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

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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

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**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:

$$C_{TL} = T_{LL} \times C_N \tag{1}$$

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

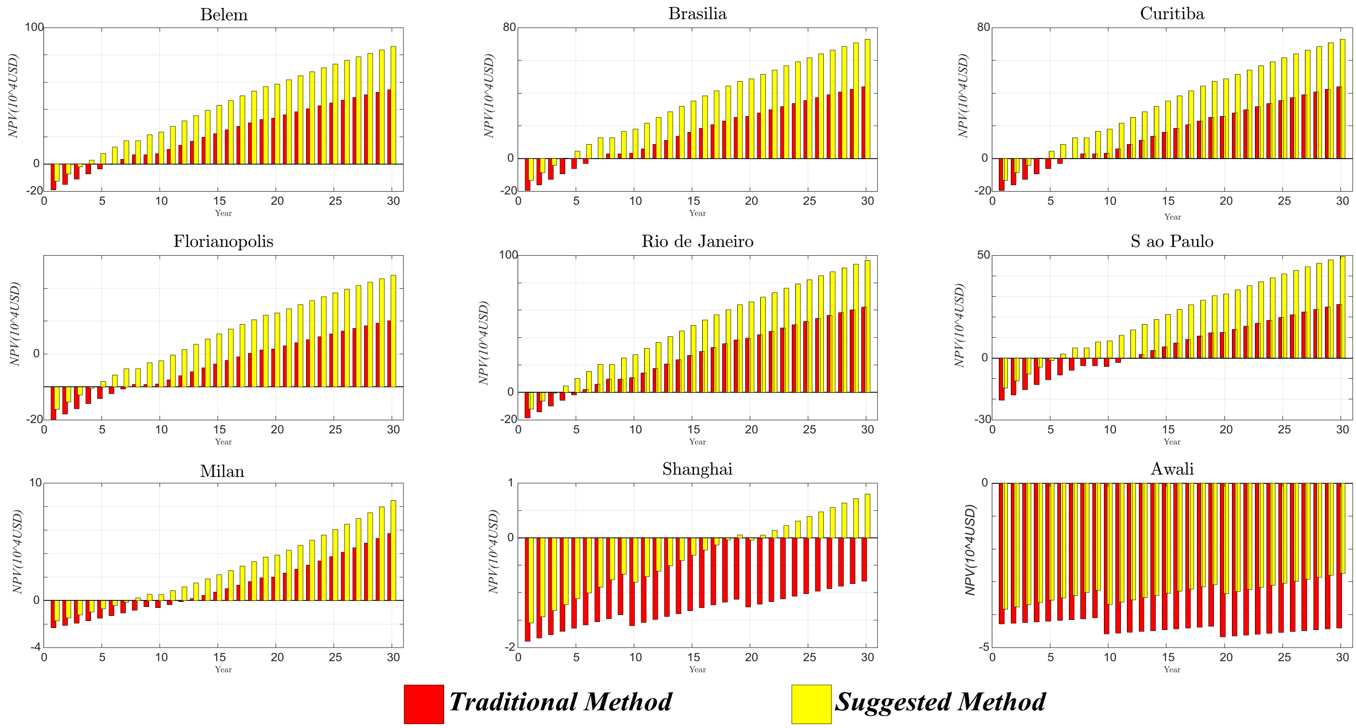


