + \sum_{t=1}^{p} \frac{NC_t}{(1+DR)^t} = 0 \tag{9}$$

2.5.3. Limitations

Since there was not any data regarding the cost of the carbon emissions during the manufacturing/transportation/disposal of the BIPV panels in referenced studies, these parameters were not taken into consideration. However, the BIPV modules and components contain glass, aluminum and semiconductor materials that can be

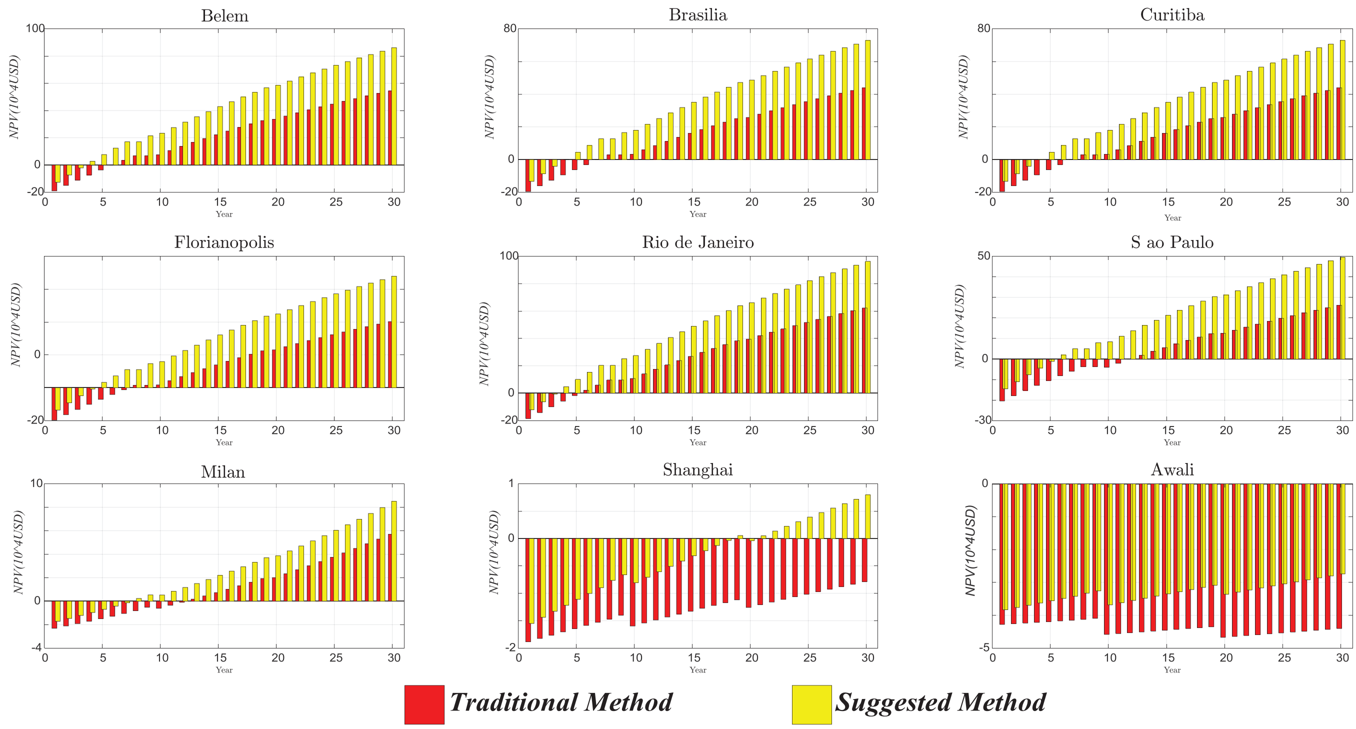


Fig. 1. NPV calculation considering the traditional method and suggested method.

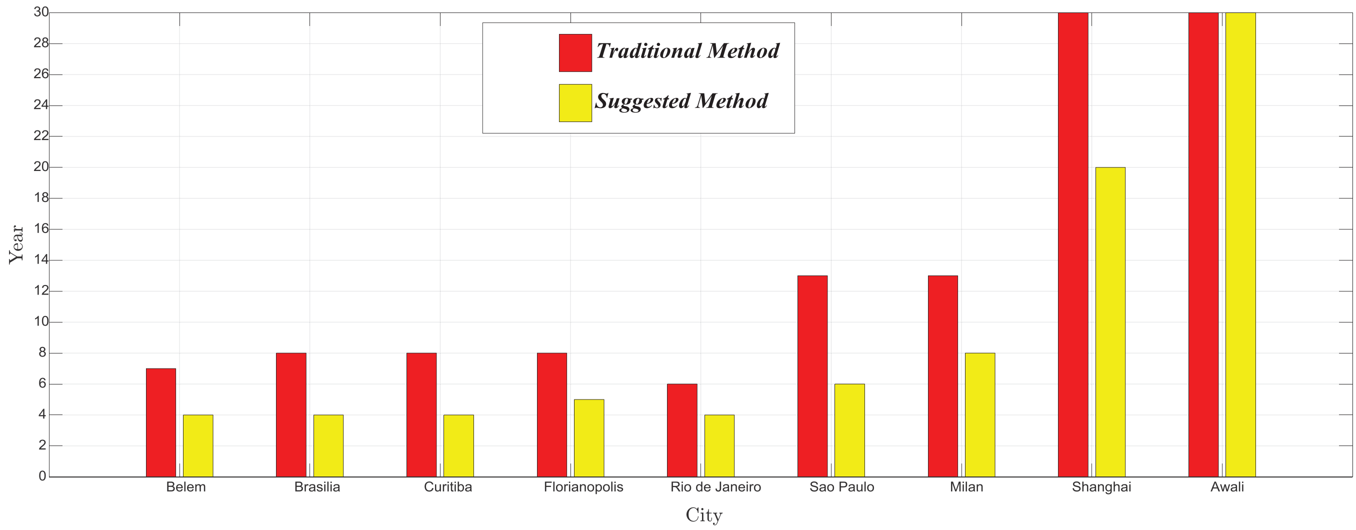


Fig. 2. DPP considering the traditional method and suggested method.

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 [70]. Moreover, it worth mentioning that the BIPV panels -as mentioned earlier- are a substitute of traditional building envelope materials which their manufacturing/transportation/disposal process also leads to the Carbon emissions and what is not imported to the suggested LCCA is the additional Carbon emission due to the use of BIPV system instead of traditional building envelope materials (if any).

3. Results and discussion

The analysis was done in Excel software and the data together with the formulation and method is publicly available in Mendeley database. Figs. 1 and 2 illustrate the simulation results for the cumulative net present value (NPV) and discounted payback period (DPP) of the case studies. As can be seen from the pictures, the suggested method improves the economic feasibility of the BIPV system. For instance, the DPP for Belem, has been decreased from seven years to four years. Concerning the Awali case study, the system is still unfeasible considering a 30 year life cycle of the BIPV system, even when applying the suggested method. There are many reasons why the BIPV system in Bahrain is still unfeasible after applying societal and environmental aspects. Fig. 3 depicts the BIPV price per watt peak, electricity tariff, CSCCs, transmission line loss of the case studies. As can be seen from Fig. 3, Bahrain has the highest initial investment cost (more than twice of other case studies) as well as the lowest electricity tariff which, leads to the system being unfeasible or a DPP longer that its life cycle.

For the Brazilian cities, the payback time with the traditional method is above six years for all cities except Sao Paulo, while with the suggested method, the payback time comes to less than five

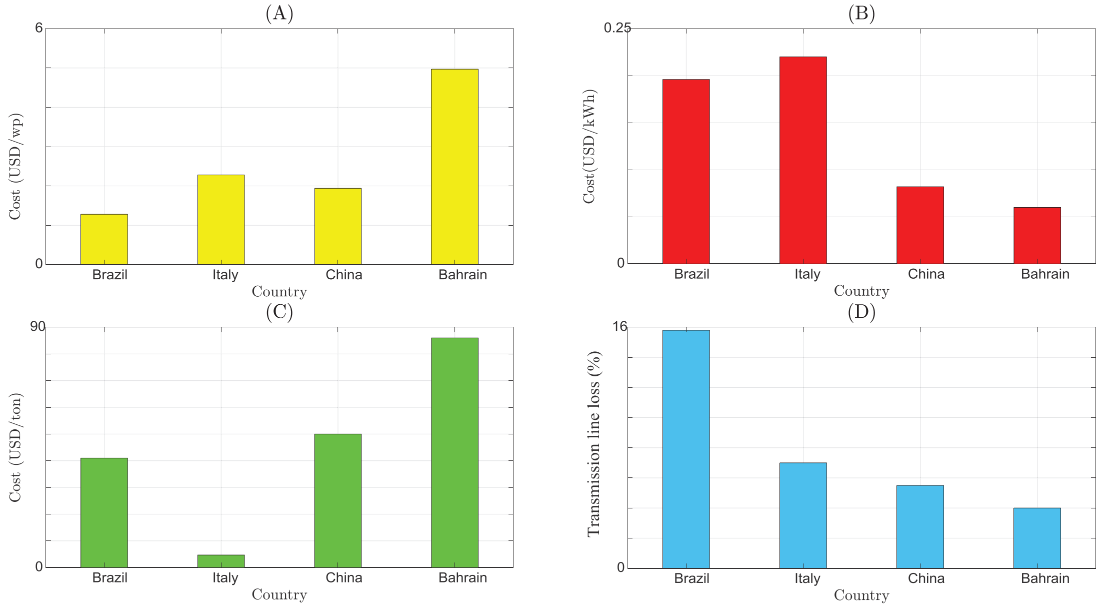


Fig. 3. (A) BIPV price, (B) Electricity tariff, (C) CSCCs, and (D) Transmission line loss of the different countries.

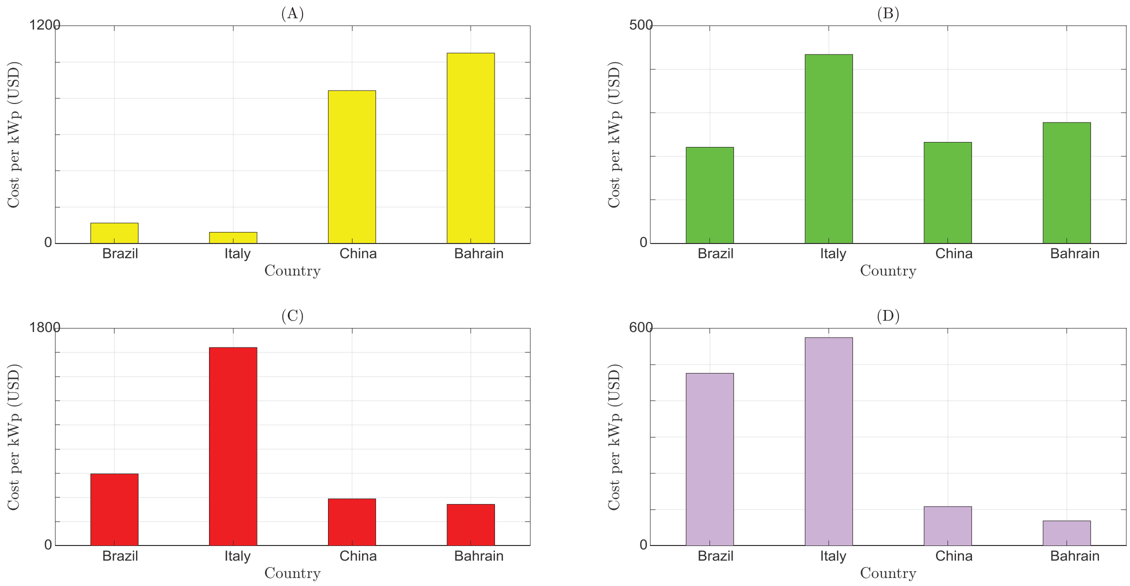


Fig. 4. Cumulative NPV of (A) CSCCs, (B) Equivalent building envelope cost (C) Transmission line cost (D) Transmission line loss of the case studies per watt peak.

years for the mentioned case studies. Regarding Sao Paulo, because of low electricity tariff, the payback time by the traditional and suggested method is thirteen and six years, respectively.

Regarding Italy, because of the low transmission line loss as well as SCC, the payback time of the traditional and suggested method is thirteen and six years, respectively. Among the studied countries, Italy with CSCCs of four USD/tons is the most environmentally friendly country and Bahrain with CSCCs of 85 USD/tons is the worst country.

The effect of the suggested method on the economic feasibility of the BIPV system in China is impressive. While the system is unfeasible considering the traditional method, the system is economically feasible by employing the suggested calculation, and its DPP would be 20 years.

Fig. 4 depicts the cumulative net present value of four societal and environmental factors per watt peak. Because of low carbon emission per kWh of Italy and Brazil [71], the NPV of SCC of these countries are much less than the two other countries. Moreover, because of high electricity tariff in Italy, the NPV value of saving in transmission line cost using BIPV system in this country is considerably higher than other case studies. Also, the NPV value of saving in transmission line cost using BIPV system in China and Bahrain is notably less than the other countries which is because of low electricity tariff in these countries.

The NPV of saving in transmission line loss by BIPV systems for Italy and Brazil is much higher than two other countries which are because of their higher electricity tariff as well as higher transmission line loss rate.

Fig. 5 illustrates the NPV value of the societal and environmental advantages of the BIPV system in different countries. The highest NPV value belongs to Italy with 2.711 USD per watt peak which is because of its high electricity tariff as well as suitable solar incident radiation. While Bahrain is number two after Italy with NPV value of 1.739 USD per watt peak, and as the results revealed, the

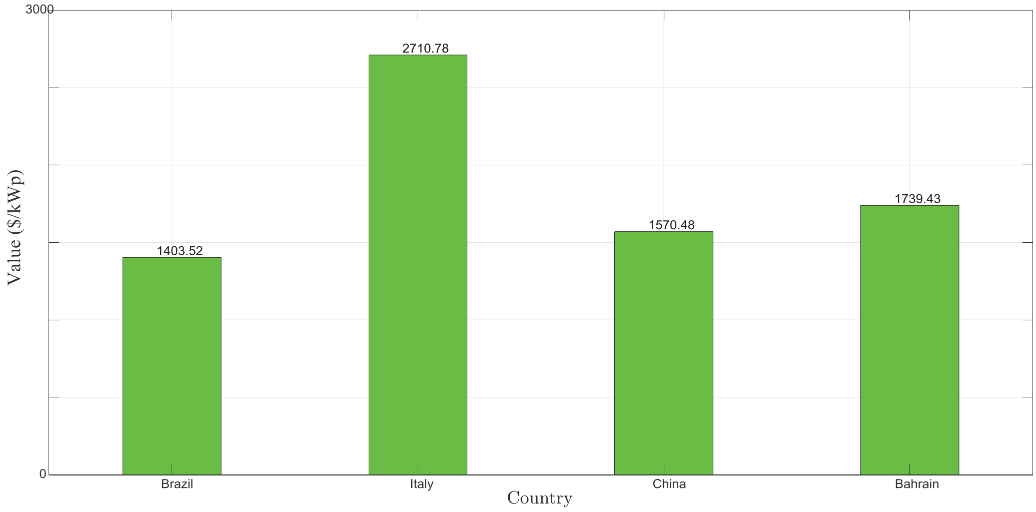


Fig. 5. The NPV of societal and environmental advantages of BIPV system in different countries.

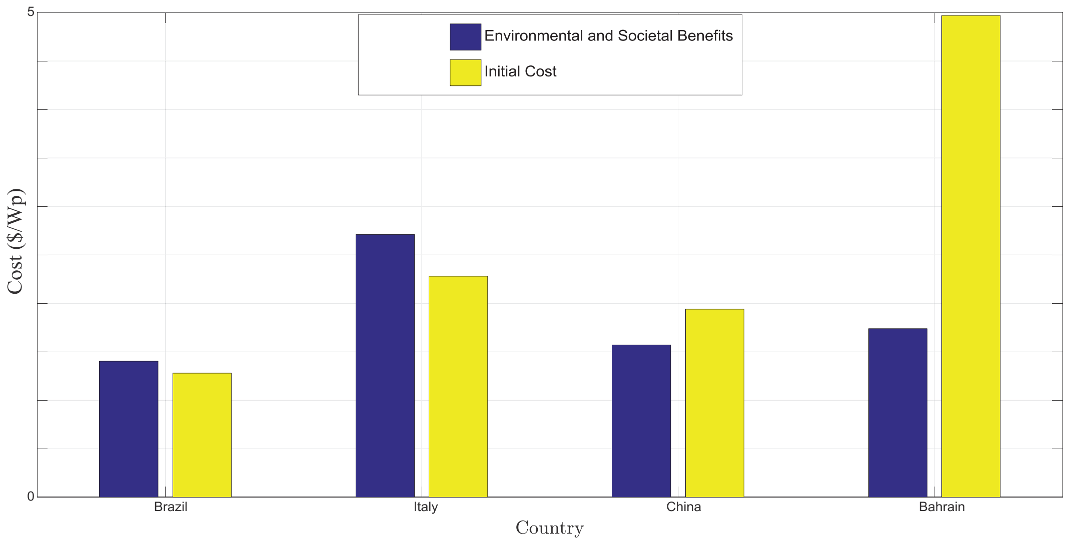


Fig. 6. Initial cost (PIC) and NPV of societal and environmental advantages of the BIPV system.

BIPV system is still unfeasible there despite the highest solar radiation potential among case studies. The reason is, as mentioned earlier, low electricity tariff as well as the irrational initial cost for the implemented BIPV system. While the electricity tariff is quite low in China, because of high CSCCs as well as high carbon emission per kWh, the NPV of the societal and environmental advantages of BIPV system in China is 1.570 USD per watt peak. Moreover, Brazil with the NPV of 1.403 USD per watt peak is the last country which is because of its better situation in carbon emission in electricity generation and CSCCs rate.

Fig. 6 compares the initial cost of BIPV system per watt peak with the NPV of the societal and environmental benefits of the system during its 30-year life cycle. The calculation showed that in Italy, the NPV of the societal and environmental advantages of the system could completely cover the required initial cost of the BIPV system installation. It means that after installation of the system and taking the societal and environmental advantages of the system into account, the BIPV owner has a generator on his/her building envelope which produces electrical power without any initial cost. For China and Brazil, it covers a significant part of the capital expenditure, and for Bahrain, it covers 34% of the initial cost.

4. Conclusions

In this paper, an innovative approach is presented in order to calculate the NPV and DPP of BIPV systems in recent case studies considering the environmental and societal consequences of the system. The considered factors in this study are the societal cost of carbon, the transmission line loss, the transmission line cost, and the equivalent material cost. The simulation showed that the NPV value of environmental and societal advantages for the studied countries could vary from 1.403 USD per watt peak to even 2.710 USD per watt peak depending on the values of the examined factors for each case study. This method can be applied to other countries in order to calculate the real NPV and DPP of the BIPV system. The suggested method showed the economic feasibility of all the case studies, but, the DPP of BIPV system in Bahrain was again more than its life cycle because of the low electricity tariff and the high initial cost of BIPV system per watt peak. Moreover, the suggested method brought the DPP of BIPV system in China to 20 years while it was more than the life cycle of the system by the traditional method. The NPV of societal and environmental advantages of the BIPV system has its highest value for Italy according to the simulation, which was because of the high electricity tariff in Italy.

All in all, the presented strategy could not only expectantly guide the end user to decide more conscious about the consequences of BIPV system implementation but also steer governments or decision-makers to support the technology by rational subsidies and incentives. In this manner, the paper accomplishes a detailed study of the societal and environmental consequences of BIPV systems in an urban area.

Declaration of Competing Interest

We wish to confirm that there are no know conflict of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Acknowledgment

The work reported in this paper was supported by the Department of Safety, Economics, and Planning (ISØP) of the University of Stavanger (Project name: Building Integrated Photovoltaic BIPV) in dense urban areas, Project number: IN-12011). The authors would like to offer their gratitude to prof. Petter Osmundsen from the Department of Safety, Economics, and Planning (ISØP) of the University of Stavanger for his valuable suggestions related to this work.

References

[1] International Energy Agency, Key World Energy Trends. Excerpt from: World Energy Balances, International Energy Agency, Paris, France, 2016.
[2] H. Gholami, A. Khalilnejad, G. Gharehpetian, Electrothermal performance and environmental effects of optimal photovoltaic–thermal system, Energy Convers. Manag. 95 (2015) 326–333.
[3] T. Zhang, M. Wang, H. Yang, A review of the energy performance and life-cycle assessment of building-integrated photovoltaic (BIPV) systems, Energies 11 (11) (2018) 3157.
[4] B.P. Jelle, C. Breivik, H.D. Røkenes, Building integrated photovoltaic products: a state-of-the-art review and future research opportunities, Solar Energy Mater. Solar Cells 100 (2012) 69–96.
[5] G.P. Hammond, H.A. Harajli, C.I. Jones, A.B. Winnett, Whole systems appraisal of a UK building integrated photovoltaic (BIPV) system: energy, environmental, and economic evaluations, Energy Policy 40 (2012) 219–230.
[6] F. Azadian, M. Radzi, A general approach toward building integrated photovoltaic systems and its implementation barriers: a review, Renew. Sustain. Energy Rev. 22 (2013) 527–538.
[7] I. Cerón, E. Caamaño-Martín, F.J. Neila, State-of-the-art of building integrated photovoltaic products, Renew. Energy 58 (2013) 127–133.
[8] C. Peng, Y. Huang, Z. Wu, Building-integrated photovoltaics (BIPV) in architectural design in China, Energy Build. 43 (12) (2011) 3592–3598.
[9] P.X.W. Zou, R.J. Yang, Building integrated photovoltaics (BIPV): costs, benefits, risks, barriers and improvement strategy, Int. J. Constr. Manag. 16 (1) (2015) 39–53.
[10] R. Wilson, A. Young, The embodied energy payback period of photovoltaic installations applied to buildings in the UK, Build. Environ. 31 (4) (1996) 299–305.
[11] A.K. Shukla, K. Sudhakar, P. Baredar, Recent advancement in BIPV product technologies: a review, Energy Build. 140 (2017) 188–195.
[12] E. Saretta, P. Caputo, F. Frontini, A review study about energy renovation of building facades with BIPV in urban environment, Sustain. Cities Soc. 44 (2018) 343–355.
[13] A. Vulkan, I. Kloog, M. Dorman, E. Erell, Modeling the potential for PV installation in residential buildings in dense urban areas, Energy Build. 169 (2018) 97–109.
[14] M. Sorgato, K. Schneider, R. Rüther, Technical and economic evaluation of thin-film CDTE building-integrated photovoltaics (BIPV) replacing façade and rooftop materials in office buildings in a warm and sunny climate, Renew. Energy 118 (2018) 84–98.
[15] M. Brito, P. Redweik, C. Catita, Photovoltaics and zero energy buildings: the role of building facades, présenté à Twenty-Eighth European Photovoltaic Solar Energy Conference and Exhibition, 2013.
[16] M. Chiu, S. Hou, C. Tzeng, C. Lai, Experimental investigations on the thermal performance of the ventilated BIPV wall, J. Appl. Sci. 15 (3) (2015) 613–618.
[17] N. Sánchez-Pantoja, R. Vidal, M.C. Pastor, and society, Aesthetic perception of photovoltaic integration within new proposals for ecological architecture, Sustain. Cities 39 (2018) 203–214.
[18] T. Hong, C. Koo, J. Oh, K. Jeong, Nonlinearity analysis of the shading effect on the technical–economic performance of the building-integrated photovoltaic blind, Appl. Energy 194 (2017) 467–480.
[19] N. Jakica, State-of-the-art review of solar design tools and methods for assessing daylighting and solar potential for building-integrated photovoltaics, Renew. Sustain. Energy Rev. 81 (2018) 1296–1328.
[20] D. Attoye, K. Tabet Aoul, A. Hassan, A review on building integrated photovoltaic façade customization potentials, Sustainability 9 (12) (2017) 2287.
[21] M. Tripathy, P. Sadhu, S. Panda, A critical review on building integrated photovoltaic products and their applications, Renew. Sustain. Energy Rev. 61 (2016) 451–465.
[22] A.K. Shukla, K. Sudhakar, P. Baredar, A comprehensive review on design of building integrated photovoltaic system, Energy Build. 128 (2016) 99–110.
[23] C. Zomer, R. Rüther, Simplified method for shading-loss analysis in BIPV systems–part 1: theoretical study, Energy Build. 141 (2017) 69–82.
[24] C. Zomer, R. Rüther, Simplified method for shading-loss analysis in BIPV systems. Part 2: application in case studies, Energy Build. 141 (2017) 83–95.
[25] C. Zomer, A. Nobre, T. Reindl, R. Rüther, Shading analysis for rooftop BIPV embedded in a high-density environment: a case study in Singapore, Energy Build. 121 (2016) 159–164.
[26] A. Sivanandan, BIPV hotspots in the EU, Renew. Energy Focus 10 (2) (2009) 54–55.
[27] L. Byrnes, C. Brown, J. Foster, L.D. Wagner, Australian renewable energy policy: barriers and challenges, Renew. Energy 60 (2013) 711–721.
[28] F.J. Osseweijer, L.B. Van Den Hurk, E.J. Teunissen, W.G. van Sark, A comparative review of building integrated photovoltaics ecosystems in selected European countries, Renew. Sustain. Energy Rev. 90 (2018) 1027–1040.
[29] N. Aste, C. Del Pero, F. Leonforte, The first Italian BIPV project case study and long-term performance analysis, Solar Energy 134 (2016) 340–352.
[30] D.C. Jordan, S.R. Kurtz, Photovoltaic degradation rates—an analytical review, Prog. Photovolt. Res. Appl. 21 (1) (2013) 12–29.
[31] W. Wang, et al., Environmental assessments and economic performance of BAPV and BIPV systems in shanghai, Energy Build. 130 (2016) 98–106.
[32] N.W. Alnaser, First smart 8.64kW BIPV in a building in Awali town at Kingdom of Bahrain, Renew. Sustain. Energy Rev. 82 (2018) 205–214.
[33] P. Eiffert, Guidelines for the Economic Evaluation of Building-Integrated Photovoltaic Power Systems, National Renewable Energy Lab., Golden, CO.(US), 2003.
[34] A.F. Antoniolli, A. Montenegro, C.D. Zomer, R. Rüther, Avaliação técnica e econômica entre sistemas fotovoltaicos aplicados a edificações (BAPV) e sistemas idealmente instalados para máxima geração anual, in: Proceedings of the CONGRESSO BRASILEIRO DE ENERGIA SOLAR, 6, 2016, p. 2016.
[35] R. d. S. Benedito, Caracterização da geração distribuída de eletricidade por meio de sistemas fotovoltaicos conectados á rede, no Brasil, sob os aspectos técnico, econômico e regulatorio, Universidade de São Paulo, 2009.
[36] T. Economics, Bahrain Interest Rate March, 2019 [Online]. Available:https://tradingeconomics.com/bahrain/interest-rate.
[37] P.G.I.S. PVGIS, Overview of PVGIS Data Sources and Calculation Methods, 2017 [Online]. Available: http://re.jrc.ec.europa.eu/pvg_static/methods.html .
[38] Sustainable Energy Unit – Kingdom of Bahrain, The Kingdom of Bahrain national energy efficiency action plan (NEEAP)," 2017, [Online]. Available: http://www.seu.gov.bh/wp-content/uploads/2018/04/02_NEEAP_full-report.pdf.
[39] N.J. Sheikh, D.F. Kocaoglu, L. Lutzenhiser, Social and political impacts of renewable energy: literature review, Technol. Forecast. Soc. Change 108 (2016) 102–110.
[40] J. West, I. Bailey, M. Winter, Renewable energy policy and public perceptions of renewable energy: a cultural theory approach, Energy Policy 38 (10) (2010) 5739–5748.
[41] B. Hinkle, D. Kenny, Energy efficiency paying the way: new financing strategies remove first-cost hurdles, CalCEF Innov. White Pap (2010). http://2030districts.org/sites/default/files/atoms/files/Removing%20First-Cost%20Hurdles%20for%20Energy%20Efficiency_CalCEF.pdf.
[42] H. Gholami, A. Sarwat, H. Hosseinian, A. Khalilnejad, Evaluation of optimal dual axis concentrated photovoltaic thermal system with active ventilation using frog leap algorithm, Energy Convers. Manag. 105 (2015) 782–790.
[43] S. Akar, D.A. Akdoğan, Environmental and economic impacts of wave energy: some public policy recommendations for implementation in Turkey, in: Sustainable Development: Concepts, Methodologies, Tools, and Applications, IGI Global, 2018, pp. 1187–1211.
[44] S. Jenniches, Assessing the regional economic impacts of renewable energy sources–a literature review, Renew. Sustain. Energy Rev. 93 (2018) 35–51.
[45] H. Sozer, M. Elnimeiri, Critical factors in reducing the cost of building integrated photovoltaic (BIPV) systems, Archit. Sci. Rev. 50 (2) (2007) 115–121.
[46] L. Lu, H. Yang, Environmental payback time analysis of a roof-mounted building-integrated photovoltaic (BIPV) system in Hong Kong, Appl. Energy 87 (12) (2010) 3625–3631.
[47] G.A. Keoleian, G.M. Lewis, Modeling the life cycle energy and environmental performance of amorphous silicon BIPV roofing in the US, Renew. Energy 28 (2) (2003) 271–293.
[48] G. Evola, G. Margani, Renovation of apartment blocks with BIPV: energy and economic evaluation in temperate climate, Energy Build. 130 (2016) 794–810.
[49] E. Esmailian, H. Gholami, H.N. Røstvik, M.B. Menhaj, A novel method for optimal performance of ships by simultaneous optimisation of hull-propulsion-BIPV systems, Energy Convers. Manag. 197 (2019) 111879.
[50] The World Bank Group, Electric Power Transmission and Distribution Losses (% of output) March 2019, 2019 [Online]. Available: https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS?locations=BR .

