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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 or 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

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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].

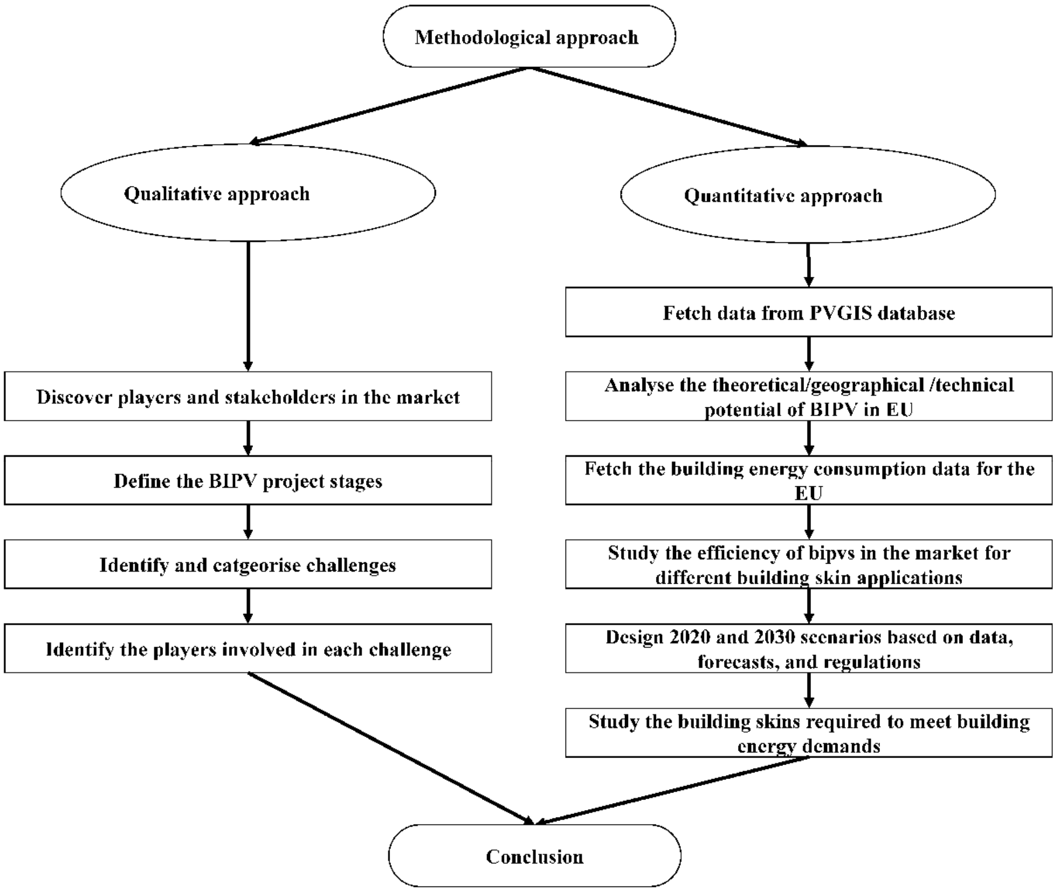

Figure 1. Flowchart of the methodology.

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.