**Fig. 1.** NPV calculation considering the traditional method and suggested method.

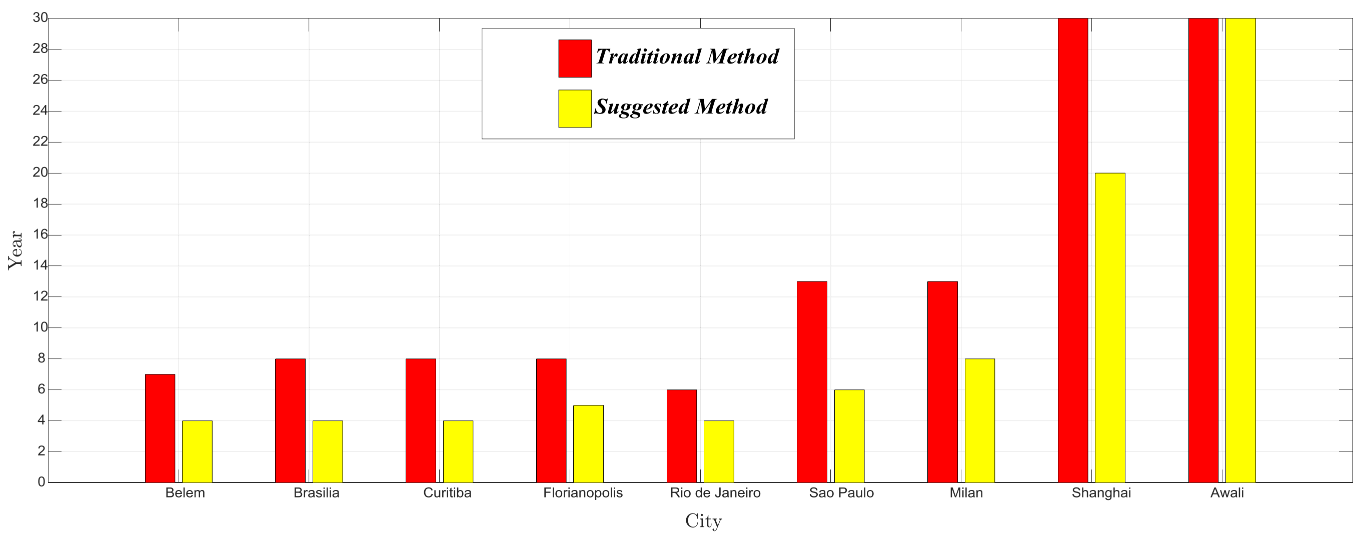


**Fig. 2.** DPP considering the traditional method and suggested method.

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

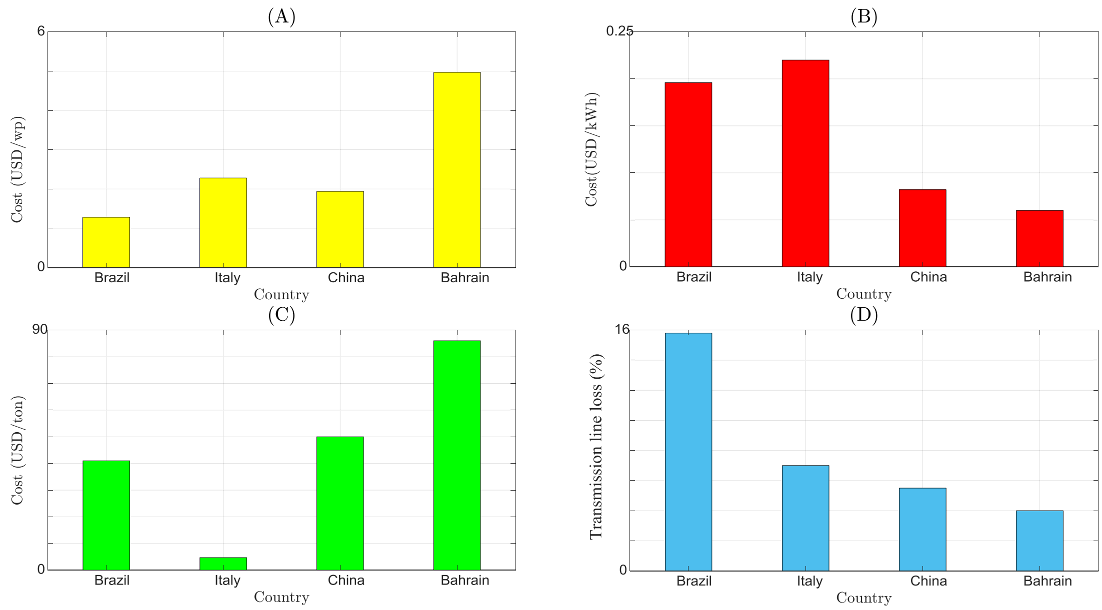


**Fig. 3.** (A) BIPV price, (B) Electricity tariff, (C) CSCCs, and (D) Transmission line loss of the different countries.