[51] T.S. Portal, Electricity Prices For Households in Norway from 2010 to 2016, Semi-Annually March 2019, 2019 [Online]. Available: https://www.statista.com/statistics/643369/electricity-prices-for-households-in-norway/ .
[52] S. Norway, Electricity Balance (MWh) by production, Contents and Month March 2019, 2019 [Online]. Available: https://www.ssb.no/en/statbank/table/08583/tableViewLayout1/ .
[53] The World Bank Group, Electric Power Transmission and Distribution Losses (% of output) of Bahrain, Italy, China and Brazil March 2019, 2019 [Online]. Available: https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS?locations=BH-CN-IT-BR .
[54] International Energy Agency, Global Energy & CO2 Status Report February, 2018 [Online]. Available: https://www.iea.org/geco/electricity/ .
[55] L. Aniti, Today in Energy, 2017, February [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=32812 .
[56] Energy Institute, The Full Cost of Electricity (FCe-) Executive Summary: The Full Cost of Electricity, The University of Texas at Austin, 2018 [Online]. Available: https://energy.utexas.edu/sites/default/files/UTAustin_FCe_Exe_Summary_2018.pdf .
[57] D. Lazos, A. Bruce, The value of commercial BIPV systems in the urban environment, in: Proceedings of the Australian Solar Council (AuSES) Academic Conference, Melbourne, 2012.
[58] B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer, Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel On Climate Change, Cambridge University Press, Cambridge, UK, 2007 2007.
[59] F. Cucchiella, I. D'adamo, M. Gastaldi, S.L. Koh, Renewable energy options for buildings: performance evaluations of integrated photovoltaic systems, Energy Build. 55 (2012) 208–217.
[60] L. Caripis, J. Peel, L. Godden, R.J. Keenan, Australia's carbon pricing mechanism, Clim. Law 2 (2011) 583.
[61] K. Ricke, L. Drouet, K. Caldeira, M. Tavoni, Country-level social cost of carbon, Nat. Clim. Change 8 (10) (2018) 895.
[62] J. Koinegg, T. Brudermann, A. Posch, M. Mrotzek, Society, "It would be a shame if we did not take advantage of the spirit of the times..." an analysis of prospects and barriers of building integrated photovoltaics, GAIA-Ecol. Perspect. Sci. 22 (1) (2013) 39–45.
[63] M. Oliver, T. Jackson, The evolution of economic and environmental cost for crystalline silicon photovoltaics, Energy Policy 28 (2000) 1011–1021.
[64] A.L.B. Lemos, L. Kauškale, Factors influencing green roof development in Recife, Brazil, Baltic J. Real Estate Econ. Constr. Manag. 5 (1) (2017) 146–159.
[65] Alibaba, Building Roof Construction Cost in China March 2019, 2019 [Online]. Available:https://www.alibaba.com/trade/search?fsb=y&IndexArea=product_en&CatId=&SearchText=building+roof+construction+cost&viewtype=.
[66] Roofy. (2019, March 2019). *The Roofy® catalog / price list* [Online]. Available: http://www.roofy.it/en/index.php.
[67] Alibaba, Building Roof Construction Cost in Bahrain March 2019), 2019 [Online]. Available: https://www.alibaba.com/showroom/bahrain-manufacturer-sandwich-panel-roof-wall.html .
[68] International Organization for Standardization, Environmental Management: Life Cycle Assessment; Principles and Framework, ISO, 2006.
[69] International Organization for Standardization, Environmental Management: Life Cycle Assessment: Requirements and Regulations, ISO, 2006.
[70] U. Eicker, E. Demir, D. Gürlich, Strategies for cost efficient refurbishment and solar energy integration in European case study buildings, Energy Build. 102 (2015) 237–249.
[71] Organization for Economic Co-operation and Development, CO2 from Electricity Generation (g/kWh) of Countries March 2019, 2019 [Online]. Available:http://www.compareyourcountry.org/climate-policies?cr=oecd&lg=en&page=2.

VI. Levelised Cost of Electricity (LCOE) of Building Integrated Photovoltaics (BIPV) in Europe, Rational Feed-In Tariffs and Subsidies

Hassan Gholami [1], Harald Nils Røstvik [2],

Department of Safety, Economics and Planning, University of Stavanger, Stavanger, Norway

[1] PhD Researcher, hassan.gholami@uis.no
[2] Professor, harald.n.rostvik@uis.no

Energies
Volume 14, Issue 9, No. 2531, 28 April 2021

https://doi.org/10.3390/en14092531

energies

Article

Levelised Cost of Electricity (LCOE) of Building Integrated Photovoltaics (BIPV) in Europe, Rational Feed-In Tariffs and Subsidies

Hassan Gholami * and Harald Nils Røstvik

City- and Regional Planning Group, Institute of Safety, Economics and Planning (ISØP), Faculty of Science and Technology, University of Stavanger, 4021 Stavanger, Norway; harald.n.rostvik@uis.no
* Correspondence: hassan.gholami@uis.no or gholami.hassan.kh@gmail.com; Tel.: +47-51833037

Abstract: Building integrated photovoltaics is one of the key technologies when it comes to electricity generation in buildings, districts or urban areas. However, the potential of building façades for the BIPV system, especially in urban areas, is often neglected. Façade-mounted building integrated photovoltaics could contribute to supply the energy demand of buildings in dense urban areas with economic feasibility where the availability of suitable rooftop areas is low. This paper deals with the levelised cost of electricity (LCOE) of building integrated photovoltaic systems (BIPV) in the capitals of all the European member state countries plus Norway and Switzerland and presents a metric to investigate a proper subsidy or incentive for BIPV systems. The results showed that the average LCOE of the BIPV system as a building envelope material for the entire outer skin of buildings in Europe is equal to 0.09 Euro per kWh if its role as the power generator is considered in the economic calculations. This value will be 0.15 Euro per kWh if the cost corresponding to its double function in the building is taken into the economic analysis (while the average electricity price is 0.18 Euro per kWh). The results indicate that the BIPV generation cost in most case studies has already reached grid parity. Furthermore, the analysis reveals that on average in Europe, the BIPV system does not need a feed-in tariff if the selling price to the grid is equal to the purchasing price from the grid. Various incentive plans based on the buying/selling price of electricity from/to the main grid together with LCOE of the BIPV systems is also investigated.

Keywords: building integrated photovoltaics; BIPV; levelised cost of electricity; LCOE; solar energy potential; building skins; building envelope materials; net present value; NPV

Citation: Gholami, H.; Nils Røstvik, H. Levelised Cost of Electricity (LCOE) of Building Integrated Photovoltaics (BIPV) in Europe, Rational Feed-In Tariffs and Subsidies. *Energies* **2021**, *14*, 2531. https://doi.org/10.3390/en14092531

Academic Editors: Nazmi Sellami, Firdaus Muhammad-Sukki and Walid Issa

Received: 4 April 2021
Accepted: 27 April 2021
Published: 28 April 2021

1. Introduction

A transition from fossil-based electricity production towards renewable-based energy production options is one of the critical metrics for reducing GHG emissions. Solar energy has recently received considerable attention as a feasible solution to facilitate and accelerate shifting toward such a goal. Solar energy could be harnessed by employing various technologies and methods [1]. Among the options, photovoltaic (PV) technology is the fastest-growing technology, leading to a sharp cost reduction and demand expansion of PV systems [2]. Therefore, it is crucial to precisely calculate solar PV electricity production cost and compare it with alternative energy sources. In this sense, the maximum power point tracking issue is also prominent [3]. PV system can be categorised and classified based on various approaches. One of them that has arisen significant attention recently is building integrated PV (BIPV) systems.

A BIPV is a photovoltaic system performing as the outer skin of a building [4]. Such a system keeps general specification of the building envelope materials, e.g., structural strength, weather and noise protection, insulation, etc. [5,6]. They can be categorised based on their type in the market, technology, connection to the grid and application [5,7]. Their application is not limited to buildings, and they can be employed by ships as an example [8].

By choosing the BIPV system for the building skins, the produced electricity by the system would be a clean energy resource to be consumed by the end-users where and when it is needed. This means less pressure on the development and expansion of the giant power transmission lines, and consequently, less transmission line lost power.

Concerning building skins, buildings play a vital role in the energy efficiency of urban areas since they are responsible for a significant percentage of the energy demand of such areas [9,10]. The remarkable radiation potential on the building skins in different climates is already explored [11]. In Europe, building energy use accounts for 41% of the total energy consumption of the cities [12]. Therefore, a transition to self-energy consumption buildings in cities is a prominent course of action toward nearly zero-energy cities. Urban energy transition (UET) has been recently come about to intensifying the endeavour towards promoting distributed generation (DG) and realign the energy production and consumption of buildings [13]. One of the leading solutions which can be of great assistance to reach such a goal is the energy prosumer notion [14]. Prosumers are consumers who can, because of their energy production capacity and by virtue of the regulatory conditions of the market and power systems, export their surpass energy to the distribution grid. BIPV is a convenient approach to proceed toward changing buildings role from energy consumers to energy prosumers.

Furthermore, the business model of building integrated photovoltaics (BIPV) is developing expeditiously. BIPV will soon be acknowledged as a building envelope material for the entire building skins, among other alternatives brick, wood, stone, metals, etc. [5,7]. In the new business model and among other things, in order to keep the uniformity of the building skin (similar to when the building skin is stone or glass), the BIPV could be employed as a building envelope material for all orientations of building skins. Therefore, the economic analysis will be carried out based on the average potential of the building skin. More explanation and logic behind this hypothesis can be found in this study [5].

Levelised cost of electricity (LCOE) is an approach to formulate and calculate the unit cost of electricity (kWh or MWh) over the economic life or full life of a project [15]. LCOE is a widely used metric among policymakers, investors, project managers, and researchers to evaluate the competitiveness and feasibility of different technologies and make decisions on whether to invest in specific renewable energy projects or not [16,17]. Furthermore, policymakers and authorities could set renewable energy policies by means of the LCOE approach. Authorities generally rely on LCOE to delineate support plans for renewable-based electricity generation technology against carbon-based electricity generation technology [18].

When it comes to the economic feasibility of BIPV or rational subsidy and incentive plans, LCOE is a great asset to evaluate the unit cost of electricity production by this technology. LCOE is used here as a metric to compare alternative sources of energy [19,20]. If the LCOE of BIPV is lower than the grid price, the project investment is concluded to be profitable and otherwise not. When the LCOE of BIPV is equal to the grid price, it is often referred to as "grid parity", which means the energy can be generated or delivered to the grid at the same cost as it can be purchased.

The regulators and policymakers generally apply different approaches and plan to promote the BIPV technology and encourage citizens to use the technology by helping them to make the system financially viable. Some measures that the European countries have taken to facilitate the transition from consumers to prosumers by means in cities are listed here:

Net metering [21], where the prosumers get a bill based on their power generation and consumption over a period (from days to years). Hence, the prosumer offsets its electricity consumption with renewable energy resources over an entire billing period. It allows the prosumers to use its generated power at a time other than when it is produced. In fact, the prosumers are using the power grid as storage.

Feed-in tariff (FiT) [22], where prosumers are paid a fixed price for the energy they deliver to the power grid. Therefore, prosumers get paid at a rate called FiT for the surplus energy produced at home via renewable energy resources and sent on to the grid.

Export price [23], where a utility and a prosumer will have a power purchase agreement or PPA. It is usually based on a fixed price per kWh.

Network charge, where the prosumers will just pay the network charge for the power they send to the grid and give it back from the grid later. For example, it could be the same as the net metering approach except for paying a charge for using the grid as storage.

Tax exemption [24], where the prosumers will be exempted from energy taxes in the retail price of energy.

Grant Schemes [6], where governments grant a portion of the investments for the installed renewable energy resources to the owner.

When it comes to the literature review of the LCOE of BIPV systems, there is a lack of research in this regard. Several studies have investigated the LCOE of photovoltaics systems [25–30], but none of them investigated the BIPV systems. However, the economic analysis of BIPV systems and their LCOE is different from the PV systems. This is among other factors, because the BIPV system has dual functionality in the building and in addition to its application as a power generator, it also serves as a building envelope material for the building.

Two primary aims of this study are, therefore, to:

- Define, formulate, calculate, and present the LCOE of BIPV as a building envelope material for the European countries.
- Present a metric to determine the rational amount of subsidy or incentive for the BIPV system in the EU countries.

The paper is structured as follows: Section 2 deals with the input parameters of the research. The formulation of the methodology is discussed in Section 3. In Section 4, results are presented and analysed. An investigation is accomplished in Section 5 to evaluate the performance of non-optimal solutions. Finally, the conclusions are drawn in Section 6.

2. Input Parameters

The input parameters and formulation are discussed in this section. The required parameters to calculate LCOE of a BIPV system together with their values are listed here. More explanation of the parameters can be found on [5,6].

- Operation and maintenance (O&M) cost: 0.5% of the initial investment in Europe.
- Inverter replacement cost: 10% of the initial investment, to be replaced every 15 years.
- BIPV degradation rate: 0.5%.
- BIPV Lifetime: 30 years.
- Building envelope material cost: 230 Euro per sq.m. for the façade and 130 Euro per sq.m. for the roof.
- Transmission line lost power: see Table 1.
- Power delivery cost: 20% of the grid electricity tariff.
- Societal cost of carbon (SCC): 50 Euro per ton with a growth rate of 4%.
- GHG emission: Table 1, with a mitigation rate of 2.1%.
- Electricity tariff: Table 1, with a growth rate of 2%.
- Discount rate: 3%.
- BIPV efficiency: 16%.
- BIPV initial investment: 450 Euro per sq.m. for facades and 350 Euro per sq.m. for roofs.

Table 1 presents the value of some of these parameters in 2020.

Table 1. Electricity tariffs, GHG and electric power transmission and distribution losses of the European countries.

No	Country	Capital	Transmission Line Lost Power (Percent) [31]	GHG Emission (g/kWh) [32]	Electricity Tariff (Euro/kWh) [33]
1	Austria	Vienna	5%	156	0.20
2	Belgium	Brussels	5%	233	0.29
3	Bulgaria	Sofia	9%	585	0.10
4	Croatia	Zagreb	13%	282	0.13
5	Cyprus	Nikosia	4%	773	0.22
6	Czechia	Prague	5%	587	0.16
7	Denmark	Copenhagen	6%	386	0.31
8	Estonia	Tallinn	7%	1152	0.14
9	Finland	Helsinki	6%	209	0.17
10	France	Paris	4%	92	0.18
11	Germany	Berlin	4%	567	0.30
12	Greece	Athens	4%	755	0.16
13	Hungary	Budapest	12%	368	0.11
14	Ireland	Dublin	8%	555	0.25
15	Italy	Rome	7%	444	0.22
16	Latvia	Riga	9%	185	0.15
17	Lithuania	Vilnius	22%	262	0.11
18	Luxembourg	Luxemburg	6%	283	0.17
19	Malta	Valleta	5%	868	0.13
20	Netherlands	Amsterdam	5%	582	0.17
21	Poland	Warsaw	6%	929	0.14
22	Portugal	Lisbon	10%	355	0.23
23	Romania	Bucharest	11%	413	0.13
24	Slovakia	Bratislava	2%	211	0.15
25	Slovenia	Ljubljana	5%	351	0.16
26	Spain	Madrid	10%	305	0.25
27	Sweden	Stockholm	5%	25	0.20
28	UK	London	8%	584	0.20
29	Norway	Oslo	6%	19	0.19
30	Switzerland	Bern	7%	37	0.17

3. Formulation

In this section, NPV_I, NPV_C and E_G, which are BIPV net present value of incomes, BIPV net present value of costs, and BIPV total electricity production, are discussed and formulated.

3.1. System Income

The income and benefits of the system are, saving in building envelope material cost, transmission line lost power, power delivery cost, societal cost of carbon and power generation. The NPV_I can, therefore, be calculated as Equation (1):

$$NPV_I = I_{BM} + I_{TR} + I_{PD} + I_{SCC} + I_{EG} \tag{1}$$

I_{BM}, I_{TR}, I_{PD}, I_{SCC}, I_{EG} represent the income from saving in building envelope material cost, transmission line lost power, power delivery cost, societal cost of carbon and power generation, respectively. The quantified value of the saving from transmission line lost power can be calculated as presented in Equation (2):

$$\begin{aligned} I_{TR} = E_{G_1} \times R_{TR} \times NP_1/(1+D_R)^1 + E_{G_2} \times R_{TR} \times NP_2/(1+D_R)^2 + \ldots \\ +E_{G_y} \times R_{TR} \times NP_y/(1+D_R)^y = \sum_{n=1}^{y} E_{G_n} \times R_{TR} \times NP_n/(1+D_R)^n \end{aligned} \tag{2}$$

E_G, R_{TR}, NP, D_R, n and y represent annual energy generation, the ratio of transmission line lost power, power grid price, discount rate, the number of the year and BIPV lifespan, respectively. The quantified value of the system due to the saving in the power delivery cost is calculatable as follows in Equation (3):

$$\begin{aligned} I_{PD} &= E_{G_1} \times R_{PD} \times NP_1/(1+D_R)^1 + E_{G_2} \times R_{PD} \times NP_2/(1+D_R)^2 + \ldots \\ &+ E_{G_y} \times R_{PD} \times NP_y/(1+D_R)^y = \sum_{n=1}^{y} E_{G_n} \times R_{PD} \times NP_n/(1+D_R)^n \end{aligned} \tag{3}$$

R_{PD} stands for the saving ratio in power delivery cost. The saving from carbon taxing is also presented in Equation (4):

$$\begin{aligned} I_{SCC} &= E_{G_1} \times R_{GHG_1} \times CP_1/(1+D_R)^1 + E_{G_2} \times R_{GHG_2} \times CP_2/(1+D_R)^2 + \ldots \\ &+ E_{G_y} \times R_{GHG_y} \times CP_y/(1+D_R)^y = \sum_{n=1}^{y} E_{G_n} \times R_{GHG_n} \times CP_n/(1+D_R)^n \end{aligned} \tag{4}$$

R_{GHG} and CP stand for the average GHG emission and societal cost of carbon, respectively. The income from system electricity generation is formulated, as shown in Equation (5):

$$\begin{aligned} I_{EG} &= E_{G_1} \times NP_1/(1+D_R)^1 + E_{G_2} \times NP_2/(1+D_R)^2 + \ldots \\ &+ E_{G_y} \times NP_y/(1+D_R)^y = \sum_{n=1}^{y} E_{G_n} \times NP_n/(1+D_R)^n \end{aligned} \tag{5}$$

The values of NP, CP, EG, and R_{GHG} associated with the nth year of the BIPV system is calculatable as presented in Equations (6)–(9):

$$NP_n = NP_1 \times (1+R_{NP})^n \tag{6}$$

$$CP_n = CP_1 \times (1+R_{CP})^n \tag{7}$$

$$EG_n = EG_1 \times (1-R_{EG})^n \tag{8}$$

$$R_{GHG_n} = R_{GHG_1} \times (1-R_{GH})^n \tag{9}$$

R_{NP}, R_{CP}, R_{EG} and R_{GH} are abbreviations for electricity tariff growth ratio, societal cost of carbon growth ratio, BIPV degradation ratio and GHG mitigation ratio, respectively. Finally, the NPV of the incomes can be determined as shown in Equation (10):

$$\begin{aligned} NPV_I &= I_{BM} \\ &+ \sum_{n=1}^{y} \left(EG_1 \times (1-R_{EG})^n\right) \times R_{TR} \times \left(\left(NP_1 \times (1+R_{NP})^n\right)/(1+D_R)^n\right) \\ &+ \sum_{n=1}^{y} \left(EG_1 \times (1-R_{EG})^n\right) \times R_{PD} \times \left(\left(NP_1 \times (1+R_{NP})^n\right)/(1+D_R)^n\right) \\ &+ \sum_{n=1}^{y} \left(EG_1 \times (1-R_{EG})^n\right) \times \left(R_{GHG_1} \times (1-R_{GH})^n\right) \times \left(\left(CP_1 \times (1+R_{CP})^n\right)/(1+D_R)^n\right) \\ &+ \sum_{n=1}^{y} \left(EG_1 \times (1-R_{EG})^n\right) \times \left(\left(NP_1 \times (1+R_{NP})^n\right)/(1+D_R)^n\right) \end{aligned} \tag{10}$$

3.2. System Cost

The cost of the system is the investment, operation and maintenance and inverter replacement cost. Therefore, NPV_C can be formulated as Equation (11):

$$NPV_C = C_Q + C_{IR} + C_{OM} \tag{11}$$

C_Q, C_{IR} and C_{OM} stand for BIPV initial investment, inverter replacement cost, and operation and maintenance cost, respectively. The inverter replacement cost can be easily calculated, as presented in Equation (12):

$$C_{IR} = C_Q \times 0.1 \tag{12}$$

The NPV of the operation and maintenance cost can be calculated as follows in Equation (13).

$$C_{OM_n} = 0.005 \times C_Q \times 30 \tag{13}$$

Therefore, the NPV of the costs can be determined as shown Equation (14):

$$\begin{aligned} NPV_C &= C_Q \\ &+ C_Q \times 0.1 \\ &+ C_{OM_n} = 0.005 \times C_Q \times 30 \end{aligned} \tag{14}$$

3.3. System Energy Production

The electricity production of BIPV systems naturally degrades over time, and the decrease ratio is called the BIPV degradation rate. Depending on the material, the BIPV degradation rate varies [34]. The total electricity production of the system over its lifespan can be calculated as indicated in Equation (15):

$$\begin{aligned} E_{GT} = EG_1 \times (1 - R_{EG})^1 + EG_1 \times (1 - R_{EG})^2 + \ldots \\ + EG_1 \times (1 - R_{EG})^y = \sum_{n=1}^{y} EG_1 \times (1 - R_{EG})^n \end{aligned} \tag{15}$$

where E_{G1} can be calculated as follows:

$$E_{G1} = G_{BS} \times BIPV_{EFF} \tag{16}$$

$BIPV_{EFF}$ represents the average efficiency of the BIPV system. G_{BS} represents the average incident solar radiation on the building skins of the capital of the investigated countries [5,35].

3.4. LCOE Formulation

LCOE, as mentioned in the introduction, is a term that stands for the cost of the power per kWh produced by the BIPV systems over the lifetime of the system, which is 30 years in this study. It can be calculated by Equation (17):

$$\text{LCOE} = NPV_C / E_{GT} \tag{17}$$

NPV_C, NPV_I, and E_{GT} represent net present value of the costs of the system over its lifetime, net present value of the incomes of the system over its lifetime and total electricity generation over its lifetime, respectively.

4. Results

The analysis was carried out using Microsoft Excel, and the dataset is publicly available and attached to this paper as a supplementary file. The starting date for the system evaluation is the beginning of 2020.

Figure 1 indicates the average incident solar radiation on the building skins (*GBS*) of the capital of the countries. *BS* stands for building skin and is the average value of building orientations (south, north, east, west and roof) for the discussed parameter. In other words, *BS* is a metric to evaluate the feasibility and suitability of BIPV systems as a building envelope material for the entire building skins in Europe. When it comes to appropriate feed-in tariff or subsidy for the BIPV system in Europe, the economic analysis of the entire building skin as an average of skin orientations is a useful tool to design and introduce rational incentives. The annual radiation on building skins varies from 631 kWh per sq.m. in Finland to 1138 kWh per sq.m. in Cyprus, with an average of 806 for the EU.

The primary raw data is taken from the Photovoltaic Geographical Information System (PVGIS) database [35]. The analysis and calculated amounts are based on the average hourly incident radiation data between 2005 and 2016 from the PVGIS (SARAH Solar Radiation Data) [35]. The secondary data is based on the analysis as explained.

Figure 2 depicts the lifetime electricity production of the BIPV system (E_{GT}) as a building envelope material for the skins of the buildings in the EU countries. The total production is between 2819 kWh per sq.m. (in Finland) and 5084 kWh per sq.m. (in Cyprus). The average production for the EU is 3601 kWh per sq.m.

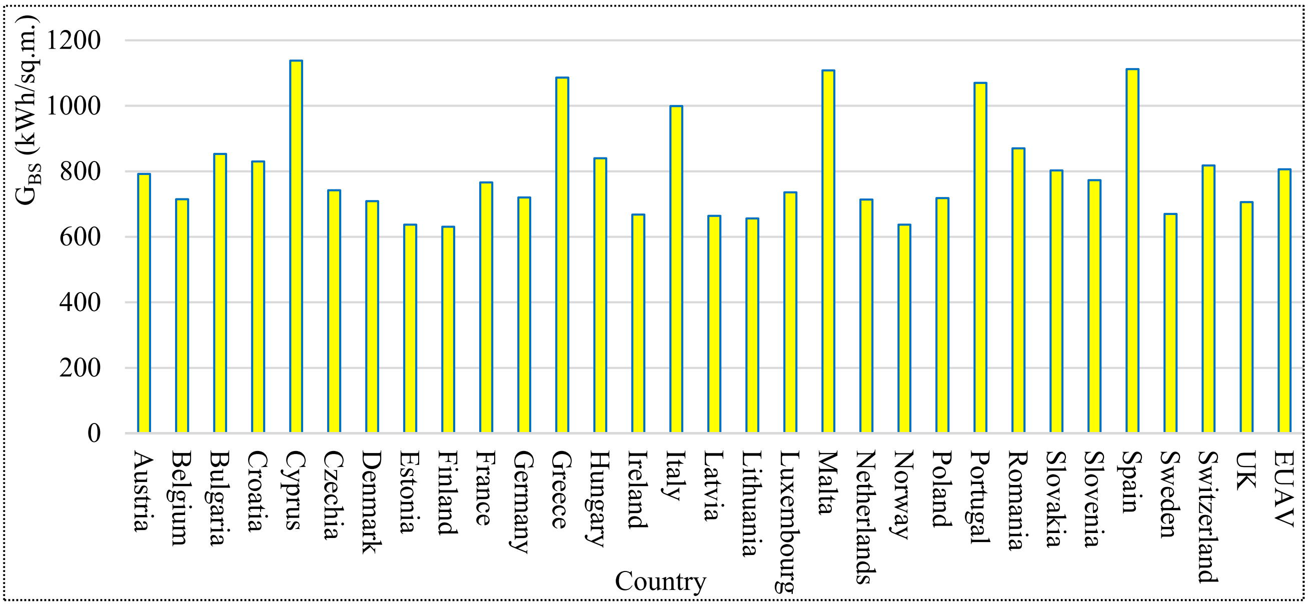


Figure 1. Average incident solar radiation on the building skins (G_{BS}) of the capital of the investigated countries.

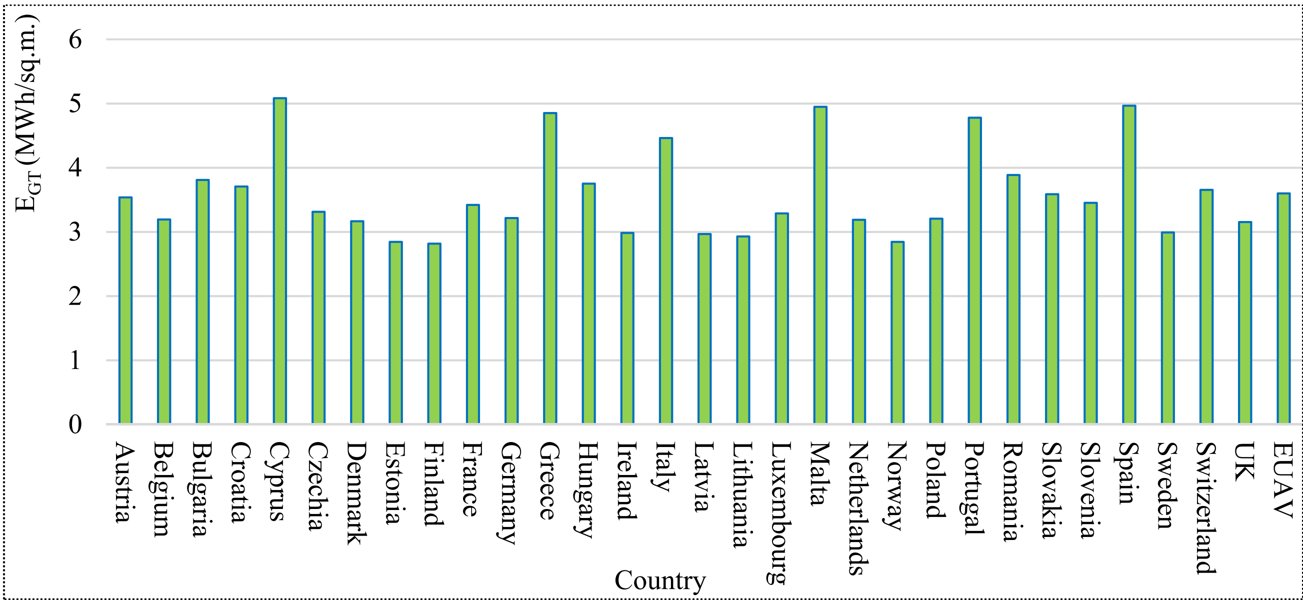


Figure 2. Lifetime electricity production of the BIPV system (E_{GT}) as building envelope material.

Table 2 illustrates the results of the analysis for the LCOE calculation. The analysis is carried out for the BIPV system as a building envelope material for the entire building skins. As can be seen from Table 2, in average in Europe, from each square meter of BIPV system as a building envelope material, 578 € income will be earned out of 3601 kWh electricity production of the system while the total cost is equal to 535 €.

Figure 3 illustrates the breakdown of the average income and the average cost for BIPV systems in the EU.

The LCOE analysis and allocated subsidy can be calculated and defined based on different points of views and approaches. They are discussed here in detail based on different scenarios.

Table 2. System financial analysis in Europe.

Country	I_{BM} (€/sq.m.)	I_{TR} (€/sq.m.)	I_{PD} (€/sq.m.)	I_{SCC} (€/sq.m.)	I_{EG} (€/sq.m.)	C_Q (€/sq.m.)	C_{IR} (€/sq.m.)	COM (€/sq.m.)	NP (€/kWh)
Austria	210	7	30	7	623	430	43	65	0.20
Belgium	210	10	39	9	821	430	43	65	0.29
Bulgaria	210	7	16	27	335	430	43	65	0.10
Croatia	210	13	20	12	429	430	43	65	0.13
Cyprus	210	9	46	47	971	430	43	65	0.22
Czechia	210	5	22	23	460	430	43	65	0.16
Denmark	210	12	41	15	866	430	43	65	0.31
Estonia	210	6	17	39	353	430	43	65	0.14
Finland	210	6	20	7	419	430	43	65	0.17
France	210	5	26	4	539	430	43	65	0.18
Germany	210	8	40	22	845	430	43	65	0.30
Greece	210	7	33	44	699	430	43	65	0.16
Hungary	210	10	17	16	367	430	43	65	0.11
Ireland	210	13	31	20	663	430	43	65	0.25
Italy	210	14	40	24	844	430	43	65	0.22
Latvia	210	8	19	7	392	430	43	65	0.15
Lithuania	210	15	13	9	281	430	43	65	0.11
Luxembourg	210	7	23	11	487	430	43	65	0.17
Malta	210	7	27	51	566	430	43	65	0.13
Netherlands	210	6	23	22	477	430	43	65	0.17
Norway	210	7	22	1	475	430	43	65	0.19
Poland	210	6	19	36	392	430	43	65	0.14
Portugal	210	23	45	20	959	430	43	65	0.23
Romania	210	12	21	19	448	430	43	65	0.13
Slovakia	210	2	22	9	459	430	43	65	0.15
Slovenia	210	6	23	14	495	430	43	65	0.16
Spain	210	25	51	18	1077	430	43	65	0.25
Sweden	210	6	25	1	521	430	43	65	0.20
Switzerland	210	9	25	2	530	430	43	65	0.17
UK	210	11	26	22	559	430	43	65	0.20
EU_{AV}	210	9	27	19	578	430	43	65	0.18

4.1. Scenario 1

This scenario discusses the traditional approach of analysis, where the investment is the net present value of the total cost (NPV_C). Figure 4 illustrates the electricity price of the grid and LCOE of BIPV as a building envelope material for the entire building.