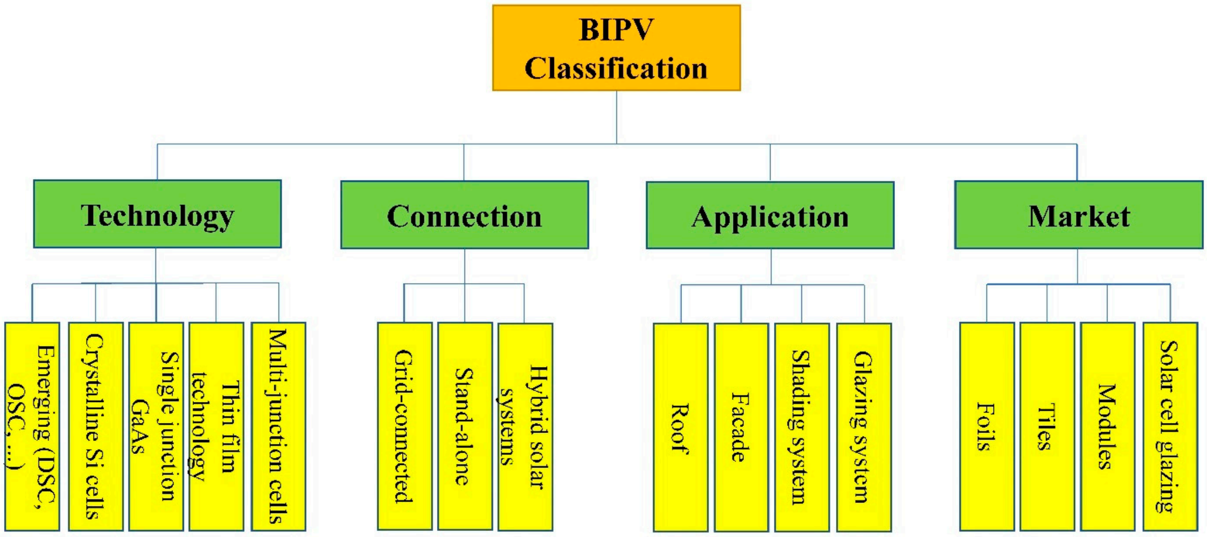

Figure 2. BIPV categorisation.

Figure 3 depicts examples of different BIPV systems available on the market [38].

BIPV Tiles BIPV Modules

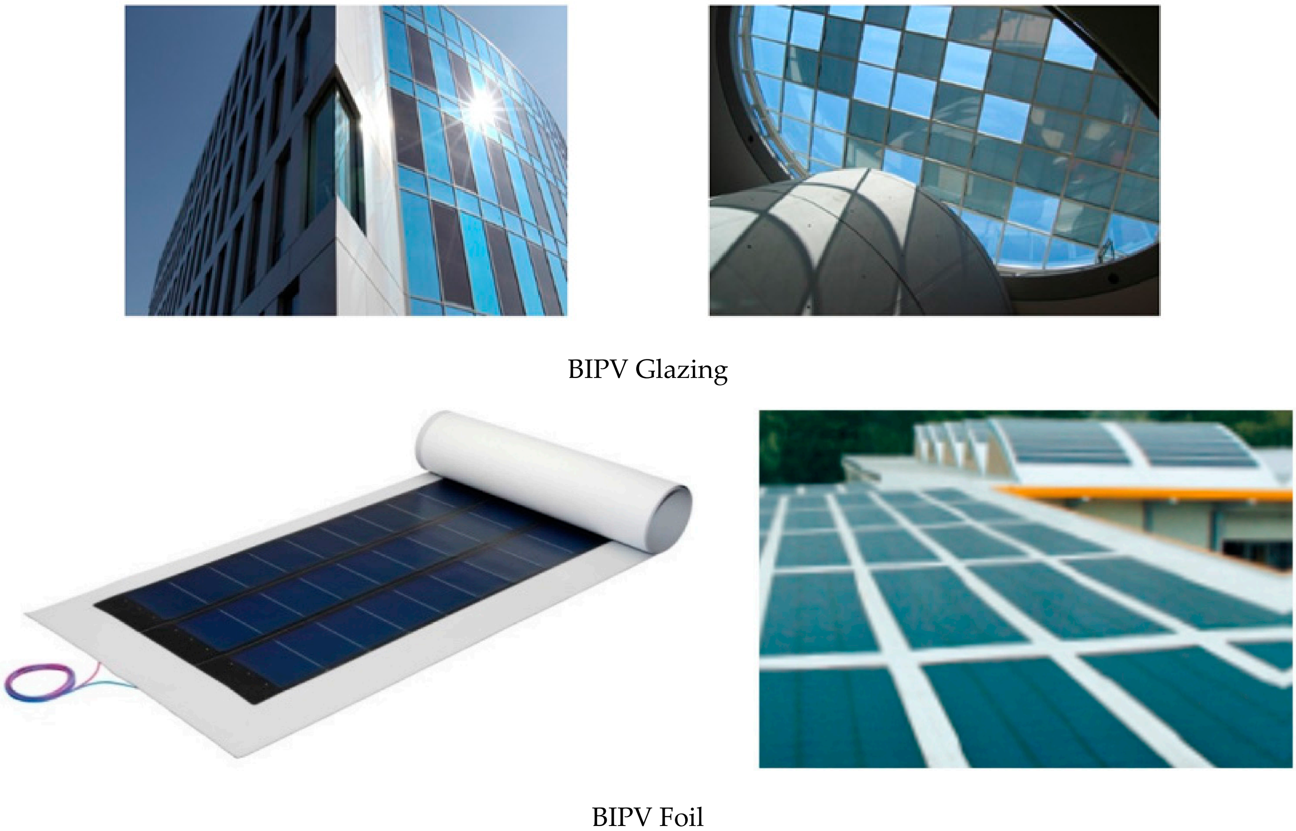

Figure 3. Examples of BIPV systems available on the market.