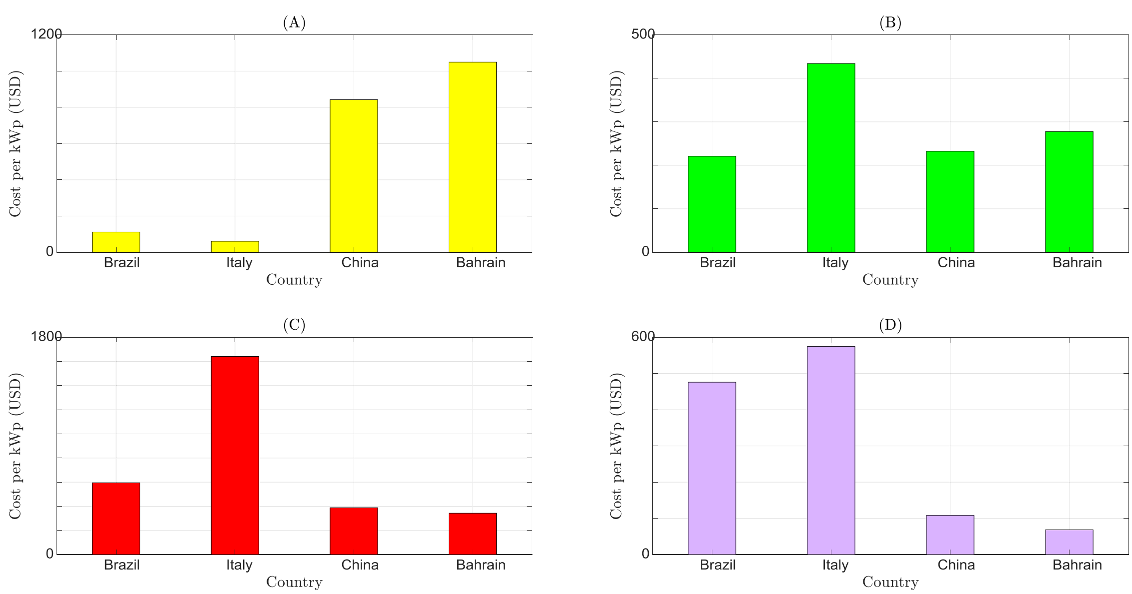


**Fig. 4.** Cumulative NPV of (A) CSCCs, (B) Equivalent building envelope cost (C) Transmission line cost (D) Transmission line loss of the case studies per watt peak.

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

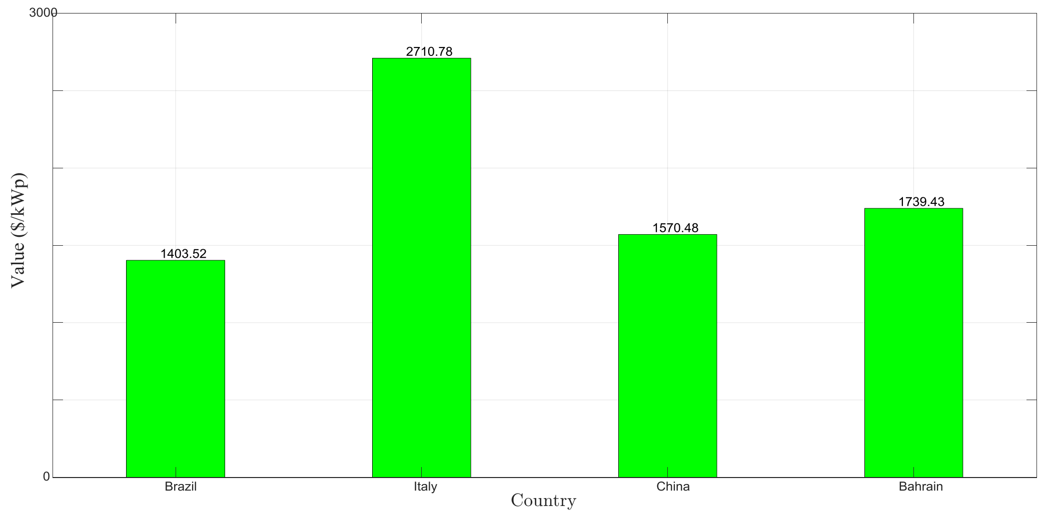


**Fig. 5.** The NPV of societal and environmental advantages of BIPV system in different countries.

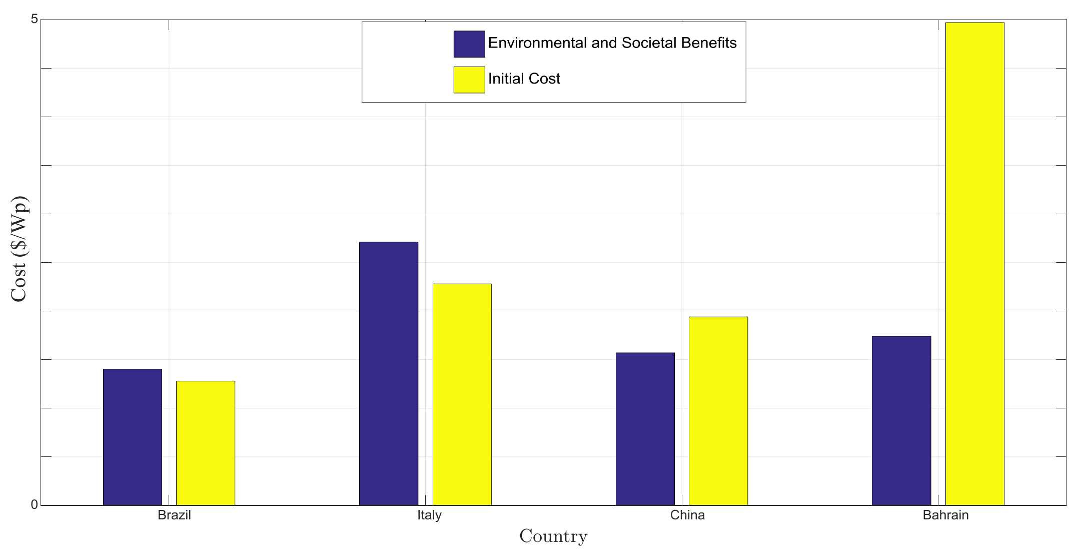


**Fig. 6.** Initial cost (PIC) and NPV of societal and environmental advantages of the BIPV system.

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.


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