As can be seen from the Figure 4, the LCOE in Bulgaria, Croatia, Czechia, Estonia, Finland, Hungary, Latvia, Lithuania, Netherlands, Norway, Poland, Romania and Slovakia is more than the network price in this scenario and in order to make the BIPV system economically feasible, a FiT rate is required (generally equal to the difference of NP and LCOE plus NP, in order to reach the grid parity). Furthermore, the analysis unfolds that on average in Europe, the BIPV system does not need a feed-in tariff if the selling price to the grid is equal to the purchasing price from the grid. This is investigated more later in this section.

4.2. Scenario 2

The scenario deals with the LCOE related to the total cost of the system associated with the BIPV system functionality as a power generator and not as a building envelope material. In other words, the hypothesis in this scenario is that the BIPV system is a substitute for other building skins materials and the cost associated to this application should not be taken into consideration when it comes to economic feasibility (because such an approach is irrational for alternative building envelope materials such as stone, wood, glass etc.). Therefore, the cost of the BIPV system must split between its applications on the building skins (as the building skin and the power generator). That fraction of the investment, which is related to the role of BIPV systems as a power generator, has been taken into consideration in the LCOE analysis of this scenario. Figure 5 represents the LCOE of this scenario in comparison with the grid price.

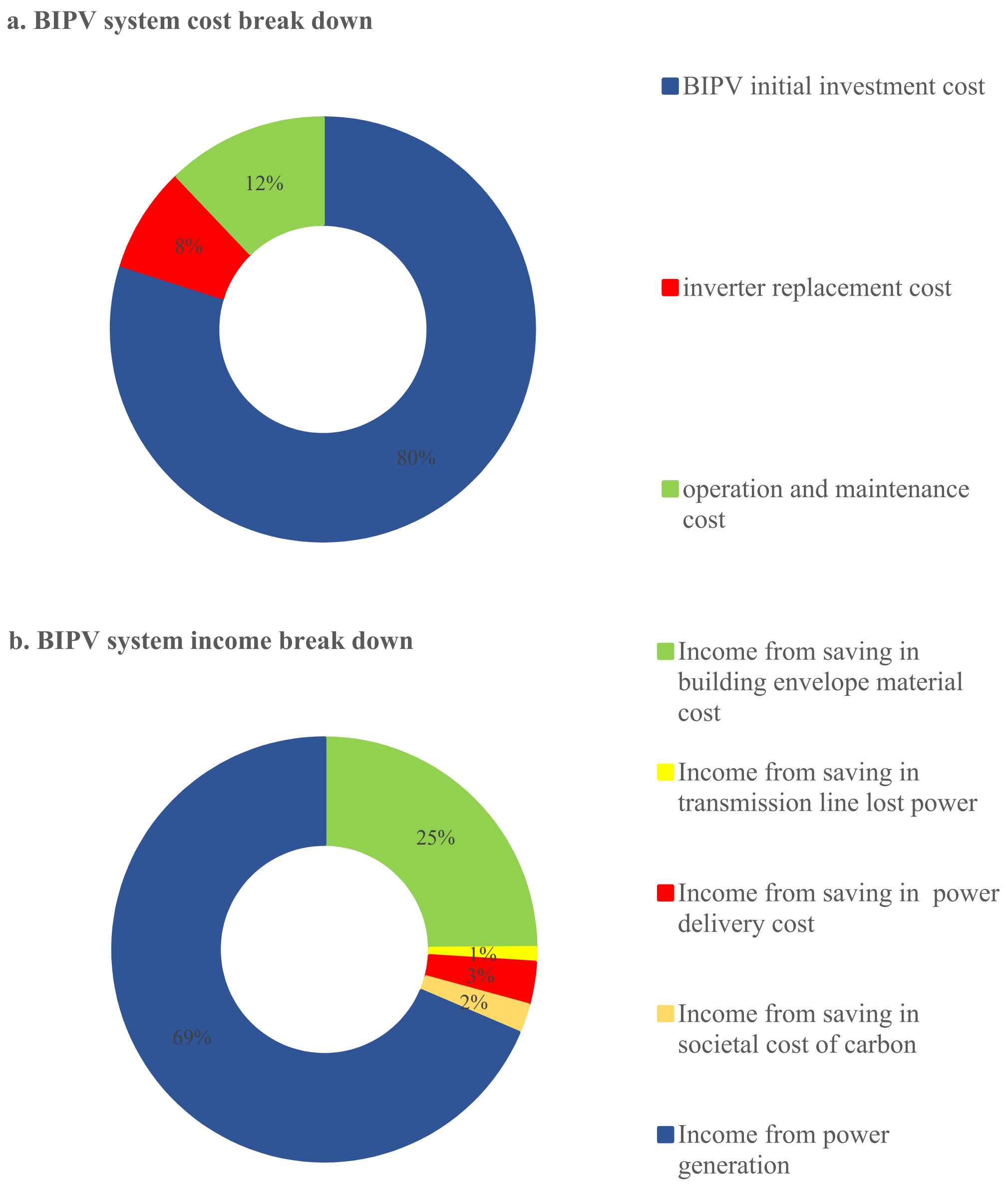


Figure 3. BIPV system cost and income break down in Europe.

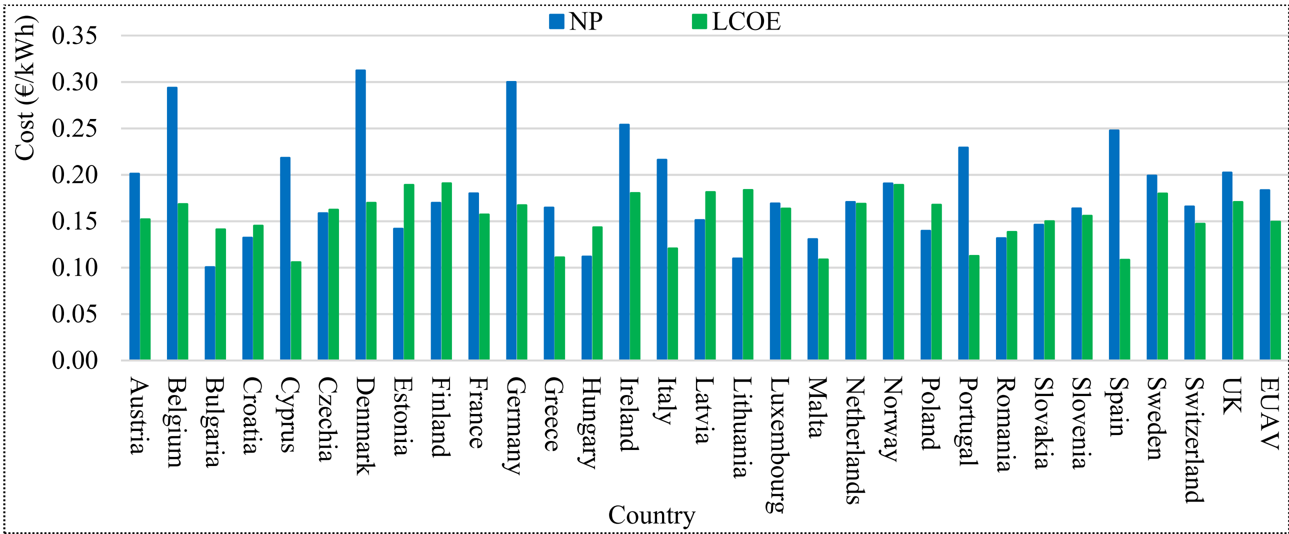


Figure 4. NP and LCOE in Scenario 1.

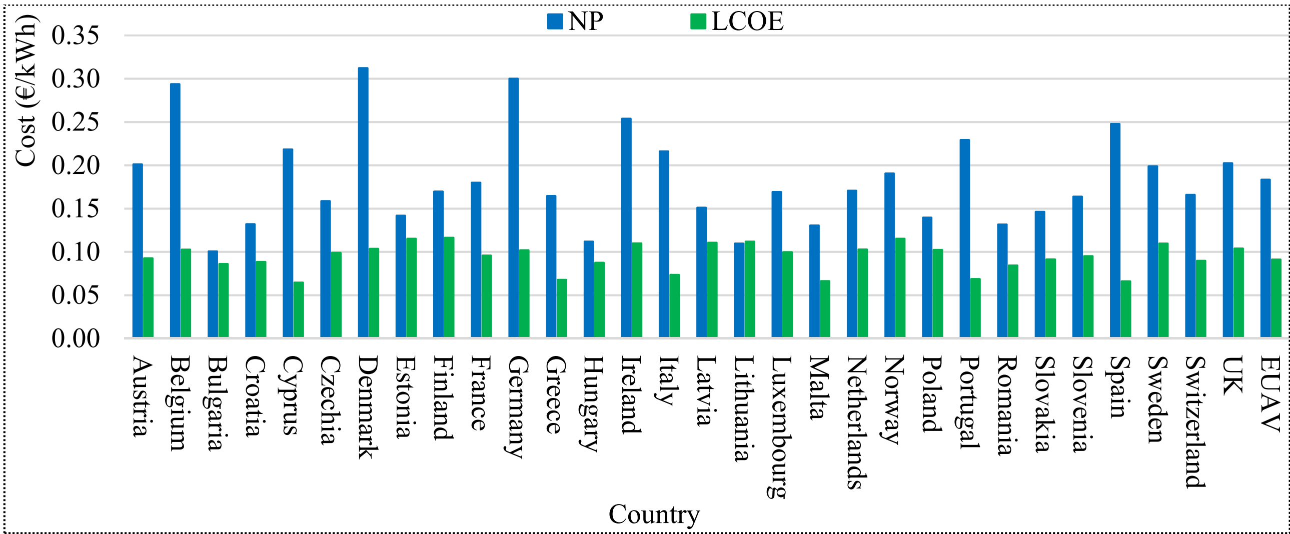


Figure 5. NP and LCOE in Scenario 2.

The result indicates that LCOE of BIPV system as a building envelope material for the entire outer skin of the buildings in all the locations is always less than the grid price if the investment related to the power generation task is taken into the analysis. The average LCOE for the EU (0.09 (€/kWh)) in this scenario is half of the average grid price in EU (0.18 (€/kWh)).

Although BIPV technology has reached the grid parity in almost all of the investigated countries, what is critical is the question that whether the local grid is willing to buy the electricity at the same price that sells it to the end-user or not. The answer to this question has a remarkable effect on the proper designing of subsidy for this technology. Answering such a question results in three different situations:

- If the grid is obliged to buy the surplus generated electricity of the BIPV from end-user at the same price that sells it to the end-user, then the technology is already mature in EU as figure shows and there is no need for additional incentive.
- If the buying price of the grid is less than its selling price but still more than the calculated LCOE, then the system is still profitable, and no subsidy is needed to make the system economically viable.

- If the buying price of the grid is even less than the calculated LCOE, then the end-user needs to either consume all the generated power of the BIPV system or receive an appropriate subsidy (normally equal to the difference between LCOE and buying price of the grid) in order to make the investment profitable.

The amount of rational subsidy, therefore, depends on the network price, LCOE and the price that the grid buy the surplus electricity generated by the BIPV system. Another approach to grant incentives to the BIPV technology is to reimburse the quantified environmental benefits of the system to the owner, which in this study are transmission line lost power, power delivery cost and societal cost of carbon (SCC). This can be allocated either in a FiT plan or a support package during the system implementation.

The levelised profit of environmental benefits (*LPOE*) of the BIPV system can be calculated as follows:

$$LPOE = NPV_E/E = (I_{TR} + I_{PD} + I_{SCC})/E_{GT} \tag{18}$$

Figures 6 and 7 illustrate the *LPOE* and NPV_E for the investigated sites. As can be seen from the figures, *LPOE* in the EU varies from 0.09 € per kWh in Slovakia to 0.022 € per kWh in Germany and Estonia. The average value for the EU is 0.015 € per kWh.

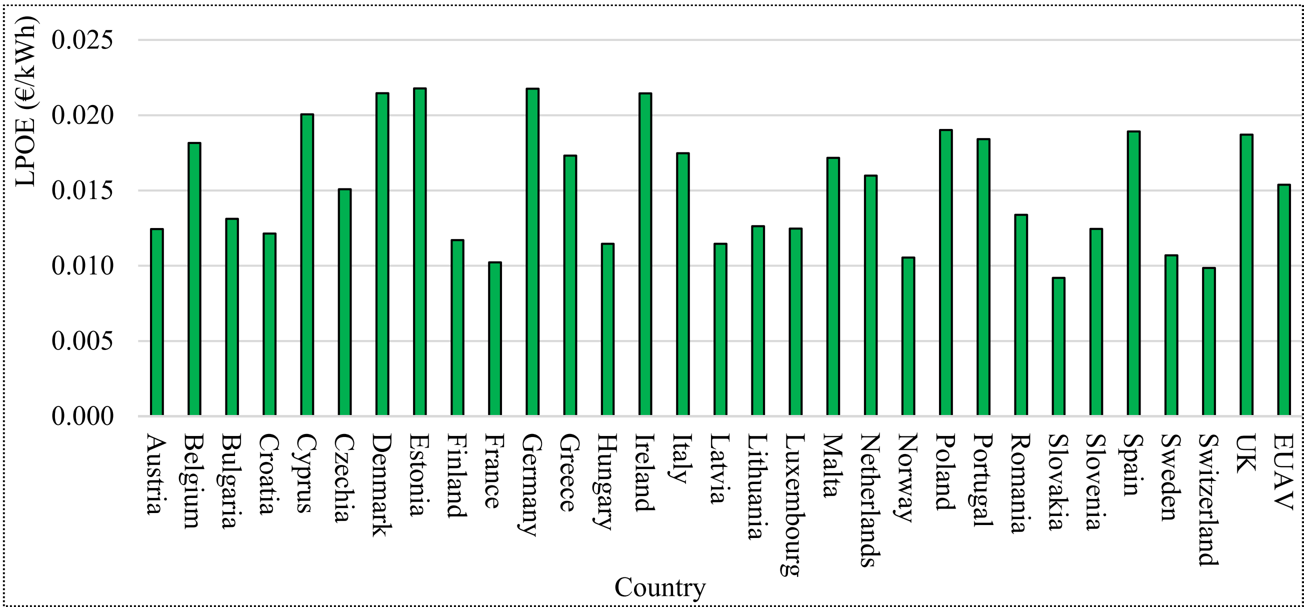


Figure 6. Levelised profit of environmental benefits (LPOE) of the BIPV system.

When it comes to NPV_E in the EU, Norway with a net present value of 30 € per sq.m. has the lowest amount, which is basically because of its low GHG emission in power production (thanks to hydropower production potential) and a quite low lost rate in the power transmission lines. The highest amount belongs to Cyprus because of its relatively high electricity price and GHG emission of its power plants.

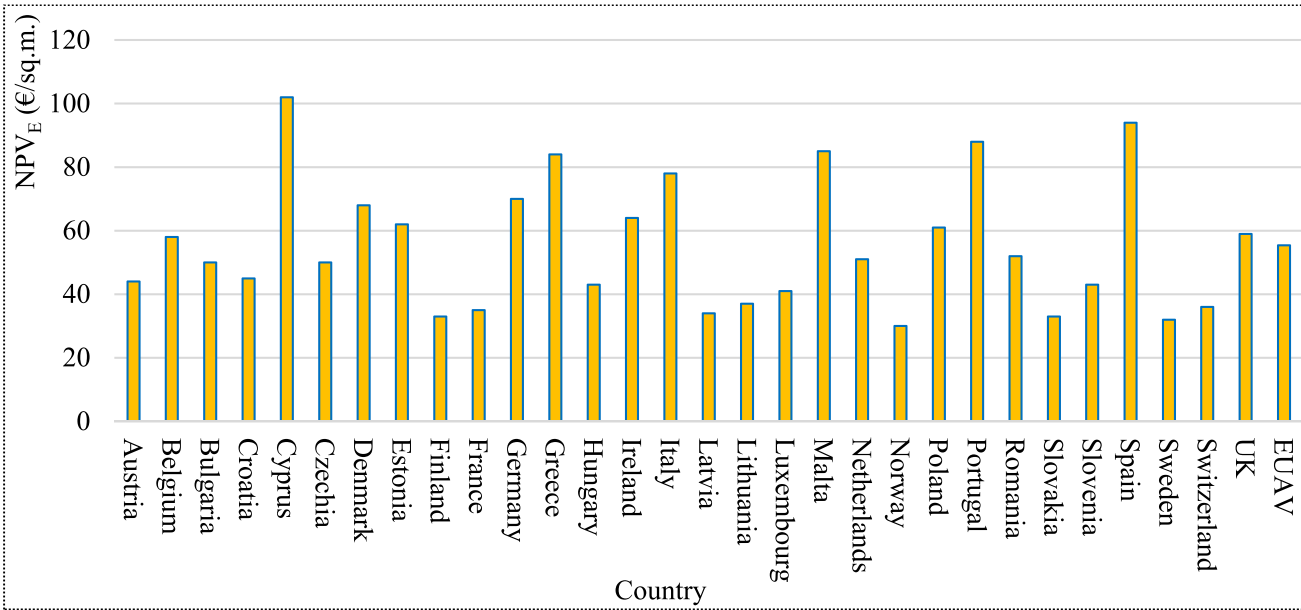


Figure 7. BIPV net present value of environmental benefits.

5. Performance of Non-Optimal Solutions

Some studies from the literature claim a low performance or low efficiency of BIPV systems [36,37]. The lifetime of inverters is also controversial. Although new models in the market offer a warranted lifetime of 15 years, there are still many models in the market with a warranted lifetime of only ten years. Therefore, this section has investigated a scenario for a BIPV system with an efficiency of 10%, a lifetime of 25 years and an inverter replacement requirement for every ten years. The result is depicted in Figure 8, where it can be seen that the non-optimal performance of the BIPV system can significantly change the LCOE analysis and increase it meaningfully. In this case, the average LCOE of BIPV in Europe has been doubled (from 0.15 €/kWh to 0.3 €/kWh). This shows the importance of system design, system component selection and system implementation.

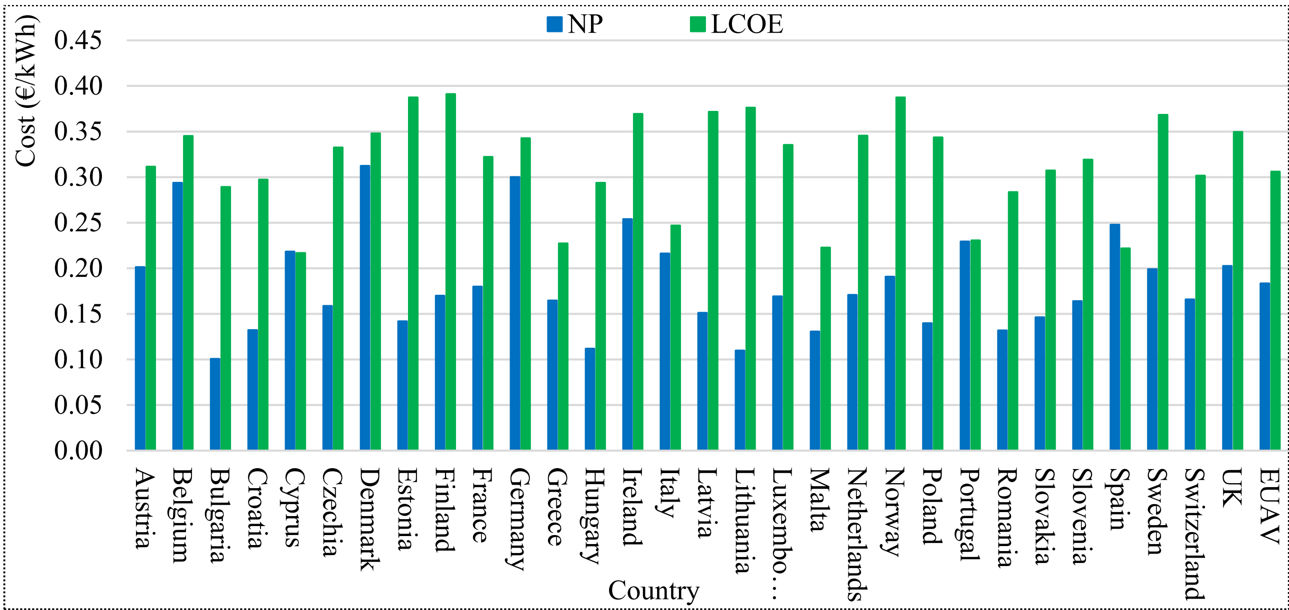


Figure 8. NP and LCOE of a non-optimal solution.

6. Conclusions

The findings from this study make several contributions to the current literature on BIPV technology. First, the study is set out to present a method, calculate and report the LCOE of BIPV systems for the EU countries and, more specifically, the LCOE for the BIPV system as a building envelope material for the outer skin of buildings. Second, the study presents a metric to the EU countries to investigate the current situation of the BIPV and determine whether the technology needs any incentive and subsidy or not by employing the discussed approach in this study.

The investigation revealed that the implementation of BIPV systems as a building envelope material has already passed the grid parity in 29 out of 30 EU countries if the corresponding cost to its role as a power generator is considered in the economic analysis. The only country in which BIPV needs support schemes to reach grid parity is Lithuania.

Moreover, the results showed BIPV systems have passed grid parity in most countries in the EU even when taking the total cost of the BIPV system as the investment into the calculation. In this case, Bulgaria, Croatia, Czechia, Estonia, Finland, Hungary, Latvia, Lithuania, Netherlands, Norway, Poland, Romania and Slovakia need support schemes to help the technology reach grid parity.

The study also illustrated that a non-optimal design of BIPV systems could double the LCOE, which highlights the importance of system design, system component selection, and system implementation.

Although the current study is based on average values and assumptions, the finding presents the underlying part and foundation of further studies regarding the LCOE of BIPV in the EU and the reasonable amount of subsidies or incentives for this technology to drive a faster rollout of BIPV in the EU.

Further work needs to be done to investigate and assess the impact of urban areas (shading, reflection, etc.) and the effect of climate on the system efficiency considering different technologies on the presented analysis.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/en14092531/s1.

Author Contributions: Conceptualization, H.G.; Data curation, H.G.; Formal analysis, H.G.; Funding acquisition, H.G. and H.N.R.; Investigation, H.G.; Methodology, H.G.; Project administration, H.G.; Resources, H.G.; Software, H.G.; Supervision, H.N.R.; Validation, H.G.; Visualization, H.G.; Writing—original draft, H.G.; Writing—review & editing, H.N.R. All authors have read and agreed to the published version of the manuscript.

Funding: The work reported in this paper was supported by the Department of Safety, Economics, and Planning of the University of Stavanger (Project name: Building Integrated Photovoltaic (BIPV) in dense urban areas, Project number: IN-12011).

Acknowledgments: The work reported in this paper was supported by the Department of Safety, Economics, and Planning of the University of Stavanger (Project name: Building Integrated Photovoltaic (BIPV) in dense urban areas, Project number: IN-12011). Special thanks also goes to the Smart City Group and Future Energy Hub at the University of Stavanger for their support.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Abbreviations

		Units
€	Euro	-
BIPV	Building integrated photovoltaics	-
$BIPV_{EFF}$	Efficiency of the BIPV system	%
BIPVT	Building integrated photovoltaic thermal	-
C_{IR}	inverter replacement cost	(€/sq.m.)
C_{OM}	operation and maintenance cost	(€/sq.m.)

CP	Societal cost of carbon	(€/g)
C_Q	BIPV initial investment	(€/sq.m.)
DG	Distributed generation	-
D_R	Discount rate	%
E_G	BIPV total electricity production	(kWh/sq.m.)
FiT	Feed-in tariff	(€/kWh)
G_{BS}	Average incident solar radiation on the building skins	(kWh/sq.m.)
GHG	Greenhaus gas	-
I_{BM}	Income from saving in building envelope material cost	(€/sq.m.)
I_{EG}	Income from power generation	(€/sq.m.)
I_{PD}	Income from saving in power delivery cost	(€/sq.m.)
I_{SCC}	Income from saving in societal cost of carbon	(€/sq.m.)
I_{TR}	Income from saving transmission line lost power	(€/sq.m.)
kWh	Kilowatt-hour	-
LCOE	Levelised cost of electricity	(€/kWh)
LPOE	Levelised profit of environmental benefits	(€/kWh)
MWh	Megawatt-hour	-
n	The number of the year	-
NP	Power grid price	(€/kWh)
NPV_C	BIPV net present value of cost	(€/sq.m.)
NPV_E	BIPV net present value of environmental benefits	(€/sq.m.)
NPV_I	BIPV net present value of incomes	(€/sq.m.)
O&M	Operation and maintenance	-
R_{CP}	Societal cost of carbon growth ratio	%
R_{EG}	BIPV degradation ratio	%
R_{GH}	GHG mitigation ratio	%
R_{GHG}	Average GHG emission	(g/kWh)
R_{NP}	Electricity tariff growth ratio	%
R_{PD}	Saving ratio in power delivery cost	%
R_{TR}	The ratio of transmission line lost power	%
UET	Urban energy transition	-
y	BIPV lifespan	years

References

1. Kabir, E.; Kumar, P.; Kumar, S.; Adelodun, A.A.; Kim, K.-H. Solar energy: Potential and future prospects. *Renew. Sustain. Energy Rev.* **2018**, *82*, 894–900. [CrossRef]
2. Lee, C.-Y.; Ahn, J. Stochastic modeling of the levelized cost of electricity for solar PV. *Energies* **2020**, *13*, 3017. [CrossRef]
3. Ko, J.-S.; Huh, J.-H.; Kim, J.-C. Overview of maximum power point tracking methods for PV system in micro grid. *Electronics* **2020**, *9*, 816. [CrossRef]
4. Gholami, H.; Røstvik, H.N.; Müller-Eie, D. Holistic economic analysis of building integrated photovoltaics (BIPV) system: Case studies evaluation. *Energy Build.* **2019**, *203*, 109461. [CrossRef]
5. Gholami, H.; Røstvik, H.N. Economic analysis of BIPV systems as a building envelope material for building skins in Europe. *Energy* **2020**, *204*, 117931. [CrossRef]
6. Gholami, H.; Nils Røstvik, H.; Manoj Kumar, N.; Chopra, S.S. Lifecycle cost analysis (LCCA) of tailor-made building integrated photovoltaics (BIPV) façade: Solsmaragden case study in Norway. *Solar Energy* **2020**, *211*, 488–502. [CrossRef]
7. Gholami, H.; Nils Røstvik, H. The effect of climate on the solar radiation components on building skins and building integrated photovoltaics (BIPV) materials. *Energies* **2021**, *14*, 1847. [CrossRef]
8. Esmailian, E.; Gholami, H.; Røstvik, H.N.; Menhaj, M.B. A novel method for optimal performance of ships by simultaneous optimisation of hull-propulsion-BIPV systems. *Energy Convers. Manag.* **2019**, *197*, 111879. [CrossRef]
9. Daly, H.; Walton, M. World Energy Outlook 2017. 2017. Available online: https://www.iea.org/reports/world-energy-outlook-2017 (accessed on 1 March 2021).
10. International Renewable Energy Agency. *Renewable Energy in Cities*; International Renewable Agency: Abu Dhabi, United Arab Emirates, 2016.
11. Gholami, H.; Røstvik, H.N.; Müller-Eie, D. Analysis of solar radiation components on building skins for selected cities. In Proceedings of the 14th Conference on Advanced Building Skins, Bern, Switzerland, 28–29 October 2019; Advanced Building Skins (ABS): Bern, Switzerland, 2019; pp. 541–549.
12. Steemers, K. Energy and the city: Density, buildings and transport. *Energy Build.* **2003**, *35*, 3–14. [CrossRef]
13. Villa-Arrieta, M.; Sumper, A. Economic evaluation of nearly zero energy cities. *Appl. Energy* **2019**, *237*, 404–416. [CrossRef]
14. Parag, Y.; Sovacool, B.K. Electricity market design for the prosumer era. *Nat. Energy* **2016**, *1*, 1–6. [CrossRef]

15. Aldersey-Williams, J.; Rubert, T. Levelised cost of energy—A theoretical justification and critical assessment. *Energy Policy* **2019**, *124*, 169–179. [CrossRef]
16. Shen, W.; Chen, X.; Qiu, J.; Hayward, J.A.; Sayeef, S.; Osman, P.; Meng, K.; Dong, Z.Y. A comprehensive review of variable renewable energy levelized cost of electricity. *Renew. Sustain. Energy Rev.* **2020**, *133*, 110301. [CrossRef]
17. Reichelstein, S.; Sahoo, A. Time of day pricing and the levelized cost of intermittent power generation. *Energy Econ.* **2015**, *48*, 97–108. [CrossRef]
18. Varro, L.; Ha, J. *Projected Costs of Generating Electricity—2015 Edition*; Nuclear Energy Agency (NEA): Paris, France, 2015.
19. Mohammadi, F.; Gholami, H.; Gharehpetian, G.B.; Hosseinian, S.H. Allocation of centralized energy storage system and its effect on daily grid energy generation cost. *IEEE Trans. Power Syst.* **2017**, *32*, 2406–2416. [CrossRef]
20. Nissen, U.; Harfst, N. Shortcomings of the traditional "levelized cost of energy" [LCOE] for the determination of grid parity. *Energy* **2019**, *171*, 1009–1016. [CrossRef]
21. Górnowicz, R.; Castro, R. Optimal design and economic analysis of a PV system operating under Net Metering or Feed-In-Tariff support mechanisms: A case study in Poland. *Sustain. Energy Technol. Assess.* **2020**, *42*, 100863. [CrossRef]
22. Castaneda, M.; Zapata, S.; Cherni, J.; Aristizabal, A.J.; Dyner, I. The long-term effects of cautious feed-in tariff reductions on photovoltaic generation in the UK residential sector. *Renew. Energy* **2020**, *155*, 1432–1443. [CrossRef]
23. Cui, Y.; Zhu, J.; Meng, F.; Zoras, S.; McKechnie, J.; Chu, J. Energy assessment and economic sensitivity analysis of a grid-connected photovoltaic system. *Renew. Energy* **2020**, *150*, 101–115. [CrossRef]
24. De Oliveira Pinto Coelho, E.; Aquila, G.; Bonatto, B.D.; Balestrassi, P.P.; de Oliveira Pamplona, E.; Nakamura, W.T. Regulatory impact of photovoltaic prosumer policies in Brazil based on a financial risk analysis. *Utilit. Policy* **2021**, *70*, 101214. [CrossRef]
25. Mundada, A.S.; Shah, K.K.; Pearce, J.M. Levelized cost of electricity for solar photovoltaic, battery and cogen hybrid systems. *Renew. Sustain. Energy Rev.* **2016**, *57*, 692–703. [CrossRef]
26. Limmanee, A.; Songtrai, S.; Udomdachanut, N.; Kaewniyompanit, S.; Sato, Y.; Nakaishi, M.; Kittisontirak, S.; Sriprapha, K.; Sakamoto, Y. Degradation analysis of photovoltaic modules under tropical climatic conditions and its impacts on LCOE. *Renew. Energy* **2017**, *102*, 199–204. [CrossRef]
27. Komilov, A. Location and orientation based LCOE: Simplified visual analysis and generalization of the levelized cost of electricity from storageless photovoltaic systems. *Int. J. Energy Res.* **2020**, *45*, 5649–5658. [CrossRef]
28. Talavera, D.L.; Muñoz-Cerón, E.; Ferrer-Rodríguez, J.P.; Pérez-Higueras, P.J. Assessment of cost-competitiveness and profitability of fixed and tracking photovoltaic systems: The case of five specific sites. *Renew. Energy* **2019**, *134*, 902–913. [CrossRef]
29. Patel, M.T.; Asadpour, R.; Woodhouse, M.; Deline, C.; Alam, M.A. LCOE*: Re-thinking LCOE for photovoltaic systems. In Proceedings of the 2019 IEEE 46th Photovoltaic Specialists Conference (PVSC), Chicago, IL, USA, 16–21 June 2019; pp. 1711–1713.
30. Sinaga, R.; Tuati, N.F.; Beily, M.D.; Sampeallo, A.S. Modeling and analysis of the solar photovoltaic levelized cost of electricity (LCoE)-case study in Kupang. *J. Phys. Conf. Ser.* **2019**, *1364*, 012066. [CrossRef]
31. World Bank Group. Electric Power Transmission and Distribution Losses (% of Output). Available online: https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS?locations=BR (accessed on 1 March 2021).
32. Moro, A.; Lonza, L. Electricity carbon intensity in European Member States: Impacts on GHG emissions of electric vehicles. *Trans. Res. Part D Trans. Environ.* **2018**, *64*, 5–14. [CrossRef] [PubMed]
33. Eurostat. Electricity Price Statistics. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics#Electricity_prices_for_household_consumers (accessed on 1 March 2021).
34. Jordan, D.C.; Kurtz, S.R. Photovoltaic degradation rates—an analytical review. *Prog. Photovolt. Res. Applicat.* **2013**, *21*, 12–29. [CrossRef]
35. Photovoltaic Geographical Information System (PVGIS). Overview of PVGIS Data Sources and Calculation Methods. Available online: https://ec.europa.eu/jrc/en/PVGIS/docs/methods (accessed on 1 March 2021).
36. Acciari, G.; Adamo, G.; Ala, G.; Busacca, A.; Caruso, M.; Giglia, G.; Imburgia, A.; Livreri, P.; Miceli, R.; Parisi, A.; et al. Experimental investigation on the performances of innovative PV vertical structures. *Photonics* **2019**, *6*, 86. [CrossRef]
37. Evola, G.; Margani, G. Renovation of apartment blocks with BIPV: Energy and economic evaluation in temperate climate. *Energy Build.* **2016**, *130*, 794–810. [CrossRef]