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].

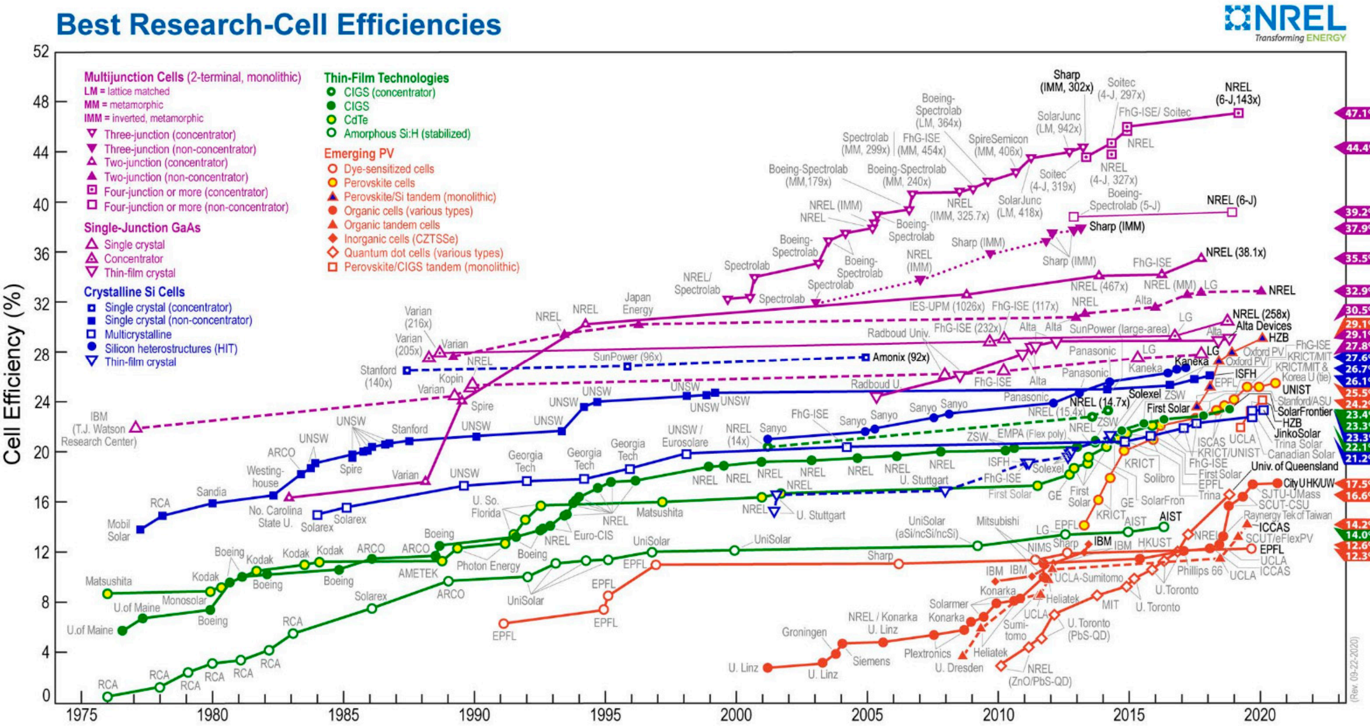

Figure 4. The NREL best research-cell efficiency chart.

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.

