Techno-Economic Evaluation of Building Integrated Photovoltaic (BIPV) System in Scotland

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Abstract

Building Integrated Photovoltaics (BIPV) presents numerous innovative and effective solutions for contributing to net-zero energy buildings, where there is a need for assessing the techno-economic advantages of BIPV systems and providing valuable insights to both solar developers and consumers regarding the cost-effectiveness of utilizing this technology. As a result, by addressing the commonly perceived barriers associated with the high upfront costs of BIPV systems, this research aims to assess the techno-economic values of BIPV systems. Herein, a 1 kWp grid-connected solar BIPV system has been evaluated for four diverse urban areas in Scotland using PVsyst software in particular due to its availability to calculate the energy generation and economic variation according to both panel orientation and tilt angle. Hence, the evaluation conducted was for 10 different tilt angles, ranging from 0° to 90° in increments of 10°, and 8 azimuth angles, spanning from -180° to 180° in increments of 45°. This approach ensures comprehensive coverage of nearly all main building orientations. Additionally, for clearer visualisation and more effective analysis, the obtained values were plotted as a 3D graph using MATLAB software. The optimal results were achieved in Aberdeen, with an annual energy generated (AEG) of 1167 kWh/year, Levelized Cost of Energy (LCOE) of 0.0606 GBP/kWh and a Payback Period (PP) of 7.2 years at (0° azimuth and 40° tilt) angles. In contrast, Portree recorded the lowest results, with 312 kWh/year, 0.2268 GBP/kWh and 17.4 years for the AEG, LCOE and PP respectively at (180° azimuth and 90° tilt) angles.

Keywords

Building integrated Photovoltaic system (BIPV); Annual Energy Generated (AEG), Levelized Cost of Energy (LCOE); Payback Period (PP);

1. Introduction

The building sector is responsible for approximately 39% of greenhouse gas (GHG) emissions[1], consequently, nations have established climate pledges, known as Nationally Determined Contributions (NDCs), which outline targets and commitments to lower emissions and enhance resilience to the impacts of climate change. The building-integrated photovoltaic (BIPV) system is one of the most practical solutions for sustainable energy generation, seamlessly integrating into the facade or roof of a building to harness clean energy from sunlight. This system performs two key functions within a building. First, it acts as a building envelope, designed to meet essential standards for structural integrity, thermal insulation, weather resistance, and noise protection, ensuring it fulfils the fundamental roles of a building skin. Second, it functions as a power generator, efficiently producing renewable energy to support the building's energy needs [2, 3]. Recent observations from solar farm operations have drawn attention to criticisms of traditional photovoltaic (PV) technology, particularly regarding its remarked impact on climate change and the utilization of agricultural land [4, 5]. However, BIPV technology presents a viable alternative to address these limitations through incorporating PV systems directly into building structure. Thus, BIPV mitigates land-use conflicts while providing notable economic and technical advantages to end-users.

1.1 BIPV Context in Scotland:

Solar energy potential can generally be assessed through four approaches: theoretical, geographical, technical, and economic potential [6].The theoretical potential refers to the availability of solar irradiance at a specific location selected for PV installation, without considering any constraints, whether geographical or technical. Geographical potential focuses on the area or land suitable for solar energy production. Technical potential, on the other hand, addresses the efficiency of photovoltaic modules. Finally, economic potential represents the portion of technical potential that assesses the economic feasibility of the system. A region's theoretical potential is the total amount of solar radiation it receives, unaffected by geometrical or technological limitations. For instance, solar PV potential in UK, global horizontal irradiance (GHI), As seen in Figure (1) it explains the theoretical potential in the UK. This GHI map includes direct and indirect irradiance, which helps both BIPV and PV system installations. The geographical potential represents the total solar irradiance received by the buildings within that specific city. This study focuses on the solar irradiance potential of BIPV systems in four locations in Scotland.