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

Hassan Gholami [1, a], Harald Nils Røstvik [2,a], Nallapaneni Manoj Kumar [3,b], Shauhrat S Chopra [4,b]

[a]Department of Safety, Economics and Planning, University of Stavanger, Stavanger, Norway
[b] School of Energy and Environment, City University of Hong Kong, Kowloon, Hong Kong

[1] PhD Researcher, hassan.gholami@uis.no
[2] Professor, harald.n.rostvik@uis.no
[1] PhD Researcher, mnallapan2-c@my.cityu.edu.hk
[2] Professor, harald.n.rostvik@uis.no

Solar Energy
Volume 211, 15 November 2020, Pages 488-502

https://doi.org/10.1016/j.solener.2020.09.087

Solar Energy 211 (2020) 488–502

Contents lists available at ScienceDirect

Solar Energy

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

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

Hassan Gholami [a,*], Harald Nils Røstvik [a], Nallapaneni Manoj Kumar [b], Shauhrat S. Chopra [b]

[a] *Department of Safety, Economics and Planning, University of Stavanger, Kjell Arholmsgate 41, 4036 Stavanger, Norway*
[b] *School of Energy and Environment, City University of Hong Kong, Kowloon, Hong Kong*

ARTICLE INFO

Keywords:
Building integrated photovoltaics (BIPV)
Lifecycle cost analysis (LCCA)
BIPV societal and environmental benefits
BIPV end-of-life material recovery
Net present value (NPV)
Building envelope materials

ABSTRACT

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

1. Introduction

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

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

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

* Corresponding author.
E-mail addresses: hassan.gholami@uis.no (H. Gholami), harald.n.rostvik@uis.no (H. Nils Røstvik), mnallapan2-c@my.cityu.edu.hk (N. Manoj Kumar), sschopra@cityu.edu.hk (S.S. Chopra).

https://doi.org/10.1016/j.solener.2020.09.087
Received 3 August 2020; Received in revised form 10 September 2020; Accepted 30 September 2020
Available online 8 October 2020

Nomenclature

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

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

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

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

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

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

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

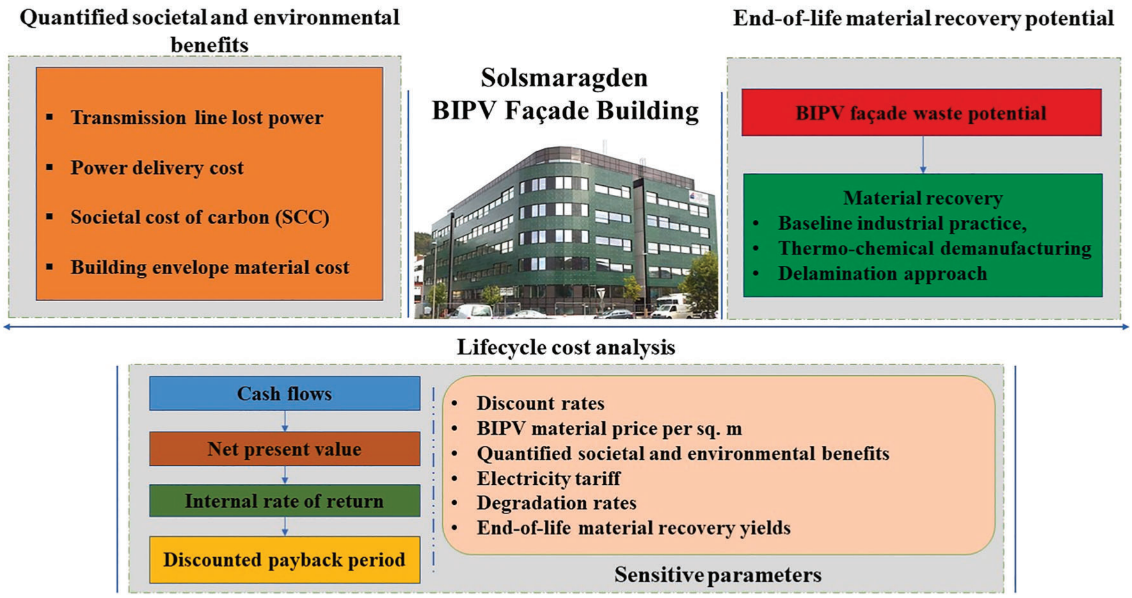


Fig. 1. The proposed methodology for LCCA of BIPV systems.

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

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

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

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

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

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

2. Methodology

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

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

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

2.1. Input parameters

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

2.1.1. Operation and maintenance (O&M) costs

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

2.1.2. Inverter replacement cost

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

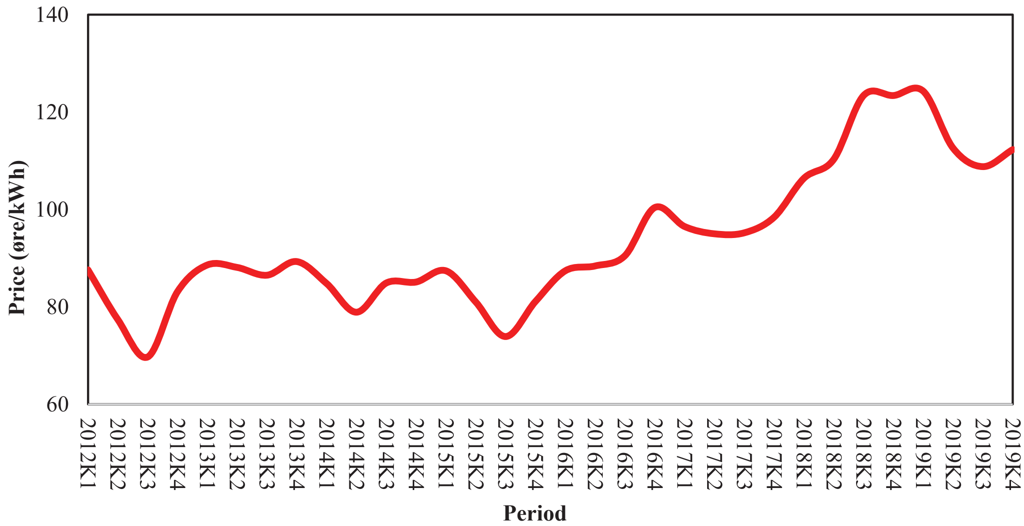


Fig. 2. Seasonal electricity price history of Norway including grid rent and taxes.

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

2.1.3. BIPV degradation rate

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

2.1.4. BIPV Life-time

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

2.1.5. Building envelope material cost

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

2.1.6. Transmission line lost power

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

2.1.7. Power delivery cost

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

2.1.8. Societal cost of carbon (SCC)

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

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

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

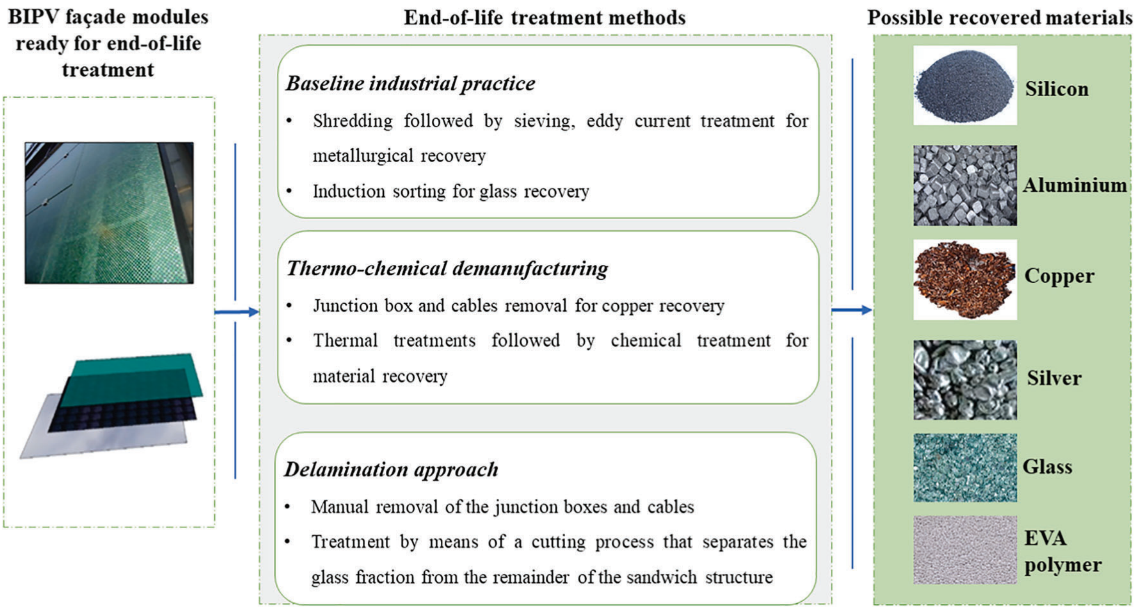


Fig. 3. End-of-life material recovery process for BIPV module.

2.1.9. GHG emission

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

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

2.1.10. Electricity tariff and its growth rate

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

2.1.11. Discount rate

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

2.2. End-of-life modelling of BIPV façade

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

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

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

2.3. LCCA formulation

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

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

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

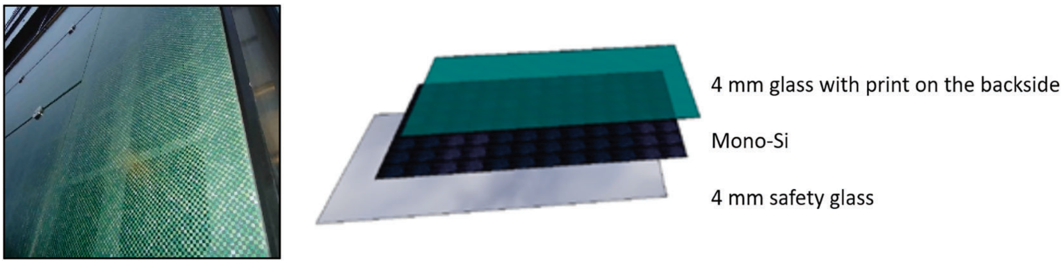


Fig. 4. a). Green pattern colouration of the BIPV front glass; b). Structure of Issol BIPV panel.

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

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

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

The initial investment, Q, is calculated as follows:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

D_R stands for the discount rate. The *DPP* can be calculated from

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

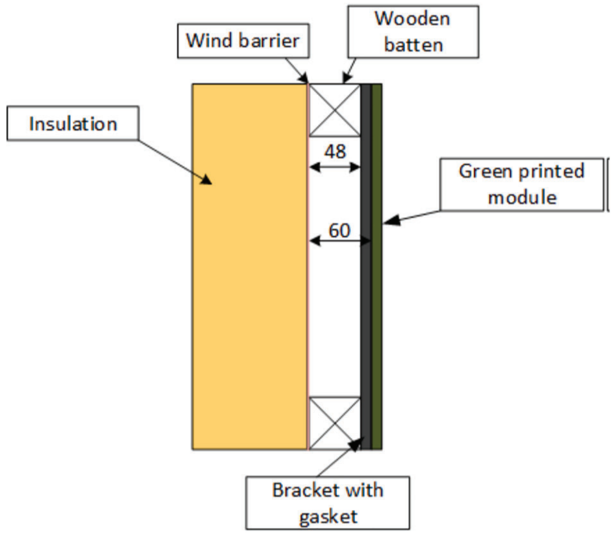


Fig. 6. The cross-section of the south facade in Solsmaragden BIPV building (dimension unit is mm) (Frivold, 2018).

Equation (13):

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

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

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

3. Description of Solsmaragden BIPV façade building

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

The project was the first project in the world that applied a printed, decoration only layer on the inside of the front glass of the PV glazing. The objective of the project was to replicate a green wall according to the requirements of the architects.

The tailor-made BIPV panels, together with glass cladding has been used for most of the building façades of this project. The facade modules consist of 4 mm glass with a printed layer on the inside of the front glass

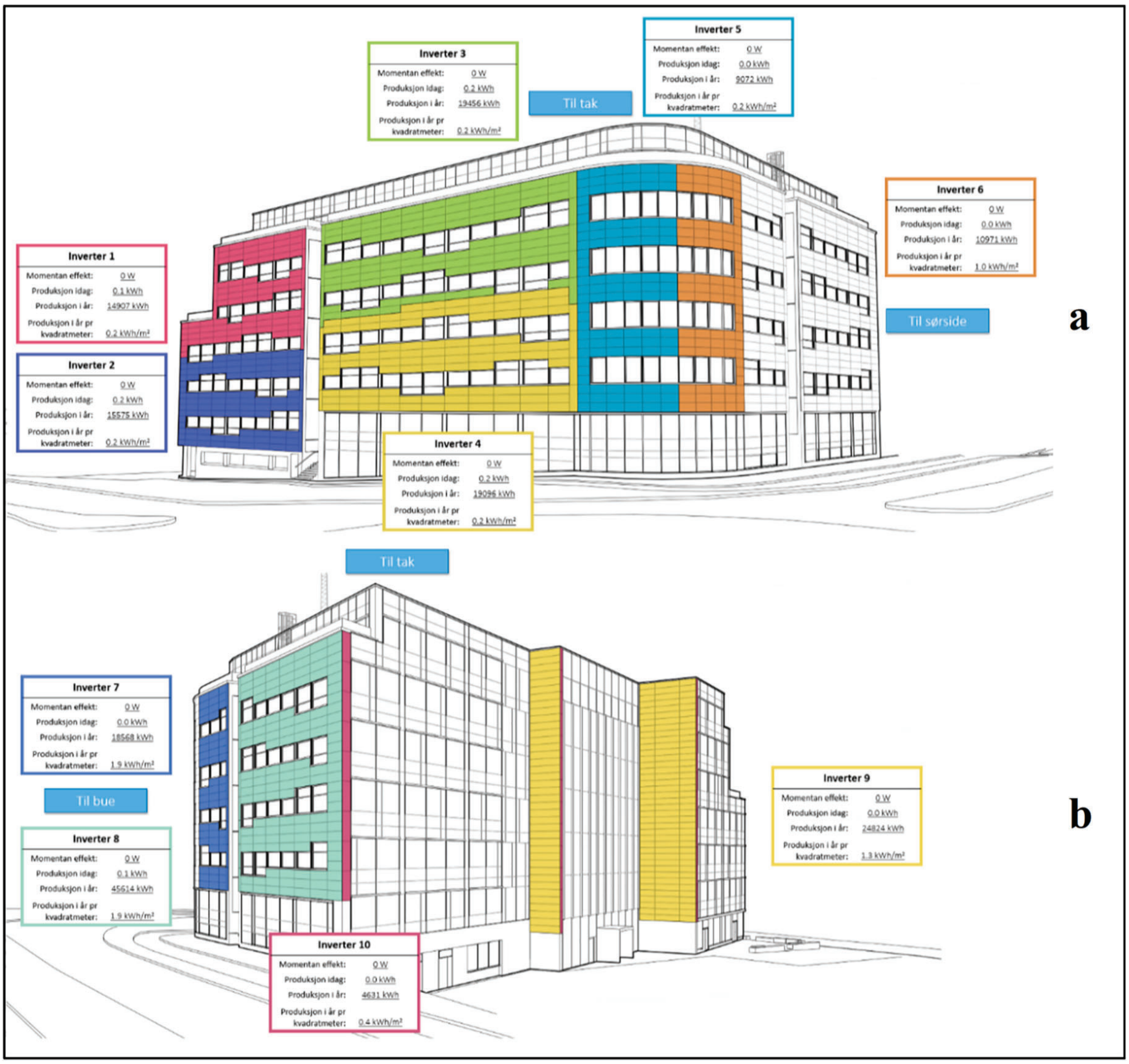


Fig. 7. Different strings of BIPV panels on the building skin (screenshot from the monitoring app).

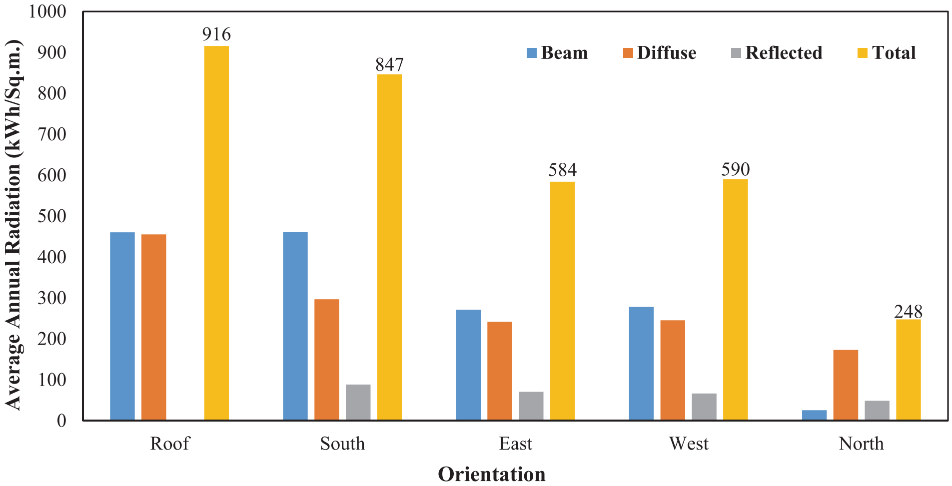


Fig. 8. Average Annual radiation on different orientations of the building skins.

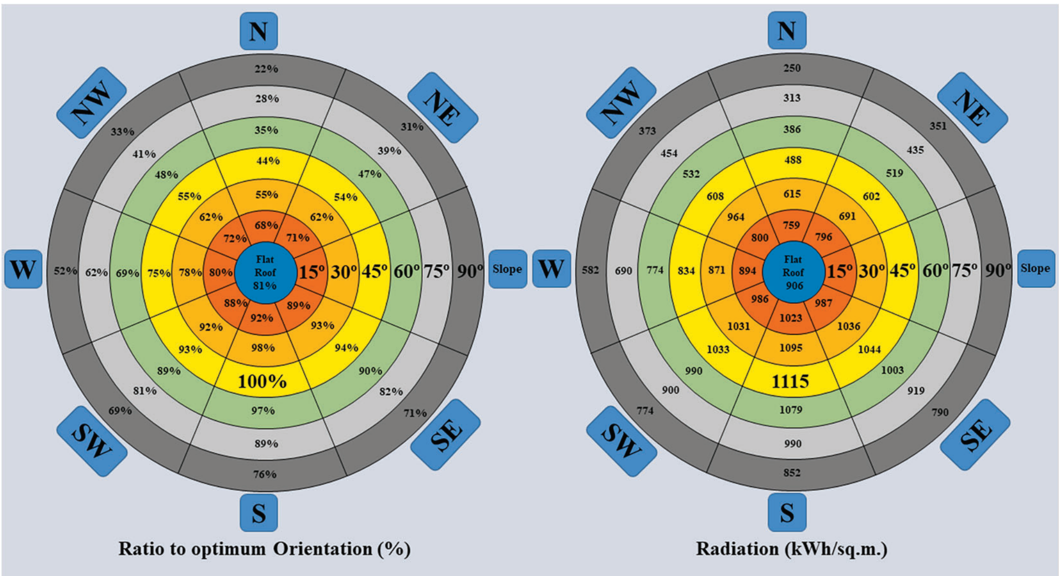


Fig. 9. Annual solar potential of building skins with different tilts and orientations in Drammen, Norway.

of the PV glazing, a layer of standard 6″ mono-crystalline silicon solar cells and another layer of 4 (mm) glass, which are laminated together (frameless glass-glass configuration). The cell efficiency is 20% and the printed green colour reduces the cells' overall efficiency by 17%. Therefore, the efficiency of the BIPV panels is 16.6%.

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

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

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

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

4. Results and discussion

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

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

As can be seen from Fig. 8, the reflected radiation component of the

Table 1
Inverter capacities and production on the building skin.

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

Table 2
BIPV annual performance.

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

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

Fig. 9 illustrates the solar irradiance potential on different orientations of building skins with different tilt in the Solsmaragden site and for the year 2016. The data has been extracted from PVGIS ((PVGIS), 2017) . The solar irradiance values for the east and west facades with different orientations were almost the same (with a maximum 1% variation). The optimum angle to gain the maximum solar irradiance for this location is the azimuth angle (the angle of the BIPV modules relative to the direction due south, in which $-90°$ is east, $0°$ is south and $90°$ is west) of zero degrees, and the slope (the angle of the BIPV modules from the horizontal plane) of $45°$. The annual solar irradiance of this orientation in 2016 was recorded 1115 kWh per square meter.

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

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

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

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

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

The recovered materials from end-of-life of BIPV waste after the 30th year lead to financial gains and these gains are estimated as per the Equation (4). Before the financial gain's estimation, the possible BIPV waste potential need to be identified based on the weight of the PV module. The BIPV façade weight is 20.5 kg per sq.m. and 1146 sq.m. of BIPV façade is installed, which accounts for a cumulative weight of 23.5 tonnes. The weight of recovered materials varies depending on EOL

Table 3
BIPV project estimated cost breakdown.

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

Table 4
Percentage of material recovery yields .

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

approaches. The percentages of materials recovery yields, which are based on the industrial data (WEEE treatment plant in the Flemish region of Belgium) as well as the literature support (Duflou et al., 2018; Gangwar et al., 2019; Huang et al., 2017; Kang et al., 2012) are provided in Table 4. The recovered materials in all the three EOL methods, as well as the financial gains, are estimated and presented in Table 5 with their NPV values.

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

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

Scenario-B: Net investment without Enova support, which is the total

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

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

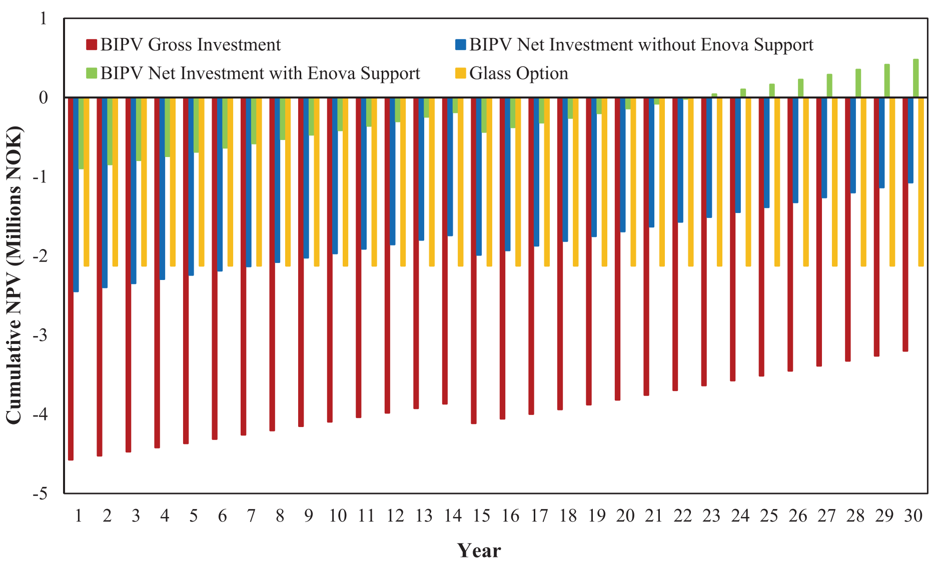


Fig. 10. The cumulative NPV of investment for different scenarios (without EOL benefits).

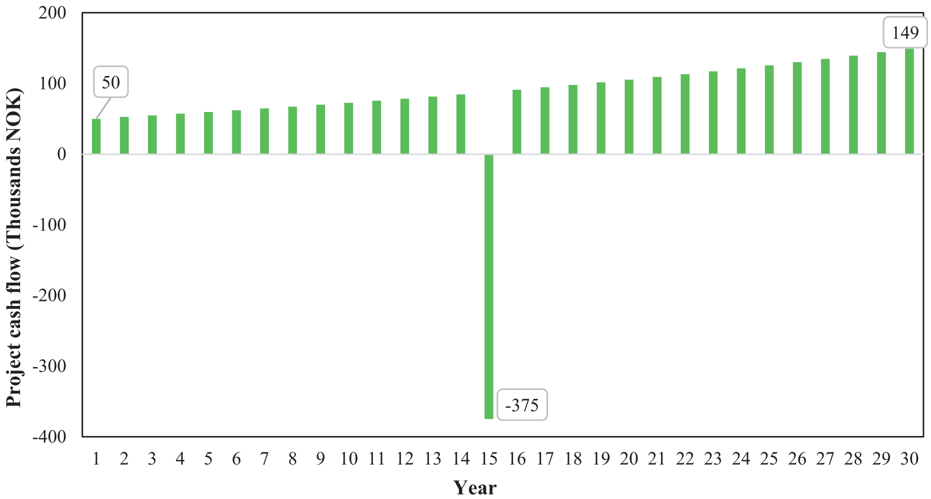


Fig. 11. BIPV cash flow without investment and EOL benefits.

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

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

invested money by the client considering the system functionality as a building envelope material (an alternative for glass façade) but without taking the Enova support into the evaluation (4,625,794 NOK − 2,125,830 NOK = 2,499,964NOK);

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

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

By taking the subsidy granted by the Enova into the calculation, the cumulative NPV of the BIPV system becomes positive, with the total value of 478,934 NOK (0.48 Million NOK, see Fig. 10). It means the BIPV system could reimburse not only the invested money but also become a source of income for the building. It is also found out that with a subsidy equal to 1,074,301 NOK, the cumulative NPV of the BIPV system would become Zero. On the other hand and in terms of the glass façade option, the cumulative NPV of the system will be −2,125,830 NOK.

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

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

Another important implication from this study is that the BIPV system as an envelope material for a significant portion of a building's skin, even in a climate and an urban area like Oslo (with lower solar irradiance and cheaper electricity price compared to many other European countries), is economically feasible. This fact has recently led to an

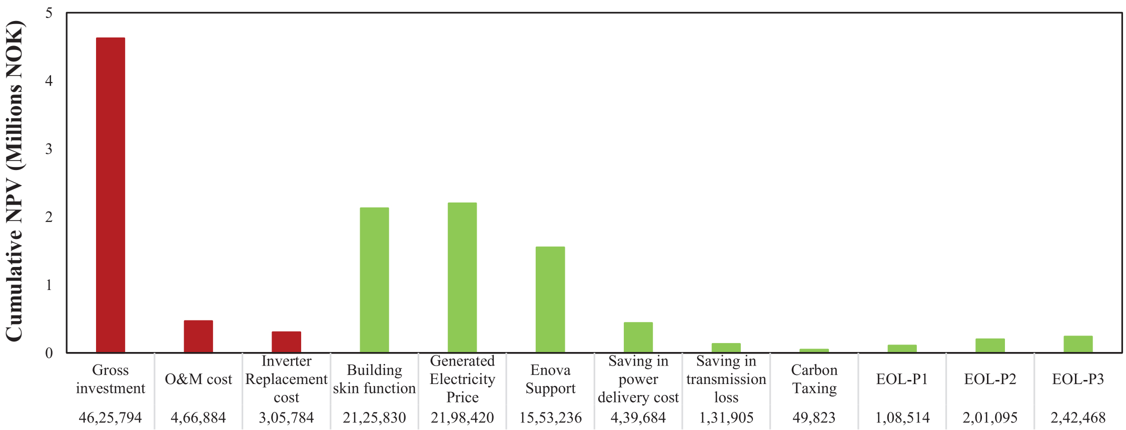


Fig. 12. The absolute cumulative NPV of different items for this project.

Table 7
The LCOE of Scenarios.

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

expeditious development of the business model of BIPV technology and it is about to be recognised soon as a building envelope material for the entire building skins in competition with other alternatives such as brick, wood, stone, metals, etc.

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

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

Fig. 12 is also a useful tool to calculate the levelised cost of energy (LCOE) for the defined Scenarios. LCOE is often referred to as a convenient summary measure of the overall competitiveness of electricity-generating technologies (EIA, 2016; Farshad Mohammadi, Gholami, Gharehpetian, & Hosseinian, 2017). In terms of BIPV technology, LCOE is a term that describes the cost of the power produced by the BIPV systems over the lifetime of the system, which is 30 years in this study.

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

$$LCOE = NPV_{TC}/T_{EP} \quad (15)$$

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

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

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

Fig. 13 presents the history of the cost breakdown of electricity for end-users in Norway (Holstad, 2019). Unfortunately, there is no feed-in tariff (FiT is a fixed electricity price that is paid to renewable energy producers for each unit of energy produced and injected into the electricity grid as an economic policy to promote active investment in renewable energy sources) for PV and BIPV on residential and commercial buildings in Norway. Generally, the reference price for the surplus energy of the end-users injected into the power grid is the "Electricity price excl. taxes". This value for the winter season of 2019 as an example is 46.8 Øre per kWh (each NOK is 100 Øre) or 0.468 NOK while the total electricity price per kWh for the end-user is equal to 112.3 Øre (1.1 NOK). Therefore, when it comes to countries with no FiT (such as Norway), it is crucial to design the BIPV system in a way that the building consumes as much as possible of the electricity production.