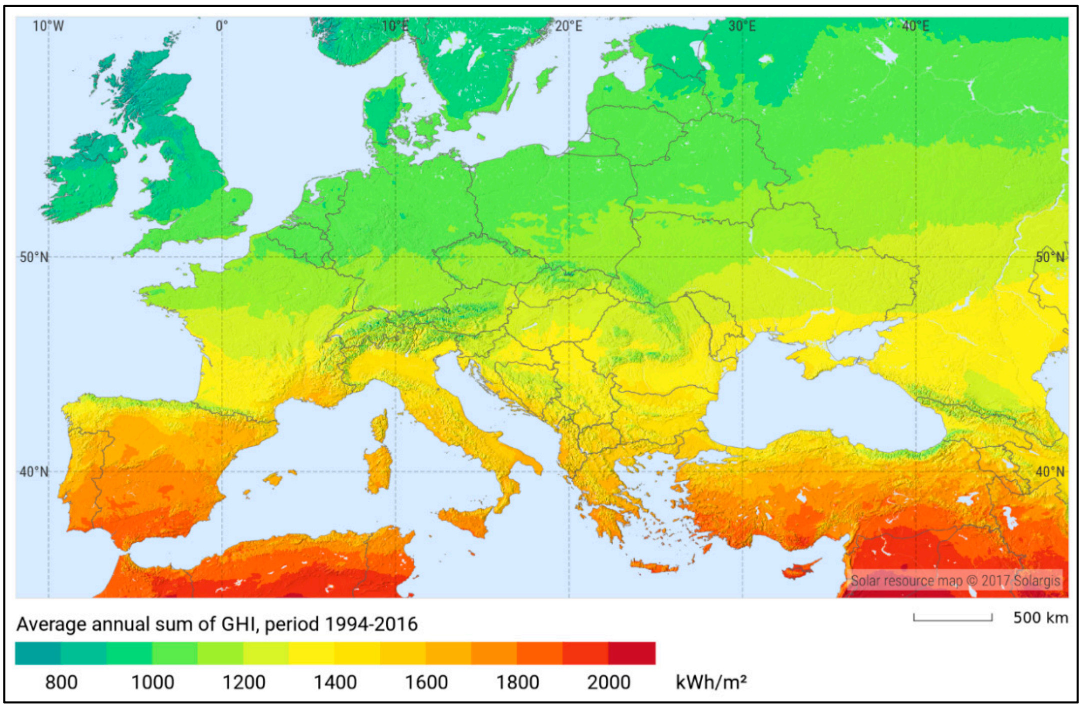

Figure 5. The theoretical solar incident radiation potential map of BIPV in Europe [48].

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].

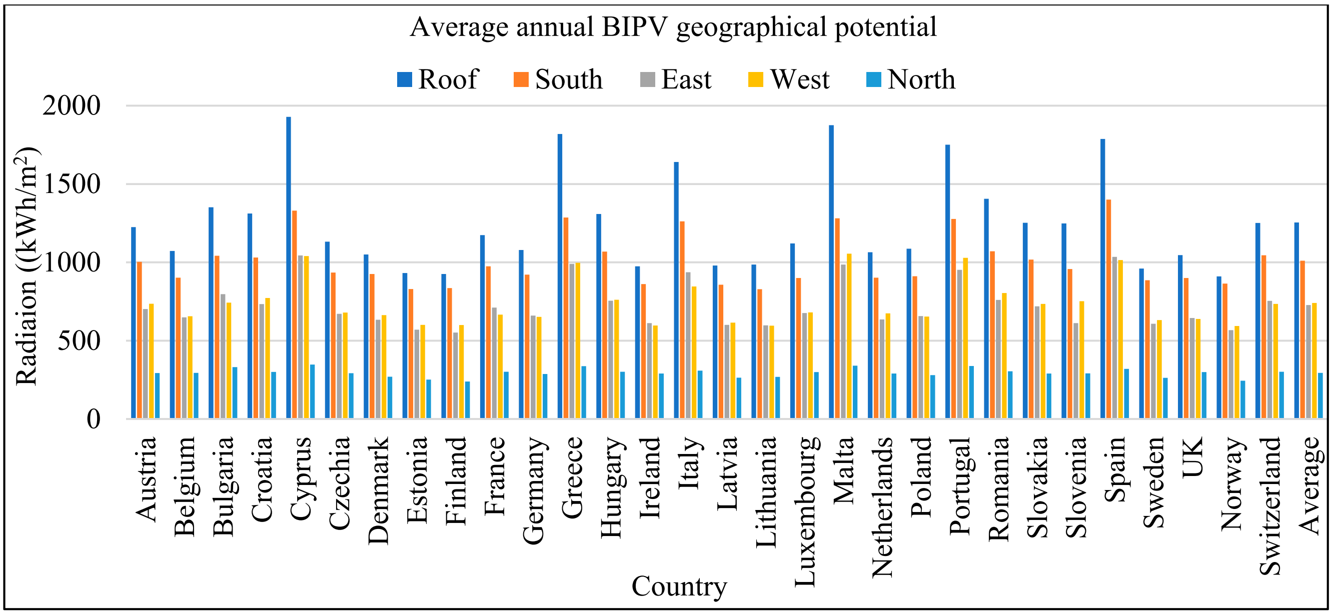

Figure 6. The average annual geographical potential of BIPV systems in Europe.

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.