The potential of BIPV in Scotland is quantified through a comprehensive economic assessment. The Scottish Government is legally obligated to meet greenhouse gas emission reduction targets outlined in the Climate Change (Scotland) Act [7], which includes an interim goal of a 42% reduction in emissions (relative to 1990 levels) by 2020. Energy consumption in residential and commercial buildings accounts for more than 40% of Scotland's CO_2 emissions. Consequently, the Scottish construction sector plays a pivotal role in achieving these emissions reduction targets. This role was emphasized in the 2007 Sullivan Report [8], whose recommendations were integrated into Scottish construction codes in 2015. These changes have significantly influenced the adoption of solar energy and other renewable technologies in newly built homes across Scotland. Section 6 of the building regulations outlines the specific impacts on the newly built housing sector in Scotland. The primary objective of this regulation is to promote the development of energy-efficient buildings with minimal carbon dioxide emissions. The regulations provide a comprehensive framework for how building design and architecture can contribute to achieving these low-carbon goals. Furthermore, they highlight the increased potential for integrating renewable energy systems, such as BIPV into building designs.

For this study as shown in Figure 2, the urban areas of Aberdeen, Edinburgh, Kirkwall, and Portree in Scotland were selected to analyze the geographical potential of each location, taking into account their unique climatic characteristics and meteorological (Meteo) values. The PVsyst software was utilized to collect and analyze monthly Meteo data and location-specific parameters, enabling a comprehensive evaluation of the geographical potential of these sites. The geographical data considered in this study included key factors such as temperature, humidity, and detailed Meteo values. The Meteo parameters incorporated into the analysis comprised global horizontal irradiance, diffuse irradiance, extraterrestrial irradiance, clearness index, ambient temperature, and wind velocity, all tailored to the specific conditions of each location. These variables were crucial in assessing the suitability and performance of BIPV systems in diverse Scottish environments.

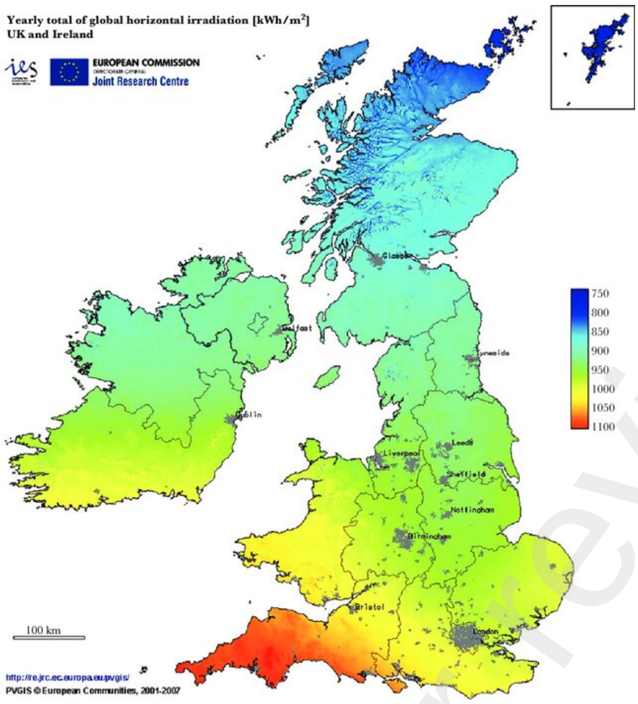

Figure 1 : The theoretical potential map of solar irradiance in UK [9]