For this particular project, two reasons made the system

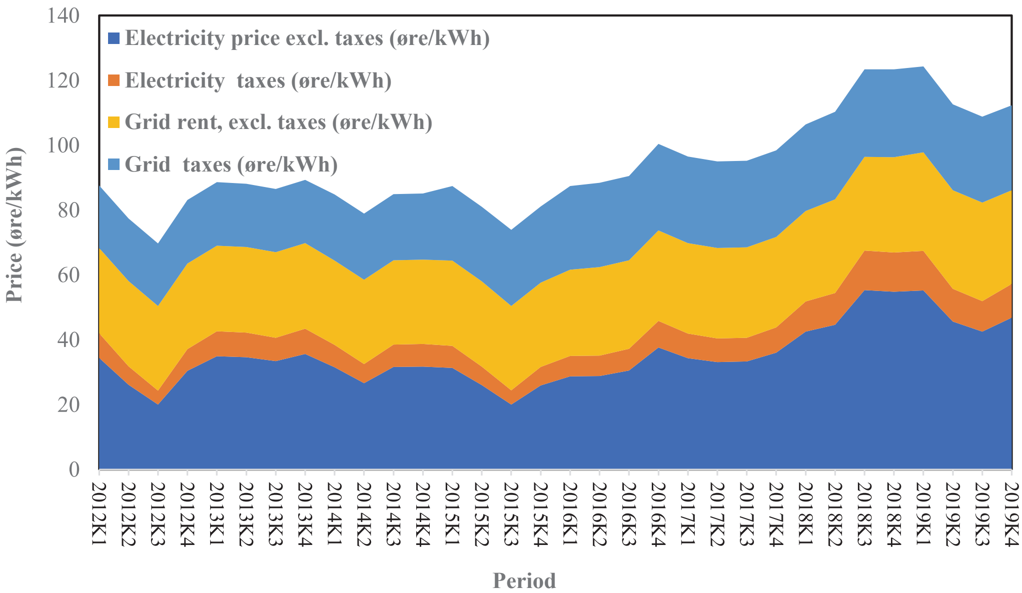


Fig. 13. Cost breakdown of electricity for end-users in Norway.

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

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

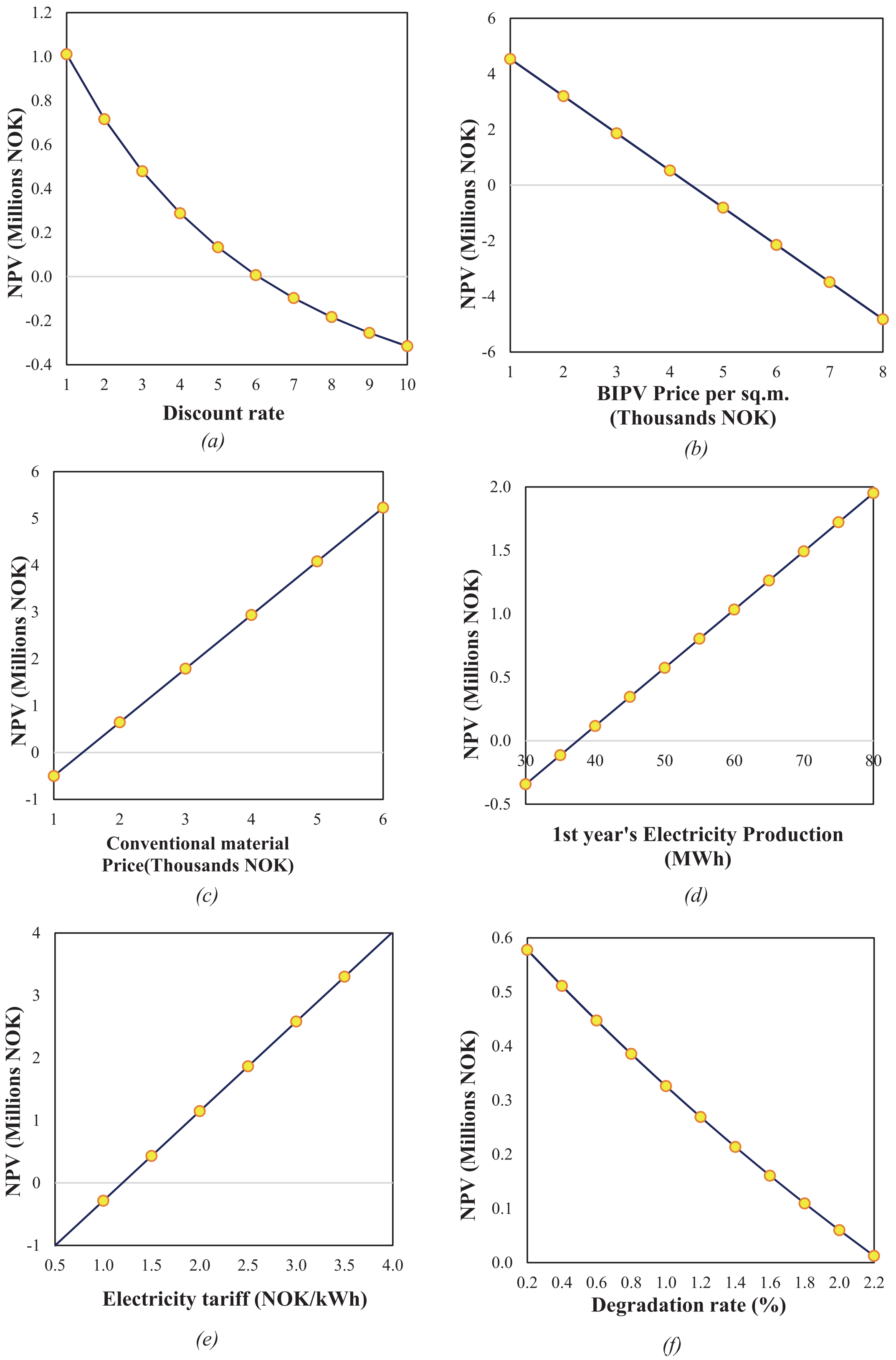


Fig. 14. Cumulative NPV of the BIPV under variation of different parameters: (a) discount rate; (b) BIPV price; (c) conventional material price; (d) BIPV Production; (e) electricity tariff; (f) degradation rate.

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

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

5. Parametric analysis

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

Fig. 14 depicts the parametric analysis of various inputs on the output. The relationship between the discount rate and NPV is a nonlinear concave relationship and the cumulative NPV of the project varies from one Million NOK to minus 320 Thousand NOK if the discount rate varies from 1% to 10%.

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

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

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

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

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

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

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

6. Conclusion

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

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

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

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

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

Declaration of Competing Interest

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

Acknowledgement

The work reported in this paper was supported by the Department of Safety, Economics, and Planning (ISØP) of the University of Stavanger (Project name: Building Integrated Photovoltaic BIPV) in dense urban areas, Project number: IN-12011). The authors would like to offer their gratitude to Trond Aasheim, Morten Gregertsen, Christine Wangsnes and Stian Monge from the Union Eiendomsutvikling AS, Steinar Nilsen from the FUSen AS and Sébastien La Fontaine from the ISSOL sa/nv for their great help by providing all the required data and information. Special thanks also goes to the Smart City Group and Future Energy Hub at the University of Stavanger for their support.

References

Agrawal, B., Tiwari, G., 2010. Life cycle cost assessment of building integrated photovoltaic thermal (BIPVT) systems. Energy and Buildings 42 (9), 1472–1481.
Alnaser, N.W., 2018. First smart 8.64 kW BIPV in a building in Awali Town at Kingdom of Bahrain. Renewable and Sustainable Energy Reviews 82, 205–214.
Aste, N., Del Pero, C., Leonforte, F., 2016. The first Italian BIPV project: Case study and long-term performance analysis. Solar Energy 134, 340–352.
Azadian, F., Radzi, M., 2013. A general approach toward building integrated photovoltaic systems and its implementation barriers: A review. Renewable Sustainable Energy Reviews 22, 527–538.
Barkaszi, S., Dunlop, J., 2001. Discussion of strategies for mounting photovoltaic arrays on rooftops. Solar Engineering 333–338.
Brito, M., Redweik, P., & Catita, C. (2013). Photovoltaics and zero energy buildings: The role of building facades. Paper presented at the présenté à 28th European Photovoltaic Solar Energy Conference and Exhibition, Paris.
Byrnes, L., Brown, C., Foster, J., Wagner, L.D., 2013. Australian renewable energy policy: Barriers and challenges. Renewable Energy 60, 711–721.
Cerón, I., Caamaño-Martín, E., Neila, F.J., 2013. 'State-of-the-art'of building integrated photovoltaic products. Renewable Energy 58, 127–133.
Chiu, M.-S., Hou, S.-P., Tzeng, C.-T., Lai, C.-M., 2015. Experimental Investigations on the Thermal Performance of the Ventilated BIPV Wall. Journal of Applied Sciences 15 (3), 613–618.
Dimitris Lazos, A. B. (2012). The value of commercial BIPV systems in the urban environment. Paper presented at the Australian Solar Council (AuSES) Academic Conference, Melbourne.
Duflou, J.R., Peeters, J.R., Altamirano, D., Bracquene, E., Dewulf, W., 2018. Demanufacturing photovoltaic panels: Comparison of end-of-life treatment strategies for improved resource recovery. CIRP Annals 67 (1), 29–32.
Eicker, U., Demir, E., Gürlich, D., 2015. Strategies for cost efficient refurbishment and solar energy integration in European Case Study buildings. Energy and Buildings 102, 237–249.

Eiffert, P. (2003). Guidelines for the economic evaluation of building-integrated photovoltaic power systems.

Esmailian, E., Gholami, H., Røstvik, H.N., Menhaj, M.B., 2019. A novel method for optimal performance of ships by simultaneous optimisation of hull-propulsion-BIPV systems. Energy Conversion and Management 197, 111879. https://doi.org/10.1016/j.enconman.2019.111879.

Freitas, S., Brito, M.C., 2019. Solar façades for future cities. Renewable energy focus 31, 73–79. https://doi.org/10.1016/j.ref.2019.09.002.

Frivold, C.H., 2018. Photovoltaic facade systems in Norway: An assessment of energy performance, building integration, and costs. University of Agder, Universitetet i Agder.

Gangwar, P., Kumar, N.M., Singh, A.K., Jayakumar, A., Mathew, M., 2019. Solar photovoltaic tree and its end-of-life management using thermal and chemical treatments for material recovery. Case Studies in Thermal Engineering 14, 100474.

García-Gusano, D., Espegren, K., Lind, A., Kirkengen, M., 2016. The role of the discount rates in energy systems optimisation models. Renewable and Sustainable Energy Reviews 59, 56–72. https://doi.org/10.1016/j.rser.2015.12.359.

Gholami, H., H. N. Røstvik, & Müller-Eie, D. (2019). Analysis of solar radiation components on building skins for selected cities. In: Proceedings of 14th Conference on Advanced Building Skins (pp. 541-549). Bern, Switzerland: Advanced Building Skins. ABS.

Gholami, H., Khalilnejad, A., Gharehpetian, G., 2015a. Electrothermal performance and environmental effects of optimal photovoltaic–thermal system. Energy Conversion Management 95, 326–333. https://doi.org/10.1016/j.enconman.2015.02.014.

Gholami, H., Røstvik, H.N., 2020. Economic analysis of BIPV systems as a building envelope material for building skins in Europe. Energy 204, 117931. https://doi.org/10.1016/j.energy.2020.117931.

Gholami, H., Røstvik, H.N., Müller-Eie, D., 2019b. Holistic economic analysis of building integrated photovoltaics (BIPV) system: Case studies evaluation. Energy and Buildings 203, 109461. https://doi.org/10.1016/j.enbuild.2019.109461.

Gholami, H., Sarwat, A., Hosseinian, H., Khalilnejad, A., 2015b. Evaluation of optimal dual axis concentrated photovoltaic thermal system with active ventilation using Frog Leap algorithm. Energy Conversion Management 105, 782–790. https://doi.org/10.1016/j.enconman.2015.08.033.

Gotzens, F., Heinrichs, H., Hake, J.-F., Allelein, H.-J., 2018. The influence of continued reductions in renewable energy cost on the European electricity system. Energy Strategy Reviews 21, 71–81. https://doi.org/10.1016/j.esr.2018.04.007.

Granata, G., Pagnanelli, F., Moscardini, E., Havlik, T., Toro, L., 2014. Recycling of photovoltaic panels by physical operations. Solar Energy Materials and Solar Cells 123, 239–248.

The World Bank Group (2018). Electric power transmission and distribution losses (% of output). Retrieved from https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS.

The World Bank Group (2019). Carbon Pricing Dashboard. Retrieved from https://carbonpricingdashboard.worldbank.org/map_data.

Hammond, G.P., Harajli, H.A., Jones, C.I., Winnett, A.B., 2012. Whole systems appraisal of a UK Building Integrated Photovoltaic (BIPV) system: Energy, environmental, and economic evaluations. Energy policy 40, 219–230.

Holstad, M. (2019). Total price of electricity and grid rent incl. taxes (øre/kWh). Retrieved from https://www.ssb.no/en/statbank/table/09387/.

Huang, B., Zhao, J., Chai, J., Xue, B., Zhao, F., Wang, X., 2017. Environmental influence assessment of China's multi-crystalline silicon (multi-Si) photovoltaic modules considering recycling process. Solar Energy 143, 132–141.

Ibrahim, A., Fudholi, A., Sopian, K., Othman, M.Y., Ruslan, M.H., 2014. Efficiencies and improvement potential of building integrated photovoltaic thermal (BIPVT) system. Energy Conversion and Management 77, 527–534.

Jelle, B.P., Breivik, C., Røkenes, H.D., 2012. Building integrated photovoltaic products: A state-of-the-art review and future research opportunities. Solar Energy Materials and Solar Cells 100, 69–96.

Jing Yang, R., Zou, X.W.P., 2015. Building integrated photovoltaics (BIPV): costs, benefits, risks, barriers and improvement strategy. International Journal of Construction Management 16 (1), 39–53.

Jordan, D.C., Kurtz, S.R., 2013. Photovoltaic degradation rates—an analytical review. Progress in photovoltaics: research applications 21 (1), 12–29.

Kang, S., Yoo, S., Lee, J., Boo, B., Ryu, H., 2012. Experimental investigations for recycling of silicon and glass from waste photovoltaic modules. Renewable Energy 47, 152–159.

Kumar, N.M., Sudhakar, K., Samykano, M., 2018. Performance of thin-film BIPV as double sloped pitched roof in buildings of Malaysia. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects 40 (20), 2476–2484.

Kumar, N.M., Sudhakar, K., Samykano, M., 2019. Performance comparison of BAPV and BIPV systems with c-Si, CIS and CdTe photovoltaic technologies under tropical weather conditions. Case Studies in Thermal Engineering 13, 100374.

Kumar, N.M., Sudhakar, K., Samykano, M., 2020. Performance evaluation of CdTe BIPV roof and façades in tropical weather conditions. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects 42 (9), 1057–1071.

Larsen, H. (2019). Klimafotavstrykket av offentlige anskaffelser. Beregning av klimafotavtrykket av offentlige anskaffelser for årene 2008 til 2017. In: Direktoratet for Forvaltning Og IKT (Difi).

Mohammadi, F., Gholami, H., Gharehpetian, G.B., Hosseinian, S.H., 2017. Allocation of centralized energy storage system and its effect on daily grid energy generation cost. IEEE Transactions on Power Systems 32 (3), 2406–2416. https://doi.org/10.1109/TPWRS.2016.2613178.

Mohammadi, F., Gholami, H., Menhaj, M.B., 2016. Effect of Ventilation on Yearly Photovoltaic Performance. Paper presented at the 1st International Conference on New Research Achievements in Electrical and Computer Engineering.

Oliver, M., Jackson, T., 2000. The evolution of economic and environmental cost for crystalline silicon photovoltaics. Energy policy 28, 1011–1021.

Osseweijer, F.J., Van Den Hurk, L.B., Teunissen, E.J., van Sark, W.G., 2018. A comparative review of building integrated photovoltaics ecosystems in selected European countries. Renewable Sustainable Energy Reviews 90, 1027–1040.

Park, J., Kim, W., Cho, N., Lee, H., Park, N., 2016. An eco-friendly method for reclaimed silicon wafers from a photovoltaic module: from separation to cell fabrication. Green Chemistry 18 (6), 1706–1714.

Pearce, D., 2003. The social cost of carbon and its policy implications. Oxford review of economic policy 19 (3), 362–384.

Ricke, K., Drouet, L., Caldeira, K., Tavoni, M., 2018. Country-level social cost of carbon. Nature Climate Change 8 (10), 895.

Sánchez-Pantoja, N., Vidal, R., Pastor, M. C., & society. (2018). Aesthetic perception of photovoltaic integration within new proposals for ecological architecture. Sustainable cities, 39, 203-214.

Saretta, E., Caputo, P., Frontini, F., 2018. A review study about energy renovation of building facades with BIPV in urban environment. Sustainable Cities and Society 44, 343–355. https://doi.org/10.1016/j.scs.2018.10.002.

Sivanandan, A., 2009. BIPV hotspots in the EU. Renewable energy focus 10 (2), 54–55.

Sorgato, M., Schneider, K., Rüther, R., 2018. Technical and economic evaluation of thin-film CdTe building-integrated photovoltaics (BIPV) replacing façade and rooftop materials in office buildings in a warm and sunny climate. Renewable Energy 118, 84–98.

Steinbach, J., & Staniaszek, D. (2015). Discount rates in energy system analysis Discussion Paper. BPIE: Berlin, Germany.

Tripathy, M., Joshi, H., Panda, S., 2017. Energy payback time and life-cycle cost analysis of building integrated photovoltaic thermal system influenced by adverse effect of shadow. Applied energy 208, 376–389.

Wang, W., Liu, Y., Wu, X., Xu, Y., Yu, W., Zhao, C., Zhong, Y., 2016. Environmental assessments and economic performance of BAPV and BIPV systems in Shanghai. Energy and Buildings 130, 98–106.

Zhang, T., Wang, M., Yang, H., 2018. A Review of the Energy Performance and Life-Cycle Assessment of Building-Integrated Photovoltaic (BIPV) Systems. Energies 11 (11), 3157.

(EI), The Energy Institute (2018). The Full Cost of Electricity (FCe-) Executive Summary: The Full Cost of Electricity. Retrieved from https://energy.utexas.edu/sites/default/files/UTAustin_FCe_Exe_Summary_2018.pdf.

(EIA), US Energy Information Administration (2019). Annual Energy Outlook 2019 with projections to 2050. Retrieved from https://www.eia.gov/outlooks/aeo/pdf/aeo2019.pdf.

(EIA), US Energy Information Administration (2016). Levelized cost and levelized avoided cost of new generation resources in the annual energy outlook 2016. Washington DC, USA.

(IMF), International Monetary Fund (2019). Fiscal Monitor: How to Mitigate Climate Change. In. Washington.

(NVE), Norwegian Water Resources and Energy Directorate (2019). Electricity disclosure 2018. Retrieved from https://www.nve.no/energy-market-and-regulation/retail-market/electricity-disclosure-2018/?ref=mainmenu.

(PVGIS), Photovoltaic Geographical Information System (2017, 22/09/2017). Overview of PVGIS data sources and calculation methods. Retrieved from http://re.jrc.ec.europa.eu/pvg_static/methods.html.

http://www.emteknikk.no/referanse/energibygget/. (Accessed 01 August 2020).

VIII. The contribution of building integrated photovoltaics (BIPV) to the concept of nearly zero-energy cities in Europe: potential and challenges ahead

Hassan Gholami [1, a], Harald Nils Røstvik [2,a], Koen Steemers [3,b]

[a]Department of Safety, Economics and Planning, University of Stavanger, Stavanger, Norway
[b] School of Energy and Environment, City University of Hong Kong, Kowloon, Hong Kong

[1] PhD Researcher, + 47 96 95 72 95, hassan.gholami@uis.no
[2] Professor, + 47 92 22 67 10, harald.n.rostvik@uis.no
[3] Professor, kas11@cam.ac.uk

Under review in the journal of Solar Energy

The Contribution of Building-Integrated Photovoltaics (BIPV) to the Concept of Nearly Zero-Energy Cities in Europe: Potential and Challenges Ahead

Hassan Gholami [1],*, Harald Nils Røstvik [1] and Koen Steemers [2]

[1] City- and Regional Planning Group, Institute of Safety, Economics and Planning, University of Stavanger,4021 Stavanger, Norway; harald.n.rostvik@uis.no;
[2] Department of Architecture, University of Cambridge, 6 Chaucer Road, Cambridge CB2 2EB, UK; kas11@cam.ac.uk
* Correspondence: hassan.gholami@uis.no (gholami.hassan.kh@gmail.com); Tel.: +47-96-95-72-95

Abstract: The main purpose of this paper is to investigate the contributions of building-integrated photovoltaic (BIPV) systems to the notion of nearly zero-energy cities in the capitals of the European Union member states (EU), Norway, and Switzerland. Moreover, an in-depth investigation of the barriers and challenges ahead of the widespread rollout of BIPV technology is undertaken. This study investigates the scalability of the nearly zero-energy concept using BIPV technology in moving from individual buildings to entire cities. This study provide a metric for architects and urban planners that can be used to assess how much of the energy consumed by buildings in Europe could be supplied by BIPV systems when installed as building envelope materials on the outer skins of buildings. The results illustrate that by 2030, when buildings in the EU become more energy-efficient and the efficiency of BIPV systems will have improved considerably, BIPV envelope materials will be a reasonable option for building skins and will help in achieving nearly zero-energy cities. This study reveals that in the EU, taking a building skin to building net surface area ratio of 0.78 and a building skin glazing ratio of 30%, buildings could cover their electricity consumption using BIPV systems by 2030. Eighteen challenges and barriers to the extensive rollout of BIPV systems are recognised, classified, and discussed in this study in detail. The challenges are categorised into five stages, namely the decision, design, implementation, operation and maintenance, and end of life challenges.

Keywords: building-integrated photovoltaics (BIPV); nearly zero-energy cities (NZEB); building envelope materials; energy resources; sustainable urban energy planning; urban energy transition; positive energy district; literature review.

1. Introduction

"The coldest year in the future will be warmer than the hottest year in the past". This is an excerpt from the paper published in 2013 [1] by Camilo Mora et al., who calculated that by 2047 plus or minus five years, the average temperatures in each year would be warmer in most locations around the globe than they had been in those areas in any year between 1860 and 2005 if no measure are taken. In other words, under the 'business-as-usual' scenario, the temperature of a given location on earth will shift to a state continuously out of the historical variability bounds.

Furthermore, the National Oceanic and Atmospheric Administration [2] reported that the average temperature of the Earth's surface between 1880 and 2016 increased by 0.95 degrees centigrade and that the temperature increase has sped up in recent years. Finally, 159 countries signed the Paris Agreement in 2015 [3] to take measures ceasing global warming at 1.5 degrees centigrade warmer than the average temperature of the Earth prior to the industrial age. An investigation led by the International Monetary Fund [4] recently proclaimed that halting global warming to less than two degrees centigrade called for an expeditious course of action on a demanding scale, such as increasing the carbon tax by up to 75 USD per ton by 2030, which might cause tremendous shock to the economies of several countries; hence, countries must start adapting themselves by taking such measures in a step-by-step manner.

Cities and urban areas are key players in climate change. In terms of size, urban areas fill only 2% of the earth's land mass[5]; however, in terms of climate impact, urban areas leave an enormous footprint and consume more than two-thirds of the world's total energy need and are responsible for more than 70% of all global GHG emissions [6]. Moreover, by 2050, the global population will increase by 30%, 68% of which will be settled in urban areas [7,8]; therefore, a structural shift and change from the consumption of fossil energy resources to the consumption of renewable energy resources and toward energy efficiency notions in urban areas is a must [9]. As such, urban areas are where the concentration and focus need to be on it. Cities are not only on the frontline of global climate change but are also well-positioned to take the leadership role in driving global action to tackle climate change.

Among renewable energy resources, solar energy could play a remarkable role, due to its uniformity in distribution on a global scale [10] and its potential [11–13]. Solar energy in urban areas could also be harnessed using various methods and technologies [14–22]. The European Union (EU), in accordance with the framework of the Paris agreement, emphasises the prominence of the role of cities in moving towards a low carbon economy [23]; however, each country and region of the world has its own drivers and challenges in this energy transition [24,25].

The buildings themselves play a vital role in the energy efficiency of urban areas, since they are responsible for a significant percentage of the energy demands in urban areas [26,27]. In Europe, building energy use accounts for 41% of the total energy consumption of the cities [28].

As such, a transition to self-sufficient buildings in cities is a prominent course of action toward nearly zero-energy cities. Urban energy transition (UET) has recently received interest as a way of promoting distributed generation (DG) and realigning the energy production and consumption of buildings [9]. One of the leading solutions, which could be of great assistance in reach these goals, is the energy prosumer notion [29]. Prosumers are consumers who can, because of their energy production capacity and by virtue of the regulatory conditions of the market and power systems, export their surplus energy to the distribution grid. The nearly zero-energy city concept is currently at the frontier of energy self-sufficiency, which is based on the consumption of renewable energy resources in buildings [30,31].

The goal of this study is, therefore, to answer the following questions:

- Is it possible to establish nearly zero-energy cities in Europe by changing the role of buildings from energy consumers to energy prosumers using their skins for BIPV applications? If yes, to what extent?
- What are the challenges on the road to achieving this goal and which stakeholders are involved in those challenges?

The paper is structured as follows. In Section 2, the methodology of the research is presented. Building-integrated photovoltaic (BIPV) systems and their potential in Europe are discussed in Section 3. The status of building energy consumption in Europe is presented in Section 4. In Section 5, the contribution of BIPVs to the concept of nearly zero-energy cities is investigated.

Challenges and barriers to the rollout of BIPV technology in urban areas are explored in Section 6. Finally, conclusions are drawn in Section 7.

2. Methodology

The research methodology used in this study is presented in Figure 1. General approaches to the research methodology were employed in this study, including quantitative and qualitative approaches [32].

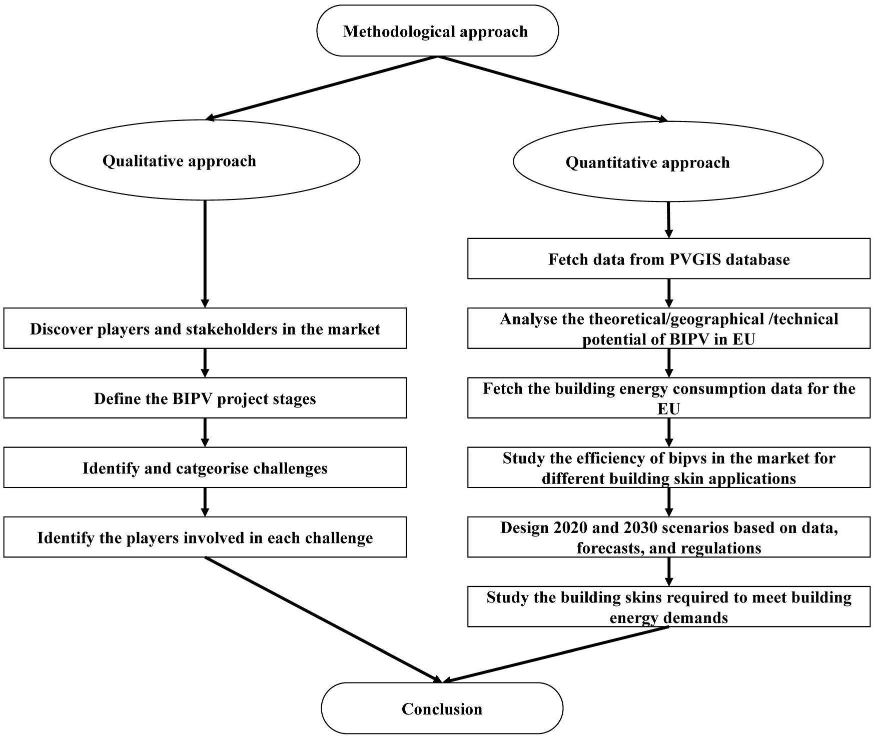


Figure 1. Flowchart of the methodology.

The designed quantitative and qualitative approaches used in this study are novel and have not been used before in previous studies in the literature. The quantitative methodology is designed to reveal the potential of a building to be shifted from an energy consumer to an energy prosumer via the effective use of its skin, and as part of the bigger picture, the role of building skins in the energy transition of cities. Furthermore, the aim of the proposed qualitative methodology is to analyse the hurdles to achieving the potential discovered via the quantitative approach.

3. BIPV Systems

Building-integrated photovoltaic (BIPV) systems consist of photovoltaic modules that can be integrated into building skins, such as the facade and roof, to generate electricity out of solar irradiation. Such systems provide buildings with two functions. First, they operate as skins for the buildings; therefore, BIPVs should meet the requirements of traditional building envelope materials, such as providing adequate structural strength, heat insulation, weather protection, and noise protection. Second, BIPVs act as power plants for buildings and generate electricity [13,33]. The applications for BIPVs are also not just limited to the building industry. They can also be utilised in other industries and for different functions. For example, they can be employed in ships to ensure their optimal operation and energy consumption [34].

A BIPV system generates and supplies energy where it is needed. Furthermore, with the aid of an energy storage system (ESS), it can provide energy when needed. This also addresses the recent debates and criticisms concerning the exploitation of land for solar power plants and the resulting effects on climate change [35,36]. Conversely, BIPV systems are located on the buildings that use the energy they produce; in other words, they are neutral systems with the least footprint on the nature.

The photovoltaic components integrated into a building's envelope (BIPV) interact with the building in many respects, influencing the buildability, design, durability, environmental issues, maintenance, performance, safety, standards, and regulations [37].

BIPV systems can be classified based on their solar cell composition, applications, names in the market, and grid connection types. A complete categorisation framework is presented in Figure 2.

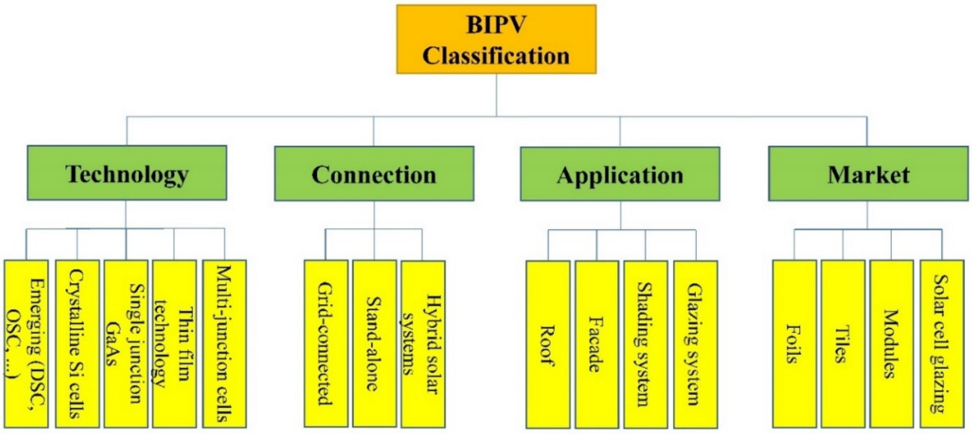


Figure 2. BIPV categorisation.