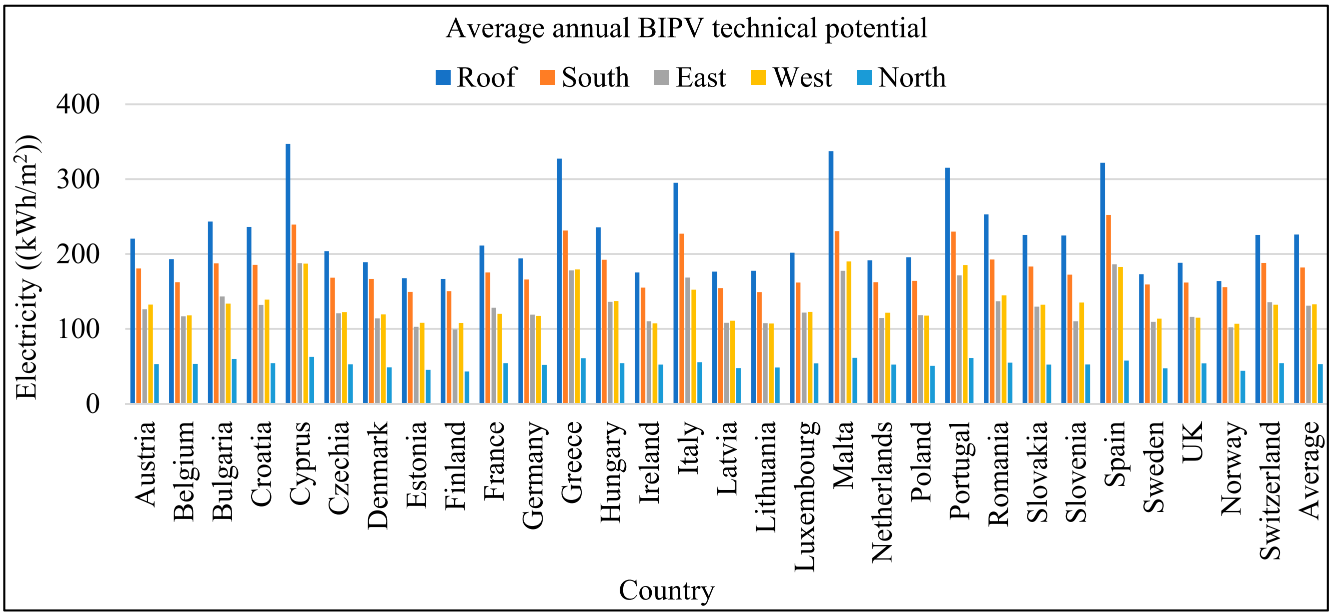

Figure 7. The average annual technical potential of BIPV systems in Europe.

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/m²)	BIPV Technical Potential of BS (kWh/m²)
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.

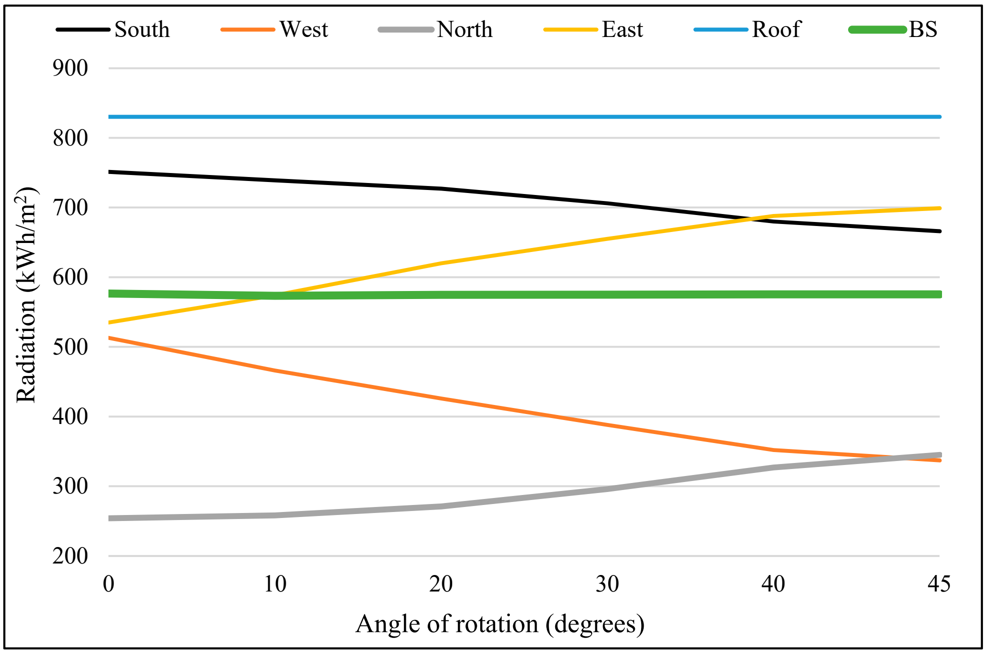

Figure 8. The correlation of the geographical irradiation potential of BS and the building orientation in Stavanger.