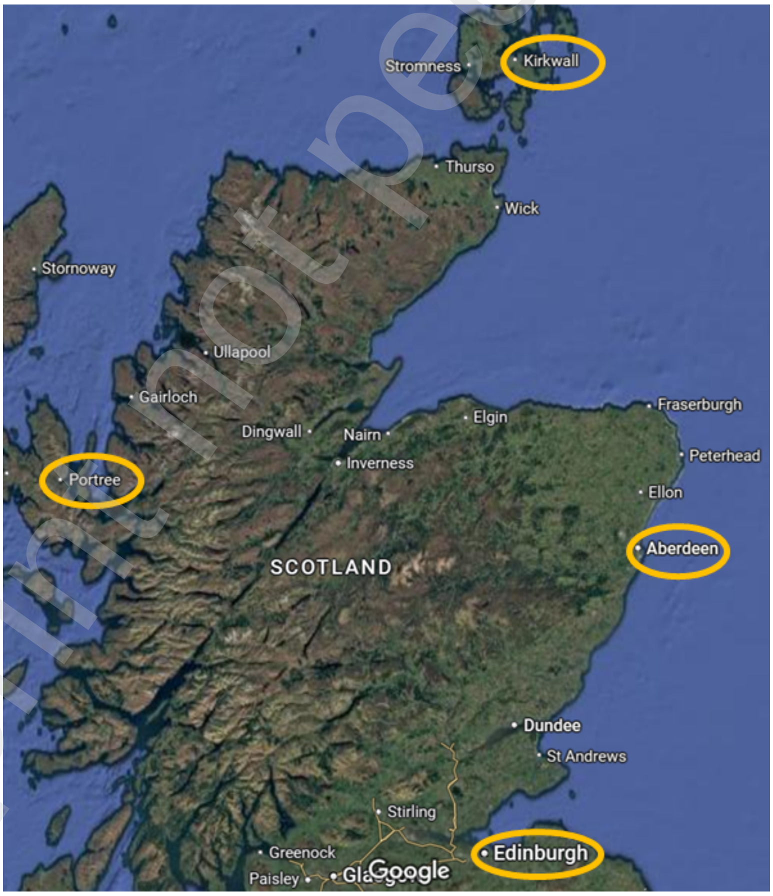

Figure 2 Selected Urban Areas in Scotland

2. Literature Review

Numerous research undertakings have used simulation models to assess the economic feasibility of BIPV within particular cities, module technologies, or building elements. Kong and colleagues [10] conducted a comprehensive assessment of building energy efficiency strategies in China during the eleventh five-year plan period. Whereas James et al. [11] examined BIPV and Building Attached Photovoltaics (BAPV) projects using variant scenarios of several module technologies, such as crystalline silicon (c-Si), amorphous silicon (a-Si), and copper indium gallium selenide (CIGS) on residential buildings. Abdul Hazeem Hamzah and Yun Ii Go [12] carried out an assessment of BIPV performance on a high-rise building in a tropical climate using BIM software, specifically Autodesk Revit, complemented by detailed analysis through PVSyst software. The semi-transparent/colored PV active coating type demonstrated the highest energy production, achieving approximately 75% of the output of a conventional PV module. Whereas Thanesh Tiagarajan and Yun Ii Go [13] performed a simulation of BIPV design to create an energy-efficient building model using Autodesk Revit. The research aimed to improve the understanding of the energy performance of the selected BIPV products. The results showed that amorphous silicon glazing consumes more energy compared to single- and double-glazing panels in rooms with high window-to-wall ratios (WWR). A Study revealed that BIPV systems have the potential to achieve system prices approximately 10% lower than ground-mount PV systems, by viewing the BIPV system in conjunction with the entire building envelope as a singular element, Bonomo et al. [14] quantified the economic value of BIPV. The authors incorporated the cost of constructing the building envelope in their calculations [11], it was found that highlighting the indirect benefits of BIPV often plays a key role in encouraging investment to include the cost of constructing the building envelope in their BIPV formulations. Additionally, the study revealed that emphasizing these indirect advantages of BIPV is particularly effective in motivating investors to commit to specific investments. Jelle et al. [15], reviewed the recent BIPV technology, since BIPV applications typically follow the changes in PV cells, they initially provided some information about existing PV technologies and their classification and concluded that new PV technologies were more cost-effective and efficient, which would shorten the payback period (PP) of the BIPV system.

In the economic feasibility assessment of BIPV, the Levelized Cost of Energy (LCOE) E also serves as a key metric for evaluating the unit cost of electricity production (in kWh or MWh) over the project lifetime [16]. This approach is widely employed by policymakers, project managers, investors, and researchers to evaluate the feasibility and market competitiveness of various technologies, thereby informing decisions on whether to advance investments in specific renewable energy projects [17, 18]. Furthermore, policymakers and legislators can utilize the LCOE method to inform the development of renewable energy policies. When evaluating the support schemes for carbon-based versus renewable energy technologies, authorities commonly rely on LCOE as a key decision-making parameter [19]. Mohammed et al. [20] developed a MATLAB code and an online techno-economic PV pre-sizing tool used to predict the energy generated and economic factors like LCOE. Herein, a BIPV project is considered financially viable if its LCOE is lower than the current grid price whereas the term "grid parity" is used when the LCOE of BIPV matches the grid price, indicating that the cost of producing and exporting energy to the grid is equivalent to the cost of purchasing it from the grid [21]. The complexity of comparing economic study outcomes arises from the varying approaches used to calculate and define solar potential. This is evident in the literature review of these relevant studies [6, 22, 23].