Figure 3 depicts examples of different BIPV systems available on the market [38].

BIPV Tiles

BIPV Modules

BIPV Glazing

BIPV Foil

Figure 3. Examples of BIPV systems available on the market.

The cell efficiency of BIPV technology has increased considerably since its inception. The National Renewable Energy Laboratory (NREL) is one of the leading organisations that publish yearly reports on solar PV efficiency improvements related to the technology and materials involved. The latest report from the NREL, which is presented in Figure 4, shows the development of PV efficiency from 1976 to 2020 [39].

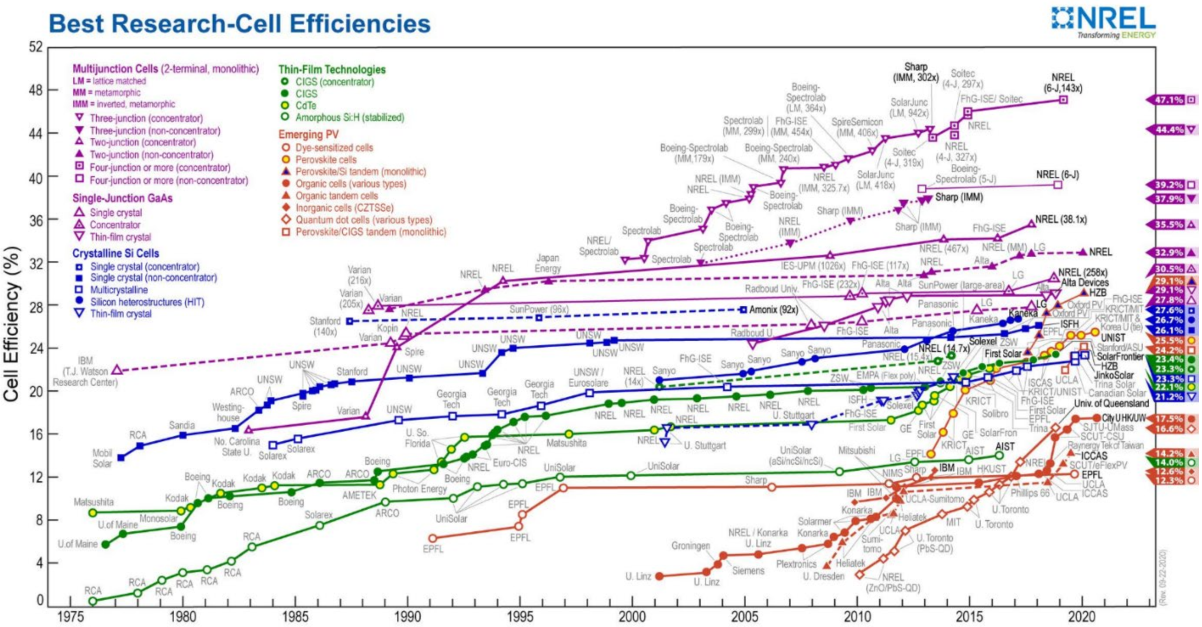


Figure 4. The NREL best research-cell efficiency chart.

It is noted that the NREL assesses the PV cell efficiency via laboratory standards, meaning the best environmental conditions are applied to find out the maximum efficiency of the PV cells but not the PV modules or panels.

The report suggests that the most efficient PV module available can reach up to 47% efficiency; however, the conventional PV cells that are available on the market for general applications are mostly mono-crystalline modules, shown in this chart with dark blue lines. The report indicates that mono-crystalline PVs can reach up to 27.6% efficiency in laboratory conditions (NREL, 2020). The slope of the chart demonstrates the changes in crystalline PVs over the past few decades.

According to a study by the Fraunhofer Institute for Solar Energy Systems, the best-performing commercial modules are based on mono-crystalline silicon, showing 24.4% efficiency in the laboratory; however, in real-world conditions, several factors such as the thermal function, snow cover, and cloud cover might affect the efficiency of PV systems. As such, the average efficiency rates for commercial mono-crystalline PV systems that are currently available in the market are in the range of 15–20% [40].

Recently, due to developments in the BIPV industry, new types of modules have emerged. The modules that are of interest in the current study are transparent and semi-transparent PV modules, which can replace windows and let light through while generating electricity. According to one of the manufacturers of such products, these PV modules can currently reach up to 7% efficiency [41].

There are different forecasts regarding how PV efficiency levels will develop by 2030. While [42] suggested that PV efficiency rates will increase by 3–4% per decade, more optimistic scenarios predict better improvements of up to 8% per decade.

There are currently different methods that are used to classify and define solar energy potential [43–47], which are not utilizable to classify the potential of BIPV systems; therefore, the aim of the next section is to define "BIPV potential" and present methodologies for assessing this parameter.

3.1. BIPV Theoretical Potential

The BIPV theoretical potential is the solar incident radiation gained by a region (on horizontal surfaces) without taking any geometrical or technical constraints into account. Solar incident radiation maps, which indicate the global horizontal irradiance (GHI), can be used to assess this parameter. The GHI indicates the total irradiation delivered from the sky to a horizontal surface on earth. A GHI map of Europe is presented in Figure 5.

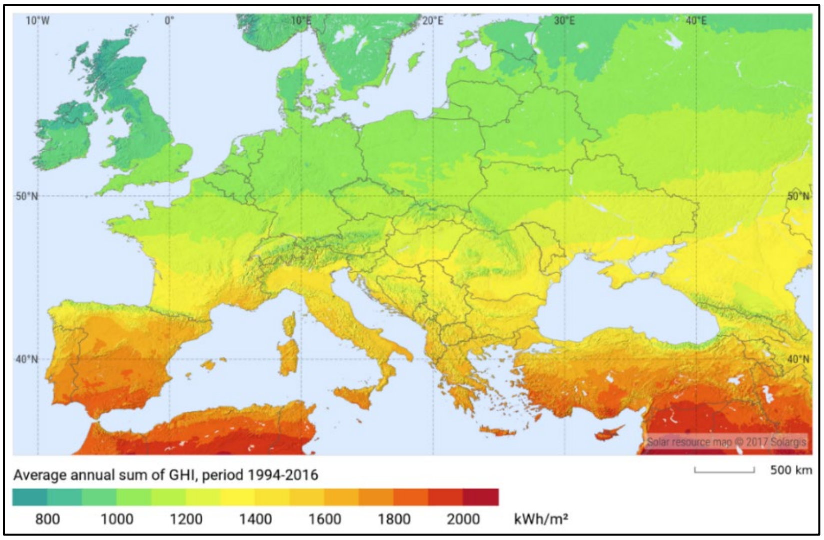


Figure 5. The theoretical solar incident radiation potential map of BIPV in Europe [48].

3.2. Geographical Potential

The exploitable or utilisable portion of the BIPV theoretical potential is called the BIPV geographical potential. The geographical potential is a portion of the BIPV theoretical potential that is capable of being exploited as an input for BIPV systems. The BIPV geographical potential for a city, therefore, represents the total solar incident radiation on the building skins of the city.

Figure 6 depicts the average annual BIPV geographical potential levels for the investigated countries. The results are based on the radiation data between 2005 and 2016 from the Photovoltaic Geographical Information System database [49].

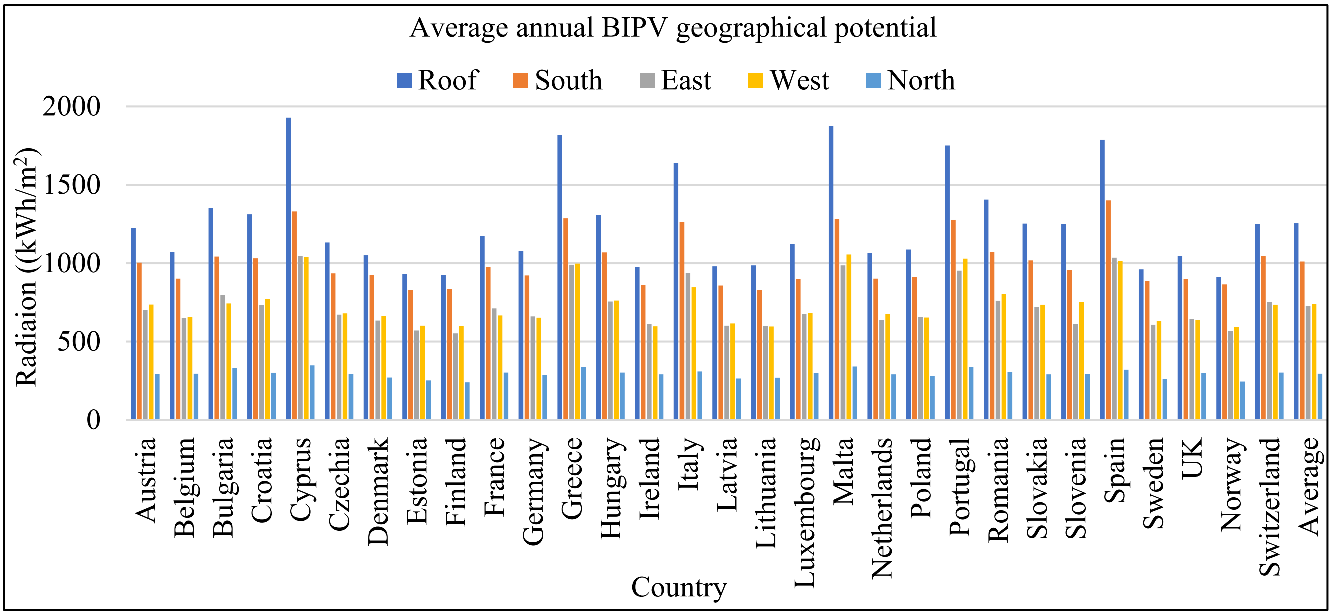


Figure 6. The average annual geographical potential of BIPV systems in Europe.

3.3. BIPV Technical Potential

The BIPV technical potential is the output power of the system taking into account the technology and efficiency. It can be calculated using the technical potential, technology, and efficiency data for the BIPV system.

The efficiency levels of BIPV systems varies depending on the technology, climate, configuration, ventilation, and other factors. [50–52]. The average efficiency of BIPV panels in the market is 18% [12]; this is the average efficiency of commercialised BIPV panels in the market, not of BIPVs system under real operating conditions. The BIPV technical potential can, hence, be calculated by multiplying the efficiency of a BIPV panel by its geographical potential. The BIPV technical potential results are presented in Figure 7.

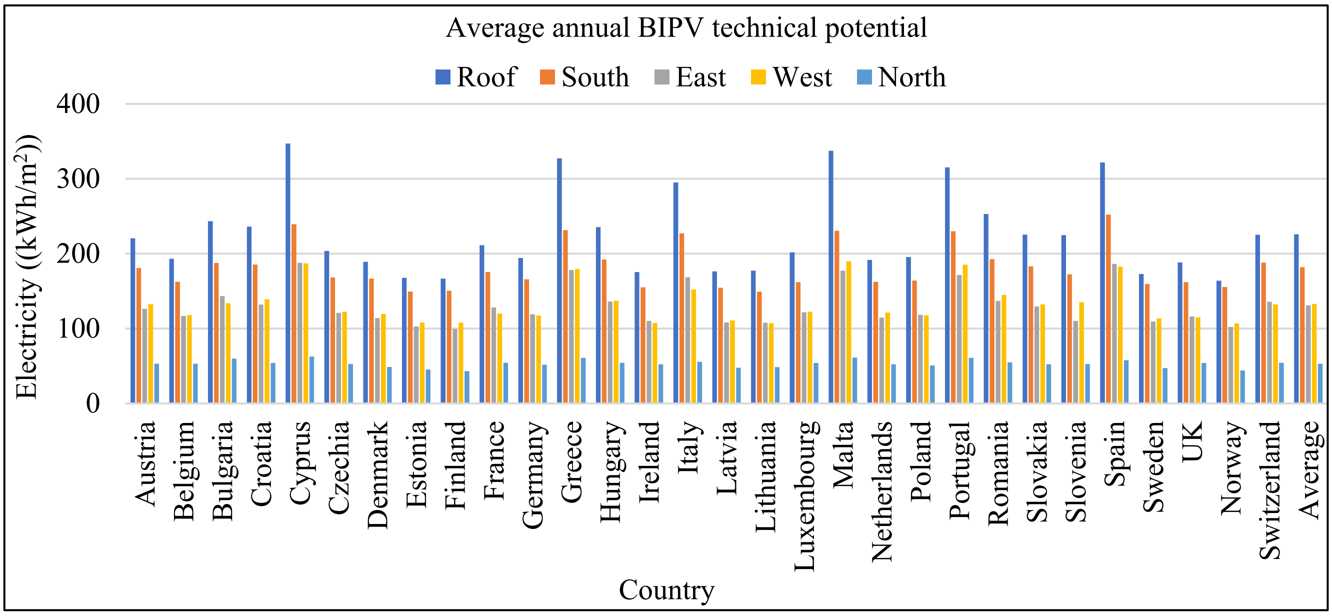


Figure 7. The average annual technical potential of BIPV systems in Europe.

3.4. BIPV Economic Potential

The economic potential of BIPVs is the fraction of the BIPV technical potential that is economically exploitable. This indicator generally require more investigation because of various parameters involved, e.g., the technology, energy tariffs, system degradation rate, market price, annual production, and possible subsidies.

4. Building Energy Consumption in Europe

The average annual specific consumption of European member states for all types of buildings was around 180 kWh per square metre in 2013. The rates vary among members, ranging from 55 kWh/m^2 in Malta and 70 kWh/m^2 for Portugal and Cyprus to 285 kWh/m^2 in Latvia and Estonia and 300 kWh/m^2 in Romania, with the latter rates being significantly higher than the EU average. Nonetheless, even for countries with similar climates, remarkable discrepancies exist. For example, the average annual specific consumption for Sweden is 200 kWh/m^2, which is 18% lower than for Finland. At the same time, both countries have similar climates. Climatic conditions, high shares of space heating or air cooling, technical characteristics of dwellings, and statistical definitions partly explain such differences [53].

The most crucial end-use in the residential sector is space heating, which is responsible for 68% of the energy consumption. Space heating accounts for 60–80% of the total energy consumption in European member state countries, except for the Mediterranean countries. The space heating rates in Malta, Cyprus, and Portugal are below 30%, well below the rate of 50% in Spain and Slovenia. Water heating ranks second, with a reasonably stable contribution of 13%.

Electrical appliances, cooking, and lighting represent 12%, 5%, and 2% of the total energy consumption, respectively [53].

Moreover, the Energy Performance of Buildings Directive (EPBD) regulation will soon come into effect, which requires that all new buildings be nearly zero-energy buildings (nZEB) [54]. The definition of nZEB are buildings that naturally reduce their energy consumption and have incredibly high energy performance. The objective is also to produce as much energy as is consumed.

Another concept that is worth mentioning is passive houses, for which energy production is not the primary goal. The aim of using passive houses is on energy reduction and the use of renewable sources to fill the energy gap. A passive house in Europe, according to the definition presented in [55], should consume 120 kWh/m^2 per year; however, the Scandinavian partners in the project have demonstrated that this benchmark is unrealistic for their countries. Consequently, for the European member state countries with cold climates such as Northern Scandinavia, a more flexible definition of the passive house concept is needed.

Overall, the average annual consumption per m^2 for all types of buildings was around 200 kWh per m^2 in 2012; however, as mentioned earlier, the consumption rates varied significantly among EU countries. For instance, the values for Sweden and Spain were 5% higher and 25% lower than the EU average, respectively.

The EU has committed itself to a 20% reduction of energy consumption by 2020 compared to baseline projections (which is an average of 200 kWh per m^2), which is also known as the 20% energy efficiency target. For the year 2030, the binding target is at least a 32.5% reduction [56]. The energy consumption data for 2012 and the expected development trajectories until 2030 are presented in Table 1, considering the EU expectations.

Table 1. The EU building energy consumption baseline value and trajectory by 2030.

Year	2012	2020	2030
Building energy consumption [kWh m^2.year]	200	160	135

5. The Contribution of BIPV to the Concept of Nearly Zero-Energy Cities

In this section, the aim is to investigate the contribution of BIPV technology to nearly zero-energy cities by assessing the technical potential of BIPV systems.

The business model for the use of BIPV technology is an updated business model that involves three players, namely BIPV manufacturers, BIPV installers, and the main contractors [57]; therefore, BIPV technology will soon be seen as a building envelope material option for building skins in the same way as traditional options such brick, wood, and aluminium. As such, the building skin (BS) potential index is introduced here, which represents the average BIPV potential of the building skins. The BS potential can be calculated from the average BIPV potential values from different aspects of the building envelope, namely the south, east, west, and north facades and the roof area. Table 2 presents the average annual geographical and technical potential of BS for BIPV systems in Europe.

Table 2. The average annual geographical and technical potential of BS for BIPV systems in Europe.

No	Country	Capital	BIPV Geographical Potential of BS (kWh/m^2)	BIPV Technical Potential of BS (kWh/m^2)
1	Austria	Vienna	792	143
2	Belgium	Brussels	715	129
3	Bulgaria	Sofia	853	154
4	Croatia	Zagreb	830	149
5	Cyprus	Nikosia	1138	205
6	Czechia	Prague	742	134
7	Denmark	Copenhagen	709	128
8	Estonia	Tallinn	637	115
9	Finland	Helsinki	631	114
10	France	Paris	766	138
11	Germany	Berlin	720	130
12	Greece	Athens	1086	195
13	Hungary	Budapest	840	151
14	Ireland	Dublin	668	120
15	Italy	Rome	999	180
16	Latvia	Riga	664	120
17	Lithuania	Vilnius	656	118
18	Luxembourg	Luxemburg	736	132
19	Malta	Valleta	1108	199
20	Netherlands	Amsterdam	714	128
21	Poland	Warsaw	718	129
22	Portugal	Lisbon	1070	193
23	Romania	Bucharest	870	157
24	Slovakia	Bratislava	803	145
25	Slovenia	Ljubljana	773	139
26	Spain	Madrid	1112	200
27	Sweden	Stockholm	670	121
28	UK	London	706	127
29	Norway	Oslo	637	115
30	Switzerland	Bern	818	147
-	**EU Average**	**-**	**806**	**145**

A sensitivity analysis is also presented here for Stavanger in Norway, in order to evaluate the effects of the different aspects of the building facades on the BS potential. The building is rotated clockwise at angles of rotation of 10, 20, 30, 40, and 45 degrees, with the results presented in Figure 8. The analysis reveals that the geographical potential of BS is constant, regardless of the building orientation. Since the radiation on the roof is constant as well, it can be concluded that the geographical irradiation potential of the building facades is always a constant value, which is spread over different facades with different orientations.

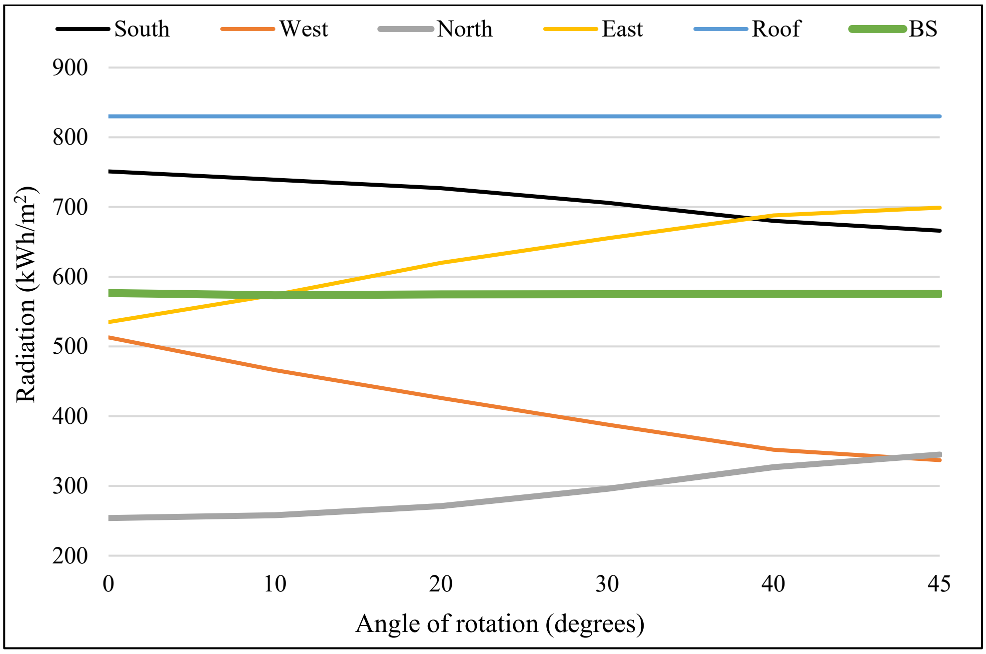


Figure 8. The correlation of the geographical irradiation potential of BS and the building orientation in Stavanger.

In the remainder of this section, the aim is to investigate the impacts of BIPV systems as building envelope materials in shaping nearly zero-energy cities in different climates and countries in Europe. Different BIPV technologies (and their efficiency levels) are investigated to assess whether it is possible to find a relationship between the building energy consumption and BS required to meet the energy demands in European countries.

Before proceeding any further, three more parameters need to be defined, which are the building gross area (BGA), building net area (BNA), and building skin glazing ratio (BSGR). The building gross area is the total area within the walls of a building structure, including the unlivable space (such as the interior walls, outer walls, and internal ducts), as well as the walls themselves. The building net area is the gross floor area of a building, excluding the area occupied by walls and partitions, the circulation area (where people walk), and the mechanical area (which contains mechanical equipment). Generally, the gross floor area is the sum of the floor areas of the spaces within the building, including basements, mezzanine, and other areas. The building energy consumption value is associated with the building net area. The building skin glazing ratio is the proportion of the glazed surface to the total surface of the building skin.

Table 3 summarises the scenario settings for the years 2020 and 2030, indicating the implementation years of the BIPV systems.

Table 3. The different scenario settings.

Year	2020	2030
Building energy consumption (kWh/m^2.year)	160	135
BIPV glass efficiency	7%	13%
BIPV panel efficiency	18%	25%

Table 4 depicts the ratio of the energy consumption of the BNA (EBNA) to the energy production of the BS (EBS) per square metre for the European capitals. In other words, the numbers illustrate how much of the building skin surface is required to meet the energy consumption of one square metre of the building net area. For example, the table shows that in terms of Vienna, which has a BSGR equal to 30% and BIPV implementation date of 2030, the energy consumed by one square metre of the building could be supplied by 0.8 square metres of building skin. In other words, a building with a building skin to building net area ratio of 0.8 in Vienna could be zero-energy by 2030 by employing BIPV technology. It is worth highlighting that the correlation between the EBS and EBNA is linear. This means that in terms of the previous example, a building with a building skin to building net area ratio of 0.6 could supply 80% of the energy consumed by the building, considering all of the mentioned assumptions.

Table 1. The ratio values of the energy consumption of the BNA (EBNA) to the energy production of the BS (EBS) per square metre for the European capitals.

No	Country	Capital	EBNA/EBS					
			BSGR 30%		BSGR 40%		BSGR 50%	
			2020	2030	2020	2030	2020	2030
1	Austria	Vienna	1.37	0.80	1.49	0.84	1.62	0.90
2	Belgium	Brussels	1.52	0.88	1.65	0.93	1.79	0.99
3	Bulgaria	Sofia	1.28	0.74	1.38	0.78	1.50	0.83
4	Croatia	Zagreb	1.31	0.76	1.42	0.81	1.54	0.86
5	Cyprus	Nikosia	0.96	0.55	1.03	0.59	1.12	0.62
6	Czechia	Prague	1.47	0.85	1.59	0.90	1.73	0.96
7	Denmark	Copenhagen	1.54	0.89	1.66	0.94	1.81	1.00
8	Estonia	Tallinn	1.71	0.99	1.85	1.05	2.01	1.12
9	Finland	Helsinki	1.72	1.00	1.86	1.06	2.03	1.13
10	France	Paris	1.42	0.82	1.54	0.87	1.67	0.93
11	Germany	Berlin	1.51	0.88	1.63	0.93	1.78	0.99
12	Greece	Athens	1.00	0.58	1.08	0.62	1.18	0.65
13	Hungary	Budapest	1.30	0.75	1.40	0.80	1.52	0.85
14	Ireland	Dublin	1.63	0.94	1.76	1.00	1.92	1.06
15	Italy	Rome	1.09	0.63	1.18	0.67	1.28	0.71
16	Latvia	Riga	1.64	0.95	1.77	1.01	1.93	1.07
17	Lithuania	Vilnius	1.66	0.96	1.79	1.02	1.95	1.08
18	Luxembourg	Luxemburg	1.48	0.86	1.60	0.91	1.74	0.97
19	Malta	Valleta	0.98	0.57	1.06	0.60	1.16	0.64
20	Netherlands	Amsterdam	1.52	0.88	1.65	0.94	1.79	1.00
21	Poland	Warsaw	1.52	0.88	1.64	0.93	1.78	0.99
22	Portugal	Lisbon	1.02	0.59	1.10	0.62	1.20	0.66
23	Romania	Bucharest	1.25	0.73	1.35	0.77	1.47	0.82
24	Slovakia	Bratislava	1.36	0.79	1.47	0.83	1.59	0.88
25	Slovenia	Ljubljana	1.41	0.82	1.52	0.86	1.66	0.92
26	Spain	Madrid	0.98	0.57	1.06	0.60	1.15	0.64
27	Sweden	Stockholm	1.62	0.94	1.76	1.00	1.91	1.06
28	UK	London	1.54	0.89	1.67	0.95	1.81	1.01
29	Norway	Oslo	1.71	0.99	1.85	1.05	2.01	1.12

30	Switzerland	Bern	1.33	0.77	1.44	0.82	1.56	0.87
-	**EU Average**	**-**	**1.35**	**0.78**	**1.46**	**0.83**	**1.59**	**0.88**

The calculation shows that in terms of the previous example, the total energy consumption of a building with a total skin area (facade + roof) of 800 square metres and a gross floor area of 1000 square metres can be covered by a BIPV system if the technology is used for the entire skin for that building. Accordingly, if half of the skin is covered with such a technology, then half of the energy can be supplied by the BIPV system.

Moreover, there is a clear trend whereby increasing the BSGR ratio will also increase the EBNA-to-EBS ratio, which makes sense because the more a building skin is glazed, the more the surface area is covered by BIPV glass, which is less efficient than BIPV panels.

The figures for Europe indicate that on average, with a building skin to building net area ratio of 0.78 and a BSGR of 30% by 2030, the EU cities could be zero-energy urban areas.

This table is a great asset, as it can be used in the design phase to predict how much of a building's energy demands can be supplied by its skin, not only in the current stage, but also in the future.

6. Challenges and Barriers

The challenges to widespread implementation of the BIPV system are discussed in this chapter. Figure 9 depicts the challenges when it comes to the different stages, as well as the players who are involved in each stage.

The main players in the BIPV market, who are also primary stakeholders with high influence and power with respect to BIPV technology, fall into eight categories, namely politicians, administrations, manufacturers, architects, consultancies, power grid authorities, BIPV contractors and installers, and end-users.

6.1. Decision Challenges.

This stage mainly involves the challenges related to society's mindset. These challenges can be divided into three groups, namely initial investment challenges, alternative options for BIPV, and market business model complications.

6.1.1. Initial Investment

People in society are aware of the high capital costs involved in the implementation of BIPV systems, as well as the long-term advantages of such systems. BIPV systems are integrated parts of buildings; hence, they are calculated into the total costs of the building or renovation project, although the costs and revenues should be priced independently. In other words, the building owners and contractors generally tend only to calculate the overall investment costs and do not consider the beneficial financial impacts of earnings from electricity sales to third parties, substituted power purchases, government incentives, and so on [58]. The literature also supports this claim that many (specifically poorer or older) individuals are not versed in financial matters and avoid making investments when they feel unqualified to make decisions [58–60].

6.1.2. Alternatives

The costs of BIPV systems for the building owners and the contractors are evaluated against alternative building components, which may result in a psychological disadvantage [58]. Such comparisons persuade clients to drop the idea of BIPV implementation in favour of the other alternatives; however, recent studies have shown that BIPV systems are economically much more feasible than other alternatives, e.g., wood, glass, and stone [12,13]. It has recently become clear that BIPV materials can be used as a solution for the entire building skin, regardless of the orientation or direction. In other words, when an architect is searching for building envelope materials, BIPV materials should be acknowledged as feasible and reasonable options that have a major advantage over other choices, namely the dual functionality of BIPV systems, which makes the building envelope a source of income for the buildings.

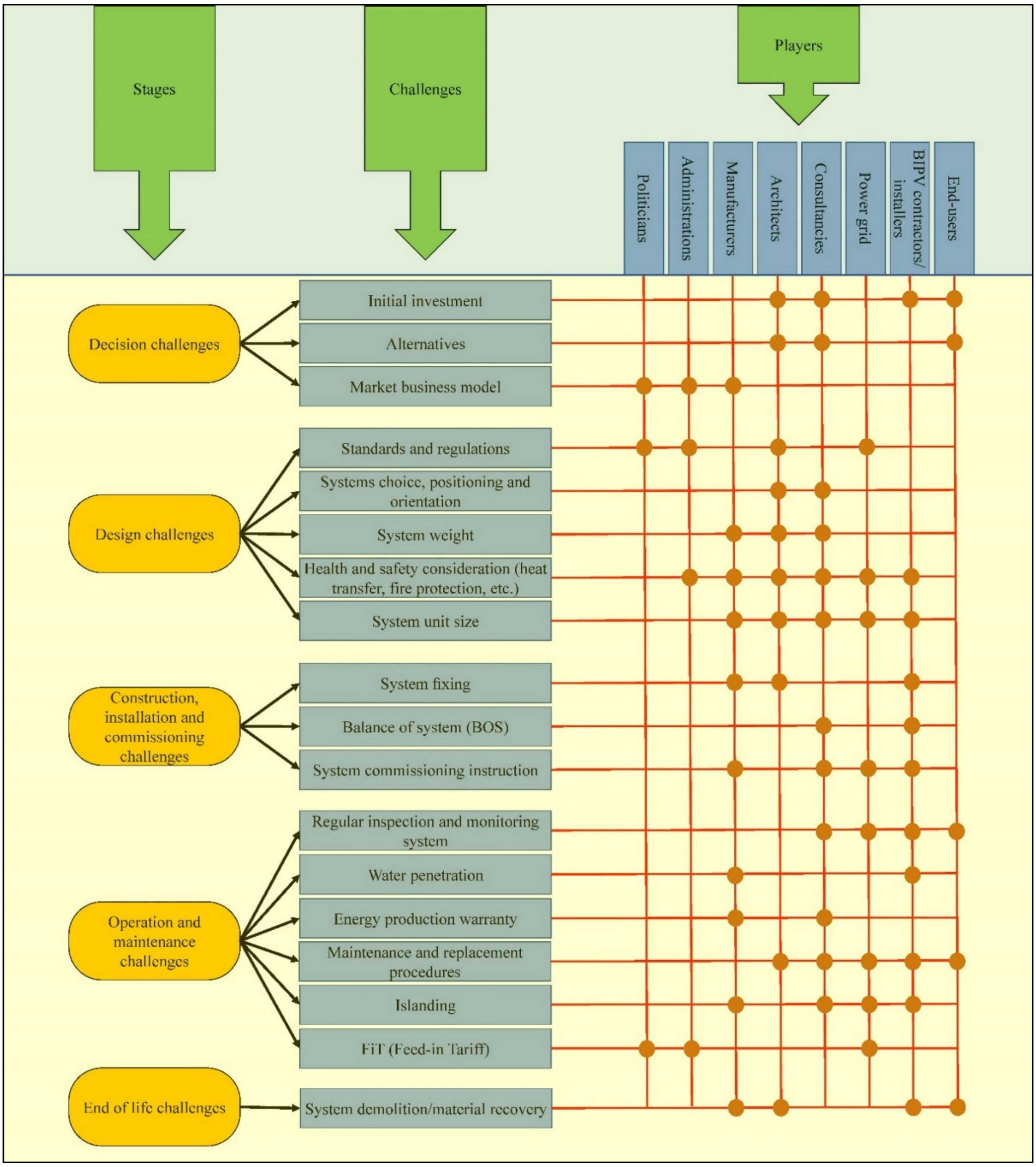


Figure 9. BIPV barrier classification and involved stakeholders who can contribute to the solutions.