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 4. 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.

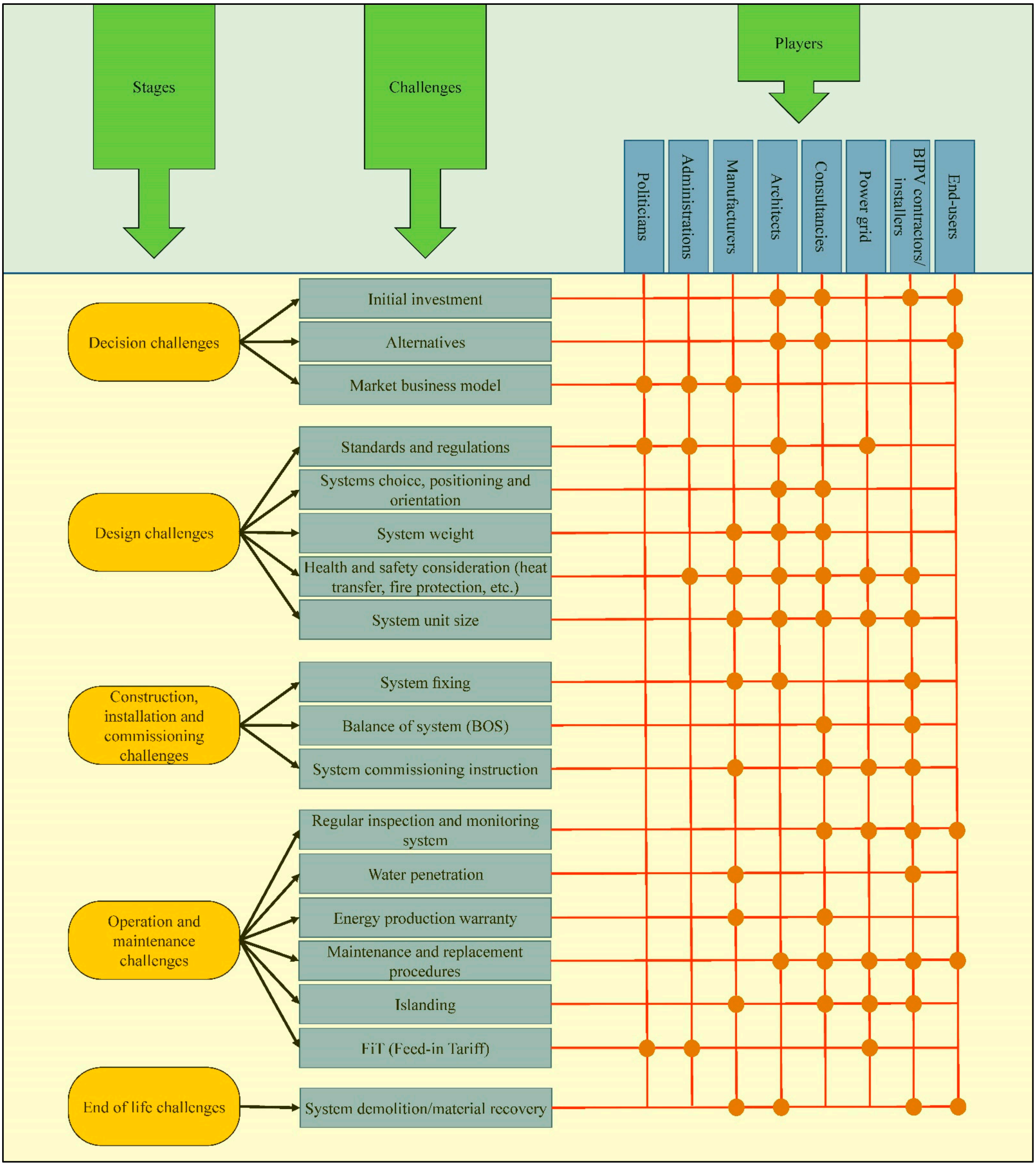

Figure 9. BIPV barrier classification and involved stakeholders who can contribute to the solutions.

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.

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.

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