The techno-economic potential of a BIPV system is primarily influenced by the performance of the photovoltaic (PV) system, which is affected by ambient temperature and the availability of solar irradiance at the selected location [24]. Therefore, during the techno-economic design phase, it is crucial to account for variations in these inputs, as they can significantly impact system performance. The electric energy produced by the PV system, which directly influences the economic feasibility of the system, is referred to as the economic potential. Hasan Baig et al [25] prepared a model of a building-integrated Concentrating Photovoltaic (BICPV) system which mainly aimed to produce maximum electric performance using a limited area by attaching a dielectric-based Symmetric Elliptical Hyperboloid (SEH) concentrating element on a silicon solar cell. Additionally, with the use of air or water as a medium for cooling the PV module and removing heat, the PV systems can be designed and operated as photovoltaic thermal (PVT) systems [26-28], It has the potential to generate both electrical and thermal energy without compromising efficiency [29, 30]. For instance, in a BIPV system with air ventilation, the PV system is usually mounted on the building's roof or façade. Naturally occurring ventilation enables fresh air to circulate behind the BIPV system, effectively cooling it. When the system uses the extracted warm air for heating, it evolves into an advanced configuration known as a Building-Integrated Photovoltaic Thermal System (BIPVT).

This study recognized the significant contributions of previous research in evaluating BIPV performance and system integration. However, to facilitate more efficient decision-making in the early stages of integrating PV technology into urban planning, it is essential to understand the economic implications of BIPV projects. This study aims to fill the gaps by evaluating the techno-economic potential of BIPV systems in four urban areas across Scotland, with a particular focus on the Annual Energy Generated (AEG), and key economic indicators such as Levelized Cost of Energy (LCOE) and Payback Period (PP). The assessment also considers variations in the building envelope's orientation and tilt angle for a 1 kWp system, aiming to analyze the economic performance of BIPV systems with diverse characteristics. The Contribution can be summarised as below points:

- Investigated the Effect of variation of both panel orientation and tilt angle on the BIPV system viability by PVsyst software in 10 different tilt angles, and 8 azimuth angles, spanning from -180° to 180° in increments of 45°.
- For more detailed analysis, the obtained results were plotted in a 3D graph using MATLAB software to clearly identify the optimum location.
- Proposed a novel approach for stakeholders to improve the techno-economic assessment for BIPV systems in multiple diverse locations.

3. Methodology

There are several ways to evaluate the potential of a project's economic feasibility. This study is focused on the techno-economic evaluation of four urban areas in Scotland particularly on the Annual Energy Generated (AEG), Levelized cost of energy (LCOE) and payback Period (PP) of the BIPV system on various locations, orientations and tilt angles, taking into account variations in energy generation based on the building envelopes designed for integration with the PV system, the overview of the methodology is illustrated in Figure 3.

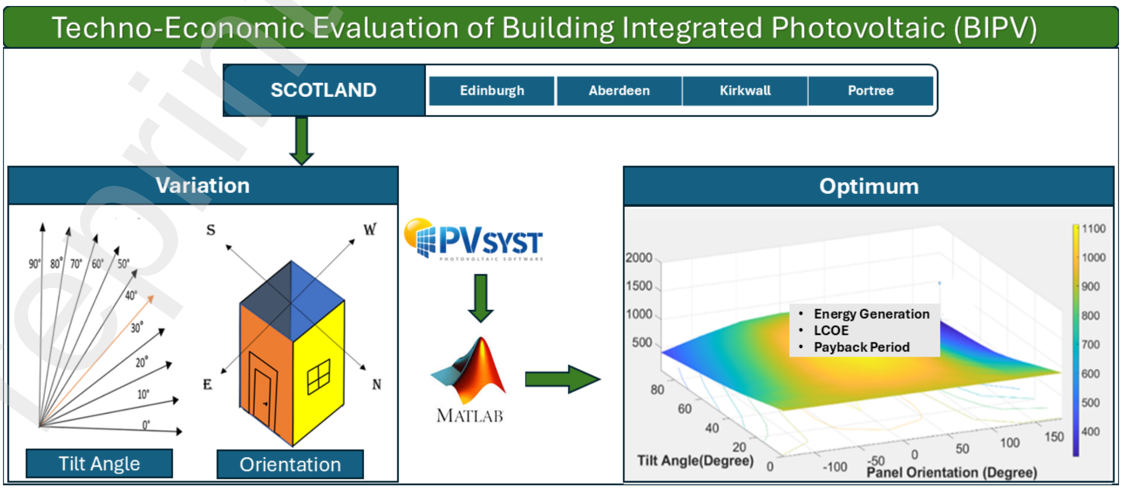

Figure 3 Overview of methodology.

The LCOE for a project is calculated by dividing the total lifetime cost by the total lifetime energy generation. The lifetime generation cost is determined by considering the project's capital cost, annual operational expenses, and maintenance costs.

$$\text{Levelized cost of energy} = \frac{Total\ costs}{Total\ electricity\ generated}$$

(Equation 1)

More specifically, the LCOE represents the cost that, when discounted to the base year and applied to each unit of energy generated by the system throughout the analysis period, equates to the total life-cycle cost. The LCOE methodology is commonly used to rank the cost-effectiveness of various energy generation technologies, serving as an abstraction of real-world complexities. When calculating LCOE for policy assessments, it is crucial to base calculations on accurate assumptions and to include all relevant system costs, such as installation, financing, depreciation, land, insurance, operation, and maintenance expenses. Additionally, factors such as carbon emissions and panel efficiency should also be incorporated. The following equation, derived from previous studies, can be used to evaluate the LCOE of PV systems [31, 32].

$$LCOE = \frac{C_0 - B_0 + \sum_{n=1}^{N} \frac{L_n + C_n}{(1+k)^n} - \sum_{n=1}^{N} \frac{B_n + (D_n + I_n)t}{(1+k)^t} - \frac{R_n}{(1+k)^n}}{\sum_{n=1}^{N} \frac{E_n}{(1+k)^n}}$$

(Equation 1)

where:

- C_0 = <u>initial investment cost</u>
- B_0 = initial benefit
- L_n = loan payment in the n-th year
- B_n = benefit in the n-th year
- D_n = depreciation in the n-th year
- I_n = interest paid in the n-th year
- R_n = residual value at the n-th year
- E_n = energy produced in the n-th year
- t = tax rate

The payback period of the BIPV project is generally constrained to a maximum of 25 years, which aligns with the minimum life expectancy of photovoltaic materials used in BIPV applications. Manufacturers of BIPV panels typically guarantee that, after 25 years of operation, the panels will still produce at least 80% of their initial rated peak power. Therefore, a payback period within 25 years indicates that the investment will be recouped before the system's guaranteed operational lifespan. Conversely, a payback period exceeding this duration is deemed economically non-viable. The benefits of investing in solar PV are often quantified through a related metric known as the payback period (PP). In this study, it is calculated using PVsyst software. The PP represents the number of years required for the cumulative, non-discounted annual cash flows to equal or exceed the initial non-discounted investment amount [33]. Alternatively, the PP can be defined as the duration needed to recover the investment amount [34]. However, to calculate the payback period for solar PV projects, the essential parameters include the system's installation capacity based on site conditions and the expected electricity production in kWh [35]. There are key factors influencing the calculation of the PP including the project's installation cost, the estimated annual electricity production, the energy price per kWh, and the rate of inflation. For typical solar PV installations, the average PP is estimated to be between 6 and 8 years [36]. However, a PP exceeding 10 years is often considered a significant barrier to the development and promotion of solar projects.

$$\text{Payback Period}=\frac{\text{Initial investment}}{\text{Annual saving}}$$

Equation 2

2.1 Input Parameters

For economic calculations, it is essential to apply financial parameters and consumption profile data. These financial parameters are determined based on government economic and energy policies. All calculations are performed using PVsyst software. To conduct the analysis, it was necessary to obtain key financial indicators, including the electricity tariff rate, the annual electricity consumption per average household in the selected locations, and the electricity price inflation rate. According to the UK's Consumer Prices Index (CPI), the average electricity tariff inflation rate is approximately 1.5% [37], with the average electricity price being 34 pence per kWh [38]. However, a change in the UK's feed-in tariff scheme occurred on 1 April 2019, affecting electricity exports to the grid from energy production units. The new scheme, known as the Smart Export Guarantee (SEG), was introduced on 1 January 2020 to promote carbon emission reduction in electricity production [39]. An analytical study by D.C. Jordan and S.R. Kurtz [40], on the degradation of photovoltaic materials reports an average degradation rate of 0.5% per year, with an average lifespan of 25 years for solar panels. For the economic evaluation in this study, the SEG price has been set at 7.5 pence per kWh. The remaining parameters, such as project costs comprising installation, operation, and maintenance are based on average expenses for implementing a 1 kWp PV system in Scotland, as outlined in Table 1 below.

Table 1: Financial parameters for Scotland BIPV projects

Financial parameters	Unit	values
Total installation cost	(GBP/ kWp)	1650
Project lifetime	(Years)	25
Inflation variation per year	(% / Year)	1.5
Discount rate variation	(% / Year)	1
Production variation (degradation)	(% / Year)	-0.50
Fixed feed-in tariff (SEG)	(GBP / kWh)	0.075
Annual tariff variation	(% / Year)	2.16
Duration of tariff warranty	(Years)	25
Fixed consumption tariff	(GBP / kWh)	0.34
Annual tariff variation	(% / Year)	0.69
Average annual consumption per household	(kWh/year)	1802
Start year	2022	

2.2 PVsyst Simulation Software

PVsyst software is a widely recognized tool for the design, simulation, and performance analysis of photovoltaic (PV) systems, utilizing extensive meteorological data to enhance accuracy and reliability [41]. For this study, a 1 kWp on-grid PV system was designed using monocrystalline PV panels, selected for their high energy conversion efficiency [42]. The system includes a 1 kW, 50–500 V inverter, which performs multiple critical functions such as power conditioning, system control and protection, maximum power point tracking, and converting the direct current (DC) electricity generated by the modules into alternating current (AC) suitable for grid supply.

To conduct a comprehensive techno-economic analysis of the BIPV system, the evaluation of power and energy generation variations based on façade orientation was prioritized. The system design incorporated multiple combinations of azimuth and tilt angles, facilitating a detailed assessment of the influence of panel orientation on system performance. This approach is conducted by the PVsyst software which enables simulation and economic analysis of energy generation while accounting for variations in panel orientation and tilt angle.

In this study, PV panels were considered as integral components of building envelopes, strategically installed across different parts of the building to optimize solar energy utilization. This methodology enabled a holistic evaluation of the economic potential of BIPV systems to generate electricity and offset the CO_2 emissions. Given that solar irradiance availability varies significantly across different orientations of a building, the power generation capacity and financial feasibility of the PV system are heavily dependent on the orientation of the photovoltaic materials. As a result, to thoroughly investigate the dependency of energy generation on tilt and azimuth angles, a novel approach was conducted. A total of ten tilt angles, ranging from 0° to 90° in increments of 10°, and eight azimuth angles, ranging from -180° to 180° in increments of 45°, these combinations covered all major building façade orientations. Consequently, a total of 80 (10 × 8) of different tilt and azimuth angle configurations were simulated for the four selected locations.

The simulations demonstrated three key outputs for each location: Annual Energy Generation (kWh/ Year), levelized cost of electricity (LCOE), and payback period (PP) for each tilt and azimuth angle combination. Additionally, the MATLAB software was employed to visualize the results, with the generated data plotted as 3D graphs to facilitate a more detailed analysis. These visualizations highlighted the impact of panel orientation on system performance and provided insights into the optimal design and economic viability of BIPV systems across different geographic and climatic conditions.

4. Results and Discussion

The building sector exhibits the highest potential for energy consumption among all sectors [43]. To date, most research and studies have primarily focused on factors such as initial investments, electricity costs, climatic conditions, and irradiance levels in assessing the economic viability of the BIPV system. However, this study adopts a novel approach to the economic evaluation of BIPV systems by examining in detail how façade orientation impacts both energy generation and economic profitability. It is well-established that BIPV systems outperform traditional photovoltaic systems [44], particularly when considering land utilization and building integration such as façades, and roofs. Thus, understanding how the placement of BIPV systems within specific building components contributes to green energy production is critical, this vital is especially for architects and solar PV designers, as it provides them with essential insights to optimize the economic outcomes of their projects.

The annual energy generated by the BIPV system for the four selected locations, based on the defined financial parameters and various combinations of tilt and azimuth angles, is illustrated in Figures 4 to 7 where the symbol denotes (X: azimuth angle, Y: tilt angel Z: annual energy generated). A consistent observation across all graphs is that maximum annual generation occurs when the system is configured with a 0° azimuth angle and a 40° tilt angle. This result can be attributed to the fact that all the investigated urban areas are located in the Northern Hemisphere. In such locations, south-facing orientations (0° azimuth) typically receive the highest solar irradiance, aligning with the default azimuth angle for optimal performance in the Northern Hemisphere. Conversely, for locations in the Southern Hemisphere, the default optimal azimuth angle would be north-facing [45]. The simulations also revealed that the lowest energy production is consistently associated with an azimuth angle of 180°. This outcome further underscores the critical role of panel orientation in determining the energy generation potential of BIPV systems.

Additionally, based on the given financial parameters and simulated energy generation, an optimal tilt angle of 40° yields optimum economic performance, the best economic performance, as reflected in metrics such as LCOE and PP is observed for the orientation yielding the highest energy generation. In the case of Scotland, BIPV systems installed on building façades facing south demonstrate an average payback period of 7.2–7.4 years, which is significantly shorter compared to other azimuth orientations. These results highlight the importance of optimizing panel orientation to improve the economic feasibility of BIPV projects. It is important to note that the payback period can vary depending on a range of factors, including energy consumption patterns, electricity costs, installation expenses, operation and maintenance (O&M) costs, and system transmission losses. However, for simplicity, this study does not account for transmission losses or other minor factors, as the primary objective was to minimize the complexity of the analysis. After performing a series of simulations and calculations for each selected 1kWp on-grid PV system on each location with different combinations of façade orientation, the LCOE (as demonstrated in Figures 8 to 11) and PP (as shown in Figures 12 to 15) where values were obtained according to the annual energy generation. All these values are assembled in a spreadsheet according to the respective location, and then the results are implemented into MATLAB code for generating 3D graphs for detailed analysis, all the obtained graphs are given below.

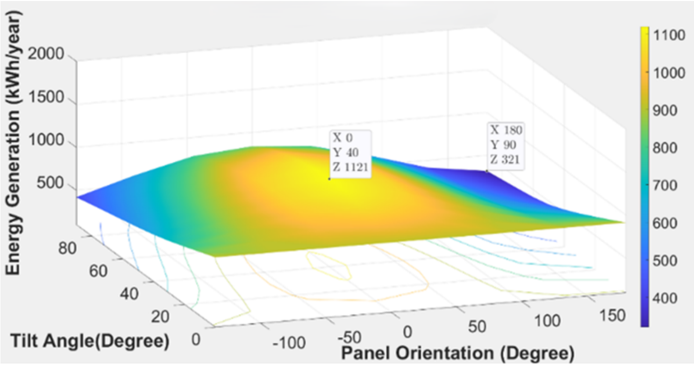

Figure 4 Edinburgh Annual Energy Generated

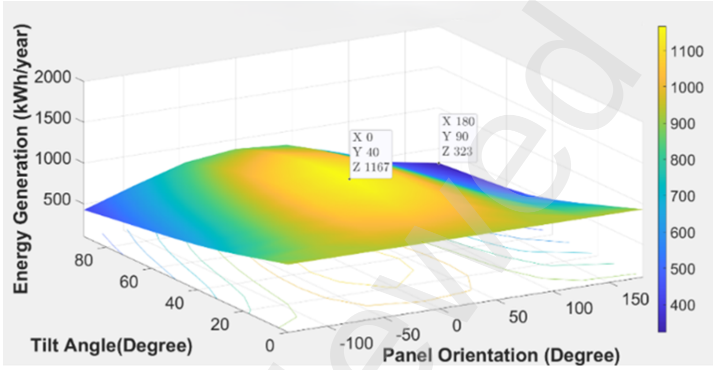

Figure 5 Aberdeen Annual Energy Generated