6.1.3. Market Business Model

The current business model for the BIPV market is complicated, with many players such as glass producers, PV producers, building element producers, building element installers, BIPV installers, and contractors. Recent developments in the BIPV market have heightened the need for new innovative business models for BIPV in order for the technology to survive as an stand-alone industry without subsidies or government support. One possibility could be to vertically combine the roles of the existing stakeholders, resulting in a new business model with only three stakeholders, namely BIPV producers, installers, and contractors [57].

6.2. Design Challenges

The challenges in the design stage are related to either BIPV manufacturing procedures or the architectural design process. Challenges related to standards and regulations, system choices and positioning, health and safety considerations, system weight, and unit size are decreased in this category.

6.2.1. Standards and Regulations

BIPV systems fulfil two functions in buildings [12], meaning they must conform to both the design standards and codes regarding the electrical characteristics of PV systems and those for buildings that are in force in the country of use. The dual functionality of BIPV systems from this point of view is an obstruction. Even something as simple as the use of metric standards can complicate BIPV deployments. The PV industry uses watt peak units to measure the system size (which measures the electrical output), while the construction industry uses square metres to measure the system size (which measures surface area). Moreover, the construction policies and regulations sometimes vary, even between the urban blocks of a city, making the market more complicated. [21].

Furthermore, countries such as Australia and Canada until recently (and perhaps still) had challenges and issues with how the building codes should be applied for different BIPV technologies and materials [61]. Architectural and building standards and regulations for protected historical buildings are also a hindrance when integrating PV systems, which calls for innovative and creative solutions for BIPV systems [62]. In Europe, BIPV technologies have not yet been independently classed under any standard, regulation, or set of guidelines that could serve as a harmonised European framework for widespread use [63]. BIPV manufacturers in Europe still demand and are looking for a plenary and comprehensive standard that can be used to promote BIPV technology [64]; therefore, the development accredited training programs and unified building regulations to promote BIPV applications via governments and other stakeholders seems crucial [65]. this transition calls for close and intertwined collaboration between politicians, administrations, architects, and power grid authorities.

6.2.2. System, Positioning, and Orientation Choices

Inappropriate choices relating to the components, positioning, and orientation of a BIPV system are additional barriers. Although architects generally decide to use BIPV systems for aesthetic reasons [58], it is crucial to investigate which kinds of systems and components are required and feasible for each building. Furthermore, the BIPV technology and materials play key roles when it comes to inclination, orientation, and shadows. Thanks to recent technological advances, a wide range of BIPV technologies are available in the market that are suitable for different climates and orientations. In terms of system configuration, the inverter is an important component in the BIPV system power production process [61,66–68].

Moreover, BIPV systems are usually designed and implemented based on the available space on the building skin or the building needs, without an assessment being performed prior to installation to show the expected performance of the system, leading to inappropriate system design and suboptimal performance [65].

The fact is that adopting appropriate components could be excessively difficult for architects and designers, and the most efficient solution might be to seek help from consultants in the BIPV system design process. This decision would also lead to the elimination of several technical issues in the early design stage [69].

6.2.3. System Weight

In many cases, BIPV systems are employed during building refurbishment or renovations, even though the building may not have been designed to support the additional weight [61,70,71]; this can potentially lead to the collapse of buildings. New technologies such as thin-film cells and organic cells have addressed this issue to a great extent; however, their efficiency is still low compared to equivalent but heavier BIPV systems, such as crystalline silicon cells.

In addition to the BIPV system weight, the system may cause other loads to act on the building from time to time, such as those caused by snow, ice, and wind [65], which might could result in system deformation. This will lead to various failures, which might require repairs or replacement. Caution is also required when it comes to defining design standards and codes for BIPV systems.

6.2.4. Health and Safety Considerations (Heat Transfer, Fire Protection, etc.)

So far there are no standards or building design codes regarding BIPV systems when it comes to health and safety, for example to cover wire failures, fires and electrical faults [65].

BIPV system temperatures can increase through heat transfer from BIPV cells, especially when they are fixed to slate or tiled roofs, meaning some overlap is involved [61]. The solar radiation heats up the BIPV tile cells. Consequently, the heat transfers to the roof space and causes an increase in the roof temperature [72]. Generally, there is no way for heat from the roof to be emitted through the tiles; therefore, the heat moves internally into the building [73]. Fortunately, several solutions to this issue have been proposed recently [61,72–74], such as creating airways at the back of tiles to ensure that air can pass through and cool them down.

In terms of fire protection, there is still a lack of standards in the building codes [75]. Fire and glass breakage tests for BIPV systems show that when they are exposed to a fire source initiated from outside of the building on which they are installed, there are high fire risks because of possible electrical arcs in the BIPV junction boxes or string connectors [61]. Furthermore, there is a lack of standards and building design codes for noise protection in BIPV systems, increasing the design challenges [61,63,75]. For example, while natural ventilation can operate passively with no noise, mechanical ventilation can be more effective in removing excess heat from the system, although it can also cause surplus noise.

6.2.5. System Unit Size

BIPV unit sizes vary from type to type. For roof-mounted BIPV solutions, the unit could be a very small roof tile, a traditional BIPV panel, or a large BIPV foil. The unit size of the BIPV solution can create additional issues. Although a smaller unit size is more desirable for architects, as it give them more flexibility in the design stage, it causes several issues. Such solutions involve a greater number of smaller components, leading to increased labour costs, more electrical connections, and more operation and maintenance challenges because of the numerous connectors required. On the other hand, a bigger unit size solution will create more constraints for the architects but leads to less system complexity, less labour costs, and less operation and maintenance expenses. The BIPV market currently is in a transition state from producing customised products to commercialised building envelope materials that can be used for building skins. In the current state, the different configurations and unit sizes are under investigation; in the near future, the market will determine which solutions will survive.

6.3. Construction, Installation, and Commissioning Challenges

The implementation stage and procedure related to it can also cause several challenges, which are listed here. System fixing, balance of the system, and system commissioning are covered in this stage.

6.3.1. System Fixing

BIPV systems must be accurately designed, engineered, and installed, with the appropriate system fixing method depending on the type of BIPV panel. Recent studies have pointed out that BIPV system fixing failures are a significant technical issue in this category [61,72]. There are currently few options for BIPV mounting systems [76,77]. Recent developments in BIPV mounting systems have fortunately increased the number of mounting system options, moving the industry closer to solving this issue. Further endeavours and collaborations between manufacturers and architects will help tremendously in solving this issue.

6.3.2. Balance of the System (BOS)

The BIPV panels installed on building skins are interconnected and linked back to inverters by wires and connectors to deliver power to the building and network. A portion of the power generated by the BIPV cells is lost in this process. Power losses can be mitigated to a great extent via precise design and installation process [66,77]. In other words, although the cables must be correctly hidden and covered, which should be considered during the design process, it is also the installers’ task to ensure all wires and connectors are installed accurately [78].

6.3.3. System Commissioning Instructions

The lack of guidelines addressing full commissioning after system installation is another issue [66]. Such instructions should be carried out by commissioning technicians to ensure the system is fully operational and free of risks, danger, and defects [73,79]. Recently implemented BIPV projects have heightened the need for a comprehensive commissioning process. The correct commissioning procedure will also ensure that maximal system output and optimal performance are achieved, increasing the financial gain from the system. The system commissioning guidelines must cover at least the following criteria [61,80]:

- Structural compliance, meaning the system conforms to both the specific electrical standards and building codes;
- Electrical safety, meaning the system will not increase the safety risks to the owner;
- System calibration to ensure the forecasted system output is met (by the installers)

6.4. Operation and Maintenance Challenges

Although PV systems (and consequently BIPV systems as a subclass of PV systems) involve low operation and maintenance costs, they can encounter certain challenges that need to be taken into consideration. The regular inspection and monitoring systems, water penetration, energy production warranties, maintenance and replacement procedures, islanding, and feed-in tariff involved in PV systems present unique challenges and barriers, which are discussed here.

6.4.1. Regular Inspection and Monitoring Systems

One of the major issues with BIPV systems when they begin operation or even during the system commissioning process (to ensure the system works as intended) is the lack of monitoring of system performance. A regular monitoring procedure is crucial in order to identify any failures and to implement the required changes to the system settings to make sure the system operates at maximum performance for a long time [61,65,80,81].

The lack of monitoring and fault alert systems, which ensure any faults throughout the system's lifespan are reported in an appropriate and timely manner, could inhibit the widespread rollout of BIPV systems and could enhance the perception of system complexity [82].

6.4.2. Water Penetration

Another crucial issue is the wind-driven rain effects [61], which lead to water penetration. Accelerated raindrops permeate through the BIPV structure via the joints and overlap sections [63]. This phenomenon causes water penetration and leads to technical problems in BIPV systems, including condensation created by humidity, which can lead to failure of the BIPV system's overall function, as well as damage to interior building components [71,72]. The implementation of a continuous and seamless underlayer sheet on the top of the roof structure and below the system during construction might be a solution to this issue when it comes to the roof-mounted BIPV systems [83].

6.4.3. Energy Production Warranty

BIPV projects could be more attractive to even conservative investors if the bidder were to receive a specific annual energy production warranty, for example for a period of ten years; however, there are few BIPV contractors willing to do so [61,84]. A long-term energy production performance warranty could be a tremendous driving factor for building owners, which could result in the rapid rollout of BIPV systems. It is the responsibility of the manufacturers and consultants to warrant the system production performance while considering the system location, orientation, components, climate, and other factors [85].

6.4.4. Maintenance and Replacement Procedures

Architects and designers generally do not take the maintenance and replacement of damaged BIPV modules and parts into consideration in the design stage, meaning there is often no appropriate access to wiring and external fixings; this causes complicated issues when BIPV modules need to be replaced [65,86]. Furthermore, BIPV systems as the skins of buildings need to be maintained regularly. System designers, therefore, should take the post-installation considerations (i.e., BIPV maintenance and replacement) of the systems into account, in addition to their design considerations [76,87–89].

Moreover, the BIPV systems installed on the building skins require regular cleaning, the frequency of which might change based on the climate, city, and season. A BIPV system with a clean surface could result in better system performance, as well as a lower degradation rate.

6.4.5. Islanding

Islanding is a state where a section of the utility system (the BIPV system in this case), which carries the load and distributed resources simultaneously, remains energised whilst being isolated physically from the rest of the utility system [78]. Islanding can cause significant damage to both the BIPV systems and the installers and maintenance workers (possibly even resulting in death).

The point of common coupling (PCC) is a crucial area involved in this issue. The PCC [90] is the point where the production facility's local electric power system (such as the BIPV) bridges to the electrical company's electricity system (such as the electric power revenue metre). It is also the location of the equipment designated to disconnect, separate, or interrupt the link between the electrical company and the generating facility.

Conventional BIPV inverters function autonomously, delivering electricity while monitoring the frequency and voltage at the PCC to check for disturbances. When it comes to a more extended level of production, this results in significant power generation that is difficult to be manage or control [61]. The utility must be able to either remotely shut down the distributed energy resources when required or apply power management functions to the grid smart inverter (individually or as an aggregate).

6.4.6. FiT (Feed-In Tariff)

A feed-in tariff (FiT) is a course of action designed to accelerate investment in renewable energy technologies via the sale of (excess) power generated by renewable energy resources at a price that is generally higher than the selling price from the power grid. Some countries such as France and Germany have promoted solar energy to a great extent by taking such actions; however, there is still no FiT in many other European countries. In Norway, as an example, the FiT for the power produced by BIPV systems is normally equal to the power production costs of the power plants. The selling price of the electricity to the end-users is the sum of the power production cost of the power plant, tax on the power production cost of the power plant, the transmission cost, tax on the transmission cost, and VAT on the total cost. In order for widespread rollout of BIPV systems in urban areas to be achieved, the FiT must equal the finished electricity price for power sold by the grid authorities to customers; however, many recent studies have illustrated that the societal and environmental benefit of BIPV systems in urban areas are significant and that the FiT should be even greater than the network price [12,13,91]

6.5. End of Life Challenges

Once the BIPV system lifetime is over, the system needs to be dismantled and demolished. The demolition and material recovery procedures present certain challenges, which are discussed in this section.

System Demolition and Material Recovery

End-of-life modelling is also another challenge. Researchers have shown increased interest in this issue recently. The studies exploring the end-of-life benefits of BIPV systems are very limited and mostly in line with the studies on conventional photovoltaics (PV) systems. It is estimated that by 2030, the generated PV waste will be around 1.7 million tonnes, while by 2050 this could even increase up to 60 million tonnes [92]. A recent study showed that from a PV or BIPV module weighing 20 kg, approximately 19 kg of useful materials can be recovered; however, this figure varied based on the demanufacturing or recycling approaches used [93].

7. Conclusions

This study goes some way towards enhancing our understanding of the impacts of BIPV systems on the energy transition of cities and the notion of nearly zero-energy cities in Europe, by defining a metric that can be used by architects and urban planners to assess how much of the energy consumed by buildings in Europe could be supplied by BIPV systems when implemented as building envelope materials over the entire building envelope surface area.

The results show how much different European countries can rely on BIPV technology in the energy transition journey in urban areas. Eighteen barriers and challenges ahead of the extensive rollout of BIPV systems are categorised and discussed in detail.

The results illustrate that BIPV technology could contribute to a great extent to meeting the energy demands in urban areas. The assessment of the capitals of all European Union member states (EU), together with the capitals of Norway and Switzerland, shows that on average, with a building skin to building net area ratio of 0.78, BSGR rate of 30%, BIPV glass and BIPV panel efficiency levels of 13% and 25%, and building energy consumption rate of 135 kWh/m^2.year by 2030, EU cities could reach the target of becoming zero-energy urban areas.

This study does not consider constraints related to the urban context of the case studies, such as shading issues; building barriers; and historical, architectural, and regulatory constraints. Future studies could evaluate the effects of the urban context, as well as the effects of climate and different technologies, on the results of this article.

The presented study could not only help the end-users and architects recognise BIPV systems as suitable options for building skins in Europe, but could also encourage governments and decision-makers to promote BIPV systems via rational subsidies and incentives to expand the role of this technology in the urban energy transition.

Funding: The work reported in this paper was supported by the Department of Safety, Economics, and Planning of the University of Stavanger (Project name: Building Integrated Photovoltaic (BIPV) in dense urban areas, Project number: IN-12011).

Acknowledgments: This paper was supported by the Department of Safety, Economics, and Planning of the University of Stavanger (Building-Integrated Photovoltaic (BIPV) Systems in Dense Urban Areas, project number: IN-12011). Special thanks also go to the Smart City Group and Future Energy Hub at the University of Stavanger for their support. The authors would like to offer their gratitude to Dr. Siddharth Sareen for his valuable comments during the summer school at the University of Bergen.

References

1. Mora, C.; Frazier, A.; Longman, R.J.; Dacks, R.S.; Walton, M.M.; Tong, E.J.; Sanchez, J.J.; Kaiser, L.; Stender, Y.O.; Anderson, J.; et al. The projected timing of climate departure from recent variability. *Nat. Cell Biol.* **2013**, *502*, 183–187.

2. National Centers for Environment Information. State of the Climate: Global Climate Report for Annual 2016. 2017. Available online: https://www.ncdc.noaa.gov/sotc/global/201613 (accessed on 1 March 2021).
3. Falkner, R. The Paris Agreement and the new logic of international climate politics. *Int. Aff.* **2016**, *92*, 1107–1125.
4. International Monetary Fund (IMF). *Fiscal Monitor: How to Mitigate Climate Change*; IMF: Washington, DC, USA, 2019.
5. Breitmeier, H.; Kuhn, J.; Schwindenhammer, S. Analyzing urban adaptation strategies to climate change: A comparison of the coastal cities of Dhaka, Lagos and Hamburg. In *Contribution to the Panel, Regieren im Klimawandel Section, Regierungssystem und Regieren in der Bundesrepublik Deutschland*; DVPW-Kongress: Berlin, Germany, 2009; Volume 21, p. 25.
6. I. Cities Climate Leadership Group. Why Cities? Available online: https://www.c40.org/why_cities (accessed on 1 March 2021).
7. United Nations, Department of Economic and Social Affairs, Population Division. *World Population Prospects: The 2017 Revision, Key Findings and Advance Tables*; Department of Economics and Social Affairs: New York, NY, USA, 2017.
8. United Nations. World Urbanization Prospects: The 2018 Revision. 2019. Available online: https://population.un.org/wup/Publications/Files/WUP2018-Report.pdf (accessed on 1 March 2021.
9. Villa-Arrieta, M.; Sumper, A. Economic evaluation of Nearly Zero Energy Cities. *Appl. Energy* **2019**, *237*, 404–416, doi:10.1016/j.apenergy.2018.12.082.
10. Check, R.; Space-based, P.; Percent, K.; Shingles, E. *The Future of Solar Energy*; MIT Press: Cambridge, MA, USA, 2015; pp. 3–6.
11. Gholami, H.; Røstvik, H.N.; Müller-Eie, D. Analysis of solar radiation components on building skins for selected cities. In Proceedings of the 14th Conference on Advanced Building Skins, Bern, Switzerland, 28–29 October 2019; pp. 541–549.
12. Gholami, H.; Røstvik, H.N. Economic analysis of BIPV systems as a building envelope material for building skins in Europe. *Energy* **2020**, *204*, 117931, doi:10.1016/j.energy.2020.117931.
13. Gholami, H.; Røstvik, H.N.; Müller-Eie, D. Holistic economic analysis of building integrated photovoltaics (BIPV) system: Case studies evaluation. *Energy Build.* **2019**, *203*, 109461, doi:10.1016/j.enbuild.2019.109461.
14. Kalogirou, S. Thermal performance, economic and environmental life cycle analysis of thermosiphon solar water heaters. *Sol. Energy* **2009**, *83*, 39–48.
15. Ibrahim, A.; Fudholi, A.; Sopian, K.; Othman, M.Y.; Ruslan, M.H. Efficiencies and improvement potential of building integrated photovoltaic thermal (BIPVT) system. *Energy Convers. Manag.* **2014**, *77*, 527–534.
16. Groppi, D.; de Santoli, L.; Cumo, F.; Garcia, D.A. A GIS-based model to assess buildings energy consumption and usable solar energy potential in urban areas. *Sustain. Cities Soc.* **2018**, *40*, 546–558, doi:10.1016/j.scs.2018.05.005.
17. Buonomano, A.; Forzano, C.; Kalogirou, S.A.; Palombo, A. Building-façade integrated solar thermal collectors: Ener-gy-economic performance and indoor comfort simulation model of a water based prototype for heating, cooling, and DHW production. *Renew. Energy* **2019**, *137*, 20–36.
18. Gholami, H.; Sarwat, A.; Hosseinian, S.H.; Khalilnejad, A. Evaluation of optimal dual axis concentrated photovoltaic thermal system with active ventilation using Frog Leap algorithm. *Energy Convers. Manag.* **2015**, *105*, 782–790, doi:10.1016/j.enconman.2015.08.033.
19. Gholami, H.; Khalilnejad, A.; Gharehpetian, G.B. Electrothermal performance and environmental effects of optimal photovoltaic–thermal system. *Energy Convers. Manag.* **2015**, *95*, 326–333, doi:10.1016/j.enconman.2015.02.014.
20. Reddy, P.; Gupta, M.V.N.; Nundy, S.; Karthick, A.; Ghosh, A. Status of BIPV and BAPV System for Less Energy-Hungry Building in India—A Review. *Appl. Sci.* **2020**, *10*, 2337.

21. Shukla, A.K.; Sudhakar, K.; Baredar, P.; Mamat, R. Solar PV and BIPV system: Barrier, challenges and policy recommendation in India. *Renew. Sustain. Energy Rev.* **2018**, *82*, 3314–3322, doi:10.1016/j.rser.2017.10.013.
22. Gholami, H.; Røstvik, H.N.; Kumar, N.M.; Chopra, S.S. Lifecycle cost analysis (LCCA) of tailor-made building integrated photovoltaics (BIPV) façade: Solsmaragden case study in Norway. *Sol. Energy* **2020**, *211*, 488–502, doi:10.1016/j.solener.2020.09.087.
23. European Commission. Communication from the Commission to the European Parliament and the Council. The Road from Paris: Assessing the Implications of the Paris Agreement and Accompanying the Proposal for a Council Decision on the Signing, on Behalf of the European Union, of the Paris Agreement Adopted Under the United Nations Framework Convention on Climate Change. 2016. Available online: https://op.europa.eu/en/publication-detail/-/publication/62d7fdfb-e607-11e5-8a50-01aa75ed71a1/language-en (accessed on 1 March 2021).
24. Cleveland, C.; Peter, S. Energy transitions past and future. In *Encyclopedia of Earth*; 2008.
25. Davidsson, S. *Global Energy Transitions: A Comparative Analysis of Key Countries and Implications for the International Energy Debate*; World Energy Council, Weltnerergierat: Berlin, Germany, 2014.
26. Daly, H.; Walton, M. *World Energy Outlook 2017*; IEA: Paris, France, 2017.
27. IRENA, I. *Renewable Energy in Cities*; International Renewable Agency: Abu Dhabi, United Arab Emirates, 2016.
28. Steemers, K. Energy and the city: Density, buildings and transport. *Energy Build.* **2003**, *35*, 3–14, doi:10.1016/s0378-7788(02)00075-0.
29. Parag, Y.; Sovacool, B.K. Electricity market design for the prosumer era. *Nat. Energy* **2016**, *1*, 16032.
30. Amado, M.; Poggi, F.; Amado, A.R.; Breu, S. A cellular approach to net-zero energy cities. *Energies* **2017**, *10*, 1826.
31. Todorovic, B. Towards zero energy buildings: New and retrofitted existing buildings. In Proceedings of the 2011 IEEE 3rd International Symposium on Exploitation of Renewable Energy Sources (EXPRES), Subotica, Serbia, 11–12 March 2011; pp. 7–14.
32. MacDonald, S.; Headlam, N. *Research Methods Handbook: Introductory Guide to Research Methods for Social Research*; Centre for Local Economic Strategies: Manchester, UK, 2008.
33. Yang, R.J.; Zou, P.X. Building integrated photovoltaics (BIPV): Costs, benefits, risks, barriers and improvement strategy. *Int. J. Constr. Manag.* **2016**, *16*, 39–53.
34. Esmailian, E.; Gholami, H.; Røstvik, H.N.; Menhaj, M.B. A novel method for optimal performance of ships by simultaneous optimisation of hull-propulsion-BIPV systems. *Energy Convers. Manag.* **2019**, *197*, 111879, doi:10.1016/j.enconman.2019.111879.
35. Nguyen, K.C.; Katzfey, J.J.; Riedl, J.; Troccoli, A. Potential impacts of solar arrays on regional climate and on array efficiency. *Int. J. Clim.* **2017**, *37*, 4053–4064, doi:10.1002/joc.4995.
36. Armstrong, A.; Waldron, S.; Whitaker, J.; Ostle, N. Wind farm and solar park effects on plant-soil carbon cycling: Uncertain impacts of changes in ground-level microclimate. *Glob. Chang. Biol.* **2014**, *20*, 1699–1706, doi:10.1111/gcb.12437.
37. Bloem, J.; Baker, P. Building integration issues for photovoltaics. In Proceedings of the BIAT–Technical Innovation in Design and Contsruction, Dublin Castle, Ireland, 2000.
38. Jelle, B.P. Building Integrated Photovoltaics: A Concise Description of the Current State of the Art and Possible Research Pathways. *Energies* **2015**, *9*, 21, doi:10.3390/en9010021.
39. NREL Efficiency Chart. Available online:https://www.nrel.gov/pv/cell-efficiency.html (accessed on 1 March 2021).
40. Fraunhofer Institute for Solar Energy Systems. Photovoltaic Report. 2020. Available online: https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf (accessed on 1 March 2021).
41. ClearVue Technologies Limited. Advanced Glazing Technology. Available online: http://www.clearvuepv.com/products-solutions/technology/ (accessed on 1 March 2021).

42. Randers, J. *2052: A Global Forecast for the Next Forty Years*; Chelsea Green Publishing: White River Junction, Vermont, VT, USA, 2012.
43. Kaltschmitt, M.; Wiese, A. *Potentiale und Kosten regenerativer Energieträger in Baden-Württemberg*; Springer: Berlin/Heidelberg, Germany, 1992.
44. Kaltschmitt, M.; Wiese, A. *Erneuerbare Energieträger in Deutschland: Potentiale und Kosten*; Springer: Berlin, Germany, 2013.
45. Mondal, M.A.H.; Denich, M. Assessment of renewable energy resources potential for electricity generation in Bangla-desh. *Renew. Sustain. Energy Rev.* **2010**, *14*, 2401–2413.
46. Quaschning, V. *Systemtechnik einer Klimaverträglichen Elektrizitätsversorgung in Deutschland für das 21. Jahrhundert*; VDI: Düsseldorf, Germany, 2000.
47. Mainzer, K.; Fath, K.; McKenna, R.; Stengel, J.; Fichtner, W.; Schultmann, F. A high-resolution determination of the technical potential for residential-roof-mounted photovoltaic systems in Germany. *Sol. Energy* **2014**, *105*, 715–731.
48. Solargis s.r.o. Solar Resource Maps of Europe. Available online: https://solargis.com (accessed on 1 March 2021).
49. Photovoltaic Geographical Information System (PVGIS). Overview of PVGIS Data Sources and Calculation Methods. Available online: https://ec.europa.eu/jrc/en/PVGIS/docs/methods (accessed on 1 March 2021).
50. Biyik, E.; Araz, M.; Hepbasli, A.; Shahrestani, M.; Yao, R.; Shao, L.; Essah, E.; Oliveira, A.; del Caño, T.; Rico, E.; et al. A key review of building integrated photovoltaic (BIPV) systems. *Eng. Sci. Technol. Int. J.* **2017**, *20*, 833–858.
51. Shukla, A.K.; Sudhakar, K.; Baredar, P. Recent advancement in BIPV product technologies: A review. *Energy Build.* **2017**, *140*, 188–195.
52. Gholami, H.; Røstvik, H.N. Dataset for the Solar Incident Radiation and Electricity Production BIPV/BAPV System on the Northern/Southern Façade in Dense Urban Areas. *Data* **2021**, *6*, 57, doi:10.3390/data6060057.
53. European Commission. Energy Use in Buildings. Available online: https://ec.europa.eu/energy/eu-buildings-factsheets-topics-tree/energy-use-buildings_en (accessed on 1 March 2021).
54. European Commission. Progress towards Nearly Zero-Energy Buildings Uptake. Available online: https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/nearly-zero-energy-buildings_en (accessed on 17 August 2020).
55. European Commission. Promotion of European Passive Houses (PEP). 2020. Available online: https://ec.europa.eu/energy/intelligent/projects/en/projects/pep#results (accessed on 1 March 2021).
56. Eurostat. Energy Saving Statistics. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_saving_statistics#cite_ref-2 (accessed on 1 March 2021).
57. Osseweijer, F.J.; Van Den Hurk, L.B.; Teunissen, E.J.; van Sark, W. A comparative review of building integrated photovoltaics ecosystems in selected European countries. *Renew. Sustain. Energy Rev.* **2018**, *90*, 1027–1040.
58. Curtius, H.C. The adoption of building-integrated photovoltaics: Barriers and facilitators. *Renew. Energy* **2018**, *126*, 783–790, doi:10.1016/j.renene.2018.04.001.
59. Lusardi, A.; Mitchell, O.S.; E Curto, V. Financial literacy and financial sophistication in the older population. *J. Pension- Econ. Finance* **2014**, *13*, 347–366.
60. Campbell, J.Y. Household finance. *J. Financ.* **2006**, *61*, 1553–1604.
61. Yang, R.J. Overcoming technical barriers and risks in the application of building integrated photovoltaics (BIPV): Hardware and software strategies. *Autom. Constr.* **2015**, *51*, 92–102, doi:10.1016/j.autcon.2014.12.005.
62. Rosa, F. Building-Integrated Photovoltaics (BIPV) in Historical Buildings: Opportunities and Constraints. *Energies* **2020**, *13*, 3628.

63. Yoon, J.-H.; Song, J.; Lee, S.-J. Practical application of building integrated photovoltaic (BIPV) system using transparent amorphous silicon thin-film PV module. *Sol. Energy* **2011**, *85*, 723–733.
64. Building Integrated PV Needs Better Regulation. Available online: https://www.pveurope.eu/solar-generator/building-integrated-pv-needs-better-regulation (accessed on 1 March 2021).
65. Agathokleous, R.A.; Kalogirou, S.A. Status, barriers and perspectives of building integrated photovoltaic systems. *Energy* **2020**, *191*, 116471, doi:10.1016/j.energy.2019.116471.
66. Lam, K.-H.; Close, J.; Lo, E.W. Dynamic Model of BIPV System for Performance Prediction. In Proceedings of the 2006 IEEE 4th World Conference on Photovoltaic Energy Conference, Waikoloa, HI, USA, 7–12 May 2006; Volume 2, pp. 2434–2437.
67. Tao, L.; Zhao, Z.Q. Several Application Methods Researches of the Solar Technology in the Architectural Design. *Appl. Mech. Mater.* **2011**, *71–78*, 1728–1731.
68. Paul, D.; Mandal, S.; Mukherjee, D.; Chaudhuri, S.B. Optimization of significant insolation distribution parameters—A new approach towards BIPV system design. *Renew. Energy* **2010**, *35*, 2182–2191.
69. Koinegg, J.; Brudermann, T.; Posch, A.; Mrotzek, M. "It would be a shame if we did not take advantage of the spirit of the times"an analysis of prospects and barriers of building integrated photovoltaics. *Gaia-Ecol. Perspect. Sci. Soc.* **2013**, *22*, 39–45.
70. Kosoric, V.; Wittkopf, S.; Huang, Y. Testing a design methodology for building integration of photovoltaics (PV) using a PV demonstration site in Singapore. *Arch. Sci. Rev.* **2011**, *54*, 192–205.
71. Ikedi, C.; Okoroh, M.; Dean, A.; Omer, S. Impact assessment for building integrated photovoltaic (BIPV). In Proceedings of the 26th Annual ARCOM Conference (Association of Researchers in Construction Management), Leeds, UK, 6–8 September 2010; pp. 1407–1415.
72. Heinstein, P.; Ballif, C.; Perret-Aebi, L.-E. Building integrated photovoltaics (BIPV): Review, potentials, barriers and myths. *Green* **2013**, *3*, 125–156.
73. Frontini, F.; Manfren, M.; Tagliabue, L.C. A Case Study of Solar Technologies Adoption: Criteria for BIPV Integration in Sensitive Built Environment. *Energy Procedia* **2012**, *30*, 1006–1015.
74. Quesada, G.; Rousse, D.; Dutil, Y.; Badache, M.; Hallé, S. A comprehensive review of solar facades. Opaque solar facades. *Renew. Sustain. Energy Rev.* **2012**, *16*, 2820–2832.
75. Scott, K.; Zielnik, A. Developing codes and standards for BIPV and integrated systems. In Proceedings of the International Photovoltaic Reliability Workshop, Tempe, Arizona, AZ, USA, 29–31 July 2009.
76. Peng, C.; Huang, Y.; Wu, Z. Building-integrated photovoltaics (BIPV) in architectural design in China. *Energy Build.* **2011**, *43*, 3592–3598.
77. Muller, M.; Rodriguez, J.; Marion, B. Performance comparison of a BIPV roofing tile system in two mounting configurations. In Proceedings of the 2009 34th IEEE Photovoltaic Specialists Conference (PVSC), Philadelphia, PA, USA, 7–12 June 2009; pp. 000817–000822.
78. Azadian, F.; Radzi, M. A general approach toward building integrated photovoltaic systems and its implementation bar-riers: A review. *Renew. Sustain. Energy Rev.* **2013**, *22*, 527–538.
79. Omer, S.; Wilson, R.; Riffat, S. Monitoring results of two examples of building integrated PV (BIPV) systems in the UK. *Renew. Energy* **2003**, *28*, 1387–1399.
80. Prasad, D.; Snow, M.; Watt, M. *Best Practice Guidelines for Solar Power Building Projects in Australia. Renewable Energy Industry Development (REID 7) Program*; The University of New South Wales (UNSW): Kensington, Australia, 2005.
81. Dougherty, B.P.; Fanney, A.H.; Davis, M.W. Measured Performance of Building Integrated Photovoltaic Panels: Round 2. *Solar Energy* **2004**, *37475*, 421–430, doi:10.1115/isec2004-65154.
82. Close, J.; Lam, K.-H.; Pang, H. From PILOT to ROLLOUT: Capacity building and stakeholder engagement to promote a territory-wide BIPV programme. In Proceedings of the 2006 IEEE 4th World Conference on Photovoltaic Energy Conference, Waikoloa, HI, USA, 7–12 May 2006; Volume 2, pp. 2536–2539.
83. Fasana, S.; Nelva, R. Improvementt of the water resistancy in the integration of photovoltaic panels on traditional roofs. *Constr. Build. Mater.* **2013**, *48*, 1081–1091.

84. Strong, S. *Building Integrated Photovoltaics (BIPV)*; Whole Building Design Guide: Washington, DC, USA, 2010; Volume 9.
85. Gholami, H.; Røstvik, H.N. The Effect of Climate on the Solar Radiation Components on Building Skins and Building Integrated Photovoltaics (BIPV) Materials. *Energies* **2021**, *14*, 1847, doi:10.3390/en14071847.
86. Sozer, H.; Elnimeiri, M. Identification of barriers to PV application into the building design. *Int. Sol. Energy Conf.* **2003**, *36762*, 527–533.
87. Sun, Y.; Mi, Z.-C.; Luo, L. Analysis on key issues about extension of BIPV. *Constr. Conserves Energy* **2011**, *39*, 41–43.
88. Urbanetz, J.; Zomer, C.D.; Rüther, R. Compromises between form and function in grid-connected, building-integrated photovoltaics (BIPV) at low-latitude sites. *Build. Environ.* **2011**, *46*, 2107–2113.
89. Roberts, S.; Guariento, N. *Building integrated Photovoltaics: A Handbook*; Walter de Gruyter: Berlin, Germany, 2009.
90. Definition of Point of Common Coupling Share Cite Open Split View. Available online: https://www.lawinsider.com/dictionary/point-of-common-coupling (accessed on 1 March 2021.
91. Gholami, H.; Røstvik, H.N. Levelised Cost of Electricity (LCOE) of Building Integrated Photovoltaics (BIPV) in Europe, rational feed-in tariffs and subsidies. *Energies* **2021**, *14*, 2531, doi:10.3390/en14092531.
92. Gangwar, P.; Kumar, N.M.; Singh, A.K.; Jayakumar, A.; Mathew, M. Solar photovoltaic tree and its end-of-life man-agement using thermal and chemical treatments for material recovery. *Case Stud. Therm. Eng.* **2019**, *14*, 100474.
93. Granata, G.; Pagnanelli, F.; Moscardini, E.; Havlik, T.; Toro, L. Recycling of photovoltaic panels by physical operations. *Sol. Energy Mater. Sol. Cells* **2014**, *123*, 239–248.

References

[1] K. Steemers, "Energy and the city: density, buildings and transport," *Energy and Buildings,* vol. 35, no. 1, pp. 3-14, 2003/01/01/ 2003, doi: https://doi.org/10.1016/S0378-7788(02)00075-0.

[2] C. Mora *et al.*, "The projected timing of climate departure from recent variability," vol. 502, no. 7470, pp. 183-187, 2013.

[3] N. N. C. f. E. Information, "State of the Climate: Global Climate Report for Annual 2016," 2017. [Online]. Available: https://www.ncdc.noaa.gov/sotc/global/201613

[4] R. J. I. A. Falkner, "The Paris Agreement and the new logic of international climate politics," vol. 92, no. 5, pp. 1107-1125, 2016.

[5] IEA, "Net Zero by 2050," Paris, 2021. [Online]. Available: https://www.iea.org/reports/net-zero-by-2050

[6] R. Cazzaniga and M. Rosa-Clot, "The booming of floating PV," *Solar Energy,* vol. 219, pp. 3-10, 2021/05/01/ 2021, doi: https://doi.org/10.1016/j.solener.2020.09.057.

[7] J. D. S. Barkaszi, "Discussion of strategies for mounting photovoltaic arrays on rooftops," in *International solar energy conference*, Washington, DC, 2001.

[8] H. Gholami, H. Nils Røstvik, N. Manoj Kumar, and S. S. Chopra, "Lifecycle cost analysis (LCCA) of tailor-made building integrated photovoltaics (BIPV) façade: Solsmaragden case study in Norway," *Solar Energy,* vol. 211, pp. 488-502, 2020/11/15/ 2020, doi: https://doi.org/10.1016/j.solener.2020.09.087.

[9] H. Gholami and H. N. Røstvik, "Economic analysis of BIPV systems as a building envelope material for building skins in Europe," *Energy,* vol. 204, p. 117931, 2020/08/01/ 2020, doi: https://doi.org/10.1016/j.energy.2020.117931.

[10] H. Gholami, H. N. Røstvik, and D. Müller-Eie, "Holistic economic analysis of building integrated photovoltaics (BIPV) system: Case studies evaluation," *Energy and Buildings,* vol. 203, p. 109461, 2019/11/15/ 2019, doi: https://doi.org/10.1016/j.enbuild.2019.109461.

[11] H. Gholami and H. Nils Røstvik, "The Effect of Climate on the Solar Radiation Components on Building Skins and Building Integrated Photovoltaics (BIPV) Materials," *Energies,* vol. 14, no. 7, p. 1847, 2021. [Online]. Available: https://www.mdpi.com/1996-1073/14/7/1847.

[12] E. Esmailian, H. Gholami, H. N. Røstvik, and M. B. Menhaj, "A novel method for optimal performance of ships by simultaneous optimisation of hull-propulsion-BIPV systems," *Energy Conversion and Management,* vol. 197, p. 111879, 2019, doi: https://doi.org/10.1016/j.enconman.2019.111879.

[13] U. e. AS. "Energibygget Project." https://www.unioneiendom.no/eiendommer-naering/energibygget/?ml=6 (accessed 2021).

[14] H. N. Røstvik, "Sustainable Architecture—What's Next?," *Encyclopedia,* vol. 1, no. 1, pp. 293-313, 2021. [Online]. Available: https://www.mdpi.com/2673-8392/1/1/25.

[15] J. Bloem and P. Baker, "Building integration issues for photovoltaics," *Proceedings of BIAT–Technical Innovation in Design and Contsruction, Dublin Castle,* 2000.

[16] H. Breitmeier, J. Kuhn, and S. Schwindenhammer, "Analyzing urban adaptation strategies to climate change: a comparison of the coastal cities of Dhaka, Lagos and Hamburg," in *Contribution to the Panel, Regieren im Klimawandel Section, Regierungssystem und Regieren in der Bundesrepublik Deutschland, DVPW-Kongress*, 2009, vol. 21, p. 25.

[17] I. Cities Climate Leadership Group. "Why Cities?" https://www.c40.org/why_cities (accessed 2020).

[18] U. Nations, "World population prospects: the 2017 revision, key findings and advance tables," *Department of Economics and Social Affairs PD, editor. New York: United Nations,* 2017.

[19] U. Nations, "World Urbanization Prospects: The 2018 Revision, Key Facts," *Technical report,* 2018.

[20] M. Villa-Arrieta and A. Sumper, "Economic evaluation of Nearly Zero Energy Cities," *Applied Energy,* vol. 237, pp. 404-416, 2019/03/01/ 2019, doi: https://doi.org/10.1016/j.apenergy.2018.12.082.

[21] R. Check, P. Space-based, K. Percent, and E. Shingles, "The Future of Solar Energy," *Mit,* pp. 3-6, 2015.

[22] H. Gholami, H. N. Røstvik, and D. Müller-Eie, "Analysis of solar radiation components on building skins for selected cities," in *Proceedings of 14th Conference on Advanced Building Skins*. Bern, Switzerland: Advanced Building Skins. ABS, 2019, pp. 541-549.

[23] S. Kalogirou, "Thermal performance, economic and environmental life cycle analysis of thermosiphon solar water heaters," *Solar energy,* vol. 83, no. 1, pp. 39-48, 2009.

[24] A. Ibrahim, A. Fudholi, K. Sopian, M. Y. Othman, and M. H. Ruslan, "Efficiencies and improvement potential of building integrated photovoltaic thermal (BIPVT) system," *Energy Conversion and Management,* vol. 77, pp. 527-534, 2014.

[25] D. Groppi, L. de Santoli, F. Cumo, and D. A. Garcia, "A GIS-based model to assess buildings energy consumption and usable solar energy potential in urban areas," *Sustainable Cities and Society,* vol. 40, pp. 546-558, 2018, doi: https://doi.org/10.1016/j.scs.2018.05.005.

[26] A. Buonomano, C. Forzano, S. A. Kalogirou, and A. Palombo, "Building-façade integrated solar thermal collectors: Energy-economic performance and indoor comfort simulation model of a water based prototype for heating, cooling, and DHW production," *Renewable Energy,* 2018.

[27] H. Gholami, A. Sarwat, H. Hosseinian, and A. Khalilnejad, "Evaluation of optimal dual axis concentrated photovoltaic thermal system with active ventilation using Frog Leap algorithm," *Energy Conversion Management,* vol. 105, pp. 782-790, 2015, doi: https://doi.org/10.1016/j.enconman.2015.08.033.

[28] H. Gholami, A. Khalilnejad, and G. Gharehpetian, "Electrothermal performance and environmental effects of optimal photovoltaic–thermal system," *Energy Conversion Management,* vol. 95, pp. 326-333, 2015, doi: https://doi.org/10.1016/j.enconman.2015.02.014.

[29] P. Reddy K, M. Gupta, S. Nundy, A. Karthick, and A. Ghosh, "Status of BIPV and BAPV System for Less Energy-Hungry Building in India—A Review," *Applied Sciences,* vol. 10, no. 7, p. 2337, 2020.

[30] A. K. Shukla, K. Sudhakar, P. Baredar, and R. Mamat, "Solar PV and BIPV system: Barrier, challenges and policy

recommendation in India," *Renewable and Sustainable Energy Reviews,* vol. 82, pp. 3314-3322, 2018/02/01/ 2018, doi: https://doi.org/10.1016/j.rser.2017.10.013.

[31] "European Commission. Communication from the Commission to the European Parliament and the Council. The Road from Paris: Assessing the Implications of the Paris Agreement and Accompanying the Proposal for a Council Decision on the Signing, on Behalf of the European Union, of the Paris Agreement Adopted Under the United Nations Framework Convention on Climate Change," 2016. [Online]. Available: https://op.europa.eu/en/publication-detail/-/publication/62d7fdfb-e607-11e5-8a50-01aa75ed71a1/language-en

[32] C. Cleveland and S. Peter, "Energy transitions past and future," *Encyclopedia of earth,* 2008.

[33] S. Davidsson, "Global Energy Transitions: A comparative analysis of key countries and implications for the international energy debate," *World Energy Council, Weltnerergierat: Berlin, Germany,* 2014.

[34] H. Daly and M. Walton, "World Energy Outlook 2017," 2017: IEA Paris, France:.

[35] I. IRENA, "Renewable energy in cities," *International Renewable Agency: Abu Dhabi, UAE,* 2016.

[36] Y. Parag and B. K. Sovacool, "Electricity market design for the prosumer era," *Nature energy,* vol. 1, no. 4, pp. 1-6, 2016.

[37] M. Amado, F. Poggi, A. Ribeiro Amado, and S. Breu, "A cellular approach to net-zero Energy Cities," *Energies,* vol. 10, no. 11, p. 1826, 2017.

[38] B. Todorovic, "Towards zero energy buildings: New and retrofitted existing buildings," in *2011 IEEE 3rd International Symposium on Exploitation of Renewable Energy Sources (EXPRES)*, 2011: IEEE, pp. 7-14.

[39] P. Heinstein, C. Ballif, and L.-E. Perret-Aebi, "Building integrated photovoltaics (BIPV): review, potentials, barriers and myths," *Green,* vol. 3, no. 2, pp. 125-156, 2013.

[40] M. Raugei and P. Frankl, "Life cycle impacts and costs of photovoltaic systems: Current state of the art and future

outlooks," *Energy,* vol. 34, no. 3, pp. 392-399, 2009/03/01/ 2009, doi: https://doi.org/10.1016/j.energy.2009.01.001.
[41] B. P. Jelle, C. Breivik, and H. D. Røkenes, "Building integrated photovoltaic products: A state-of-the-art review and future research opportunities," *Solar Energy Materials and Solar Cells,* vol. 100, pp. 69-96, 2012.
[42] E. Biyik *et al.*, "A key review of building integrated photovoltaic (BIPV) systems," *Engineering science technology, an international journal,* vol. 20, no. 3, pp. 833-858, 2017.
[43] N. R. E. L. (NREL). "Best Research-Cell Efficiency Chart." US Department of Energy. https://www.nrel.gov/pv/cell-efficiency.html (accessed 2020).
[44] I. Fraunhofer Institute for Solar Energy Systems, "Photovoltaic Report," 2020. [Online]. Available: https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf
[45] C. T. Limited. "Advanced glazing technology." http://www.clearvuepv.com/products-solutions/technology/ (accessed 2020).
[46] L. National Technology and Engineering Solutions of Sandia. "Spectral Response." https://pvpmc.sandia.gov/modeling-steps/2-dc-module-iv/effective-irradiance/spectral-response/ (accessed 2020).
[47] M. Kaltschmitt and A. Wiese, *Potentiale und Kosten regenerativer Energieträger in Baden-Württemberg*. Univ., 1992.
[48] M. Kaltschmitt and A. Wiese, *Erneuerbare Energieträger in Deutschland: Potentiale und Kosten*. Springer-Verlag, 2013.
[49] M. A. H. Mondal and M. Denich, "Assessment of renewable energy resources potential for electricity generation in Bangladesh," *Renewable and Sustainable Energy Reviews,* vol. 14, no. 8, pp. 2401-2413, 2010.
[50] V. Quaschning, *Systemtechnik einer klimaverträglichen Elektrizitätsversorgung in Deutschland für das 21. Jahrhundert*. VDI-Verlag, 2000.
[51] K. Mainzer, K. Fath, R. McKenna, J. Stengel, W. Fichtner, and F. Schultmann, "A high-resolution determination of the technical

potential for residential-roof-mounted photovoltaic systems in Germany," *Solar Energy,* vol. 105, pp. 715-731, 2014.
[52] S. r. m. Solargis. "Solar resource maps of Europe." https://solargis.com (accessed 2019).
[53] A. K. Shukla, K. Sudhakar, and P. Baredar, "Recent advancement in BIPV product technologies: A review," *Energy and Buildings,* vol. 140, pp. 188-195, 2017.
[54] Y. Asiedu and P. Gu, "Product life cycle cost analysis: state of the art review," *International journal of production research,* vol. 36, no. 4, pp. 883-908, 1998.
[55] M. Sorgato, K. Schneider, and R. Rüther, "Technical and economic evaluation of thin-film CdTe building-integrated photovoltaics (BIPV) replacing façade and rooftop materials in office buildings in a warm and sunny climate," *Renewable Energy,* vol. 118, pp. 84-98, 2018.
[56] N. Aste, C. Del Pero, and F. Leonforte, "The first Italian BIPV project: Case study and long-term performance analysis," *Solar Energy,* vol. 134, pp. 340-352, 2016.
[57] D. C. Jordan and S. R. Kurtz, "Photovoltaic degradation rates—an analytical review," *Progress in photovoltaics: Research Applications,* vol. 21, no. 1, pp. 12-29, 2013.
[58] W. Wang *et al.*, "Environmental assessments and economic performance of BAPV and BIPV systems in Shanghai," *Energy and Buildings,* vol. 130, pp. 98-106, 2016.
[59] U. Eicker, E. Demir, and D. Gürlich, "Strategies for cost efficient refurbishment and solar energy integration in European Case Study buildings," *Energy and Buildings,* vol. 102, pp. 237-249, 2015.
[60] P. Eiffert, "Guidelines for the economic evaluation of building-integrated photovoltaic power systems," National Renewable Energy Lab., Golden, CO.(US), 2003.
[61] N. W. Alnaser, "First smart 8.64 kW BIPV in a building in Awali Town at Kingdom of Bahrain," *Renewable and Sustainable Energy Reviews,* vol. 82, pp. 205-214, 2018.
[62] E. Saretta, P. Caputo, and F. Frontini, "A review study about energy renovation of building facades with BIPV in urban environment," *Sustainable Cities and Society,* vol. 44, pp. 343-355, 2018, doi: https://doi.org/10.1016/j.scs.2018.10.002.

[63] M. Brito, S. Freitas, S. Guimarães, C. Catita, and P. Redweik, "The importance of facades for the solar PV potential of a Mediterranean city using LiDAR data," *Renewable Energy,* vol. 111, pp. 85-94, 2017.

[64] T. Zhang, M. Wang, and H. Yang, "A Review of the Energy Performance and Life-Cycle Assessment of Building-Integrated Photovoltaic (BIPV) Systems," *Energies,* vol. 11, no. 11, p. 3157, 2018.

[65] G. P. Hammond, H. A. Harajli, C. I. Jones, and A. B. Winnett, "Whole systems appraisal of a UK Building Integrated Photovoltaic (BIPV) system: Energy, environmental, and economic evaluations," *Energy Policy,* vol. 40, pp. 219-230, 2012.

[66] R. Jing Yang and P. X.W. Zou, "Building integrated photovoltaics (BIPV): costs, benefits, risks, barriers and improvement strategy," *International Journal of Construction Management,* vol. 16, no. 1, pp. 39-53, 2015.

[67] A. Sivanandan, "BIPV hotspots in the EU," *Renewable energy focus,* vol. 10, no. 2, pp. 54-55, 2009.

[68] L. Byrnes, C. Brown, J. Foster, and L. D. Wagner, "Australian renewable energy policy: Barriers and challenges," *Renewable Energy,* vol. 60, pp. 711-721, 2013.

[69] F. J. Osseweijer, L. B. Van Den Hurk, E. J. Teunissen, and W. G. van Sark, "A comparative review of building integrated photovoltaics ecosystems in selected European countries," *Renewable Sustainable Energy Reviews,* vol. 90, pp. 1027-1040, 2018.

[70] A. Scognamiglio and H. N. Røstvik, "Photovoltaics and zero energy buildings: a new opportunity and challenge for design," *Progress in Photovoltaics: Research and applications,* vol. 21, no. 6, pp. 1319-1336, 2013.

[71] T. C. Grenfell, S. G. Warren, and P. C. Mullen, "Reflection of solar radiation by the Antarctic snow surface at ultraviolet, visible, and near-infrared wavelengths," *Journal of Geophysical Research: Atmospheres,* vol. 99, no. D9, pp. 18669-18684, 1994, doi: https://doi.org/10.1029/94JD01484.

[72] W. Muehleisen *et al.*, "Energy yield measurement of an elevated PV system on a white flat roof and a performance comparison of

monofacial and bifacial modules," *Renewable Energy,* vol. 170, pp. 613-619, 2021/06/01/ 2021, doi: https://doi.org/10.1016/j.renene.2021.02.015.

[73] E. Molin, B. Stridh, A. Molin, and E. Wäckelgård, "Experimental yield study of bifacial PV modules in nordic conditions," *IEEE Journal of Photovoltaics,* vol. 8, no. 6, pp. 1457-1463, 2018.

[74] M. Tripathy, S. Yadav, P. Sadhu, and S. Panda, "Determination of optimum tilt angle and accurate insolation of BIPV panel influenced by adverse effect of shadow," *Renewable Energy,* vol. 104, pp. 211-223, 2017.

[75] C. Zomer, A. Nobre, T. Reindl, and R. Rüther, "Shading analysis for rooftop BIPV embedded in a high-density environment: A case study in Singapore," *Energy and Buildings,* vol. 121, pp. 159-164, 2016.

[76] N. M. Kumar, K. Sudhakar, and M. Samykano, "Performance of thin-film BIPV as double sloped pitched roof in buildings of Malaysia," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects,* vol. 40, no. 20, pp. 2476-2484, 2018.

[77] F. Frontini, M. Manfren, and L. C. Tagliabue, "A case study of solar technologies adoption: criteria for BIPV integration in sensitive built environment," *Energy Procedia,* vol. 30, pp. 1006-1015, 2012.

[78] N. M. Kumar, K. Sudhakar, and M. Samykano, "Performance comparison of BAPV and BIPV systems with c-Si, CIS and CdTe photovoltaic technologies under tropical weather conditions," *Case Studies in Thermal Engineering,* vol. 13, p. 100374, 2019.

[79] N. Poh KhaiNg, "Lifetime performance of semi-transparent building-integrated photovoltaic (BIPV) glazing systems in the tropics," *Renewable and Sustainable Energy Reviews,* vol. 31, pp. 736-745, 2014.

[80] P. Jayathissa, M. Luzzatto, J. Schmidli, J. Hofer, Z. Nagy, and A. Schlueter, "Optimising building net energy demand with dynamic BIPV shading," *Applied Energy,* vol. 202, pp. 726-735, 2017.

[81] W. Shen *et al.*, "A comprehensive review of variable renewable energy levelized cost of electricity," *Renewable and Sustainable Energy Reviews,* vol. 133, p. 110301, 2020/11/01/ 2020, doi: https://doi.org/10.1016/j.rser.2020.110301.

[82] S. Reichelstein and A. Sahoo, "Time of day pricing and the levelized cost of intermittent power generation," *Energy Economics,* vol. 48, pp. 97-108, 2015/03/01/ 2015, doi: https://doi.org/10.1016/j.eneco.2014.12.005.

[83] K. Branker, M. Pathak, and J. M. Pearce, "A review of solar photovoltaic levelized cost of electricity," *Renewable and sustainable energy reviews,* vol. 15, no. 9, pp. 4470-4482, 2011.

[84] U. Nissen and N. Harfst, "Shortcomings of the traditional “levelized cost of energy” [LCOE] for the determination of grid parity," *Energy,* vol. 171, pp. 1009-1016, 2019/03/15/ 2019, doi: https://doi.org/10.1016/j.energy.2019.01.093.

[85] G. Pamparana, W. Kracht, J. Haas, G. Díaz-Ferrán, R. Palma-Behnke, and R. Román, "Integrating photovoltaic solar energy and a battery energy storage system to operate a semi-autogenous grinding mill," *Journal of Cleaner Production,* vol. 165, pp. 273-280, 2017/11/01/ 2017, doi: https://doi.org/10.1016/j.jclepro.2017.07.110.

[86] J. N. Mayer, P. Simon, N. S. H. Philipps, T. Schlegl, and C. Senkpiel, "Current and future cost of photovoltaics," *Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems (Fraunhofer ISE, Study on behalf of Agora Energiewende, Freiburg, 2015),* 2015.

[87] A. S. Mundada, K. K. Shah, and J. M. Pearce, "Levelized cost of electricity for solar photovoltaic, battery and cogen hybrid systems," *Renewable and Sustainable Energy Reviews,* vol. 57, pp. 692-703, 2016/05/01/ 2016, doi: https://doi.org/10.1016/j.rser.2015.12.084.

[88] A. Limmanee *et al.*, "Degradation analysis of photovoltaic modules under tropical climatic conditions and its impacts on LCOE," *Renewable Energy,* vol. 102, pp. 199-204, 2017/03/01/ 2017, doi: https://doi.org/10.1016/j.renene.2016.10.052.

[89] C. Parrado, A. Girard, F. Simon, and E. Fuentealba, "2050 LCOE (Levelized Cost of Energy) projection for a hybrid PV (photovoltaic)-CSP (concentrated solar power) plant in the Atacama Desert, Chile," *Energy,* vol. 94, pp. 422-430, 2016/01/01/ 2016, doi: https://doi.org/10.1016/j.energy.2015.11.015.

[90] A. Komilov, "Location and orientation based LCOE: Simplified visual analysis and generalization of the levelized cost of electricity from storageless photovoltaic systems," *International Journal of Energy Research,* 2020.

[91] D. L. Talavera, E. Muñoz-Cerón, J. P. Ferrer-Rodríguez, and P. J. Pérez-Higueras, "Assessment of cost-competitiveness and profitability of fixed and tracking photovoltaic systems: The case of five specific sites," *Renewable Energy,* vol. 134, pp. 902-913, 2019/04/01/ 2019, doi: https://doi.org/10.1016/j.renene.2018.11.091.

[92] M. T. Patel, R. Asadpour, M. Woodhouse, C. Deline, and M. A. Alam, "LCOE*: Re-thinking LCOE for Photovoltaic Systems," in *2019 IEEE 46th Photovoltaic Specialists Conference (PVSC)*, 2019: IEEE, pp. 1711-1713.

[93] R. Sinaga, N. F. Tuati, M. D. Beily, and A. S. Sampeallo, "Modeling and analysis of the solar photovoltaic levelized cost of electricity (LCoE)-case study in Kupang," in *Journal of Physics: Conference Series*, 2019, vol. 1364, no. 1: IOP Publishing, p. 012066.

[94] C. S. Lai and M. D. McCulloch, "Levelized cost of electricity for solar photovoltaic and electrical energy storage," *Applied energy,* vol. 190, pp. 191-203, 2017.

[95] S. MacDonald and N. Headlam, *Research Methods Handbook: Introductory guide to research methods for social research*. Centre for Local Economic Strategies, 2008.

[96] I. Zanetti *et al.*, "Building Integrated Photovoltaics: Product Overview for Solar Building Skins-Status Report 2017," in "Kidlington, UK," 2017.

[97] P. Bonomo, A. Chatzipanagi, and F. Frontini, "Overview and analysis of current BIPV products: new criteria for supporting the technological transfer in the building sector," *VITRUVIO-International Journal of Architectural Technology and Sustainability,* no. 1, pp. 67-85, 2015.

[98] K. Deb, A. Pratap, S. Agarwal, and T. Meyarivan, "A fast and elitist multiobjective genetic algorithm: NSGA-II," *IEEE transactions on evolutionary computation,* vol. 6, no. 2, pp. 182-197, 2002.

[99] J. Aldersey-Williams and T. Rubert, "Levelised cost of energy–A theoretical justification and critical assessment," *Energy Policy,* vol. 124, pp. 169-179, 2019.

[100] L. Varro and J. Ha, "Projected costs of generating electricity–2015 Edition," *Paris, France,* 2015.

[101] T. W. B. Group. "Electric power transmission and distribution losses (% of output)." https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS?locations=BR (accessed March 2019.

[102] A. Moro and L. Lonza, "Electricity carbon intensity in European Member States: Impacts on GHG emissions of electric vehicles," *Transportation Research Part D: Transport and Environment,* vol. 64, pp. 5-14, 2018/10/01/ 2018, doi: https://doi.org/10.1016/j.trd.2017.07.012.

[103] Eurostat. "Electricity price statistics." https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics#Electricity_prices_for_household_consumers (accessed 2019).

[104] S. Kang, S. Yoo, J. Lee, B. Boo, and H. Ryu, "Experimental investigations for recycling of silicon and glass from waste photovoltaic modules," *Renewable Energy,* vol. 47, pp. 152-159, 2012.

[105] B. Huang, J. Zhao, J. Chai, B. Xue, F. Zhao, and X. Wang, "Environmental influence assessment of China's multi-crystalline silicon (multi-Si) photovoltaic modules considering recycling process," *Solar Energy,* vol. 143, pp. 132-141, 2017.

[106] J. R. Duflou, J. R. Peeters, D. Altamirano, E. Bracquene, and W. Dewulf, "Demanufacturing photovoltaic panels: Comparison of end-of-life treatment strategies for improved resource recovery," *CIRP Annals,* vol. 67, no. 1, pp. 29-32, 2018.

[107] P. Gangwar, N. M. Kumar, A. K. Singh, A. Jayakumar, and M. Mathew, "Solar photovoltaic tree and its end-of-life management using thermal and chemical treatments for material recovery," *Case Studies in Thermal Engineering,* vol. 14, p. 100474, 2019.

[108] N. w. r. a. e. d. (NVE). "Electricity disclosure 2018." https://www.nve.no/energy-market-and-regulation/retail-market/electricity-disclosure-2018/?ref=mainmenu (accessed 2019).

[109] H. Larsen, "Klimafotavstrykket av offentlige anskaffelser. Beregning av klimafotavtrykket av offentlige anskaffelser for årene 2008 til 2017," in *Direktoratet for Forvaltning Og IKT (Difi)*, 2019.

University
of Stavanger

4036 Stavanger
Tel: +47 51 83 10 00
E-mail: post@uis.no
www.uis.no

ISBN: 978-82-8439-031-4
ISSN: 1890-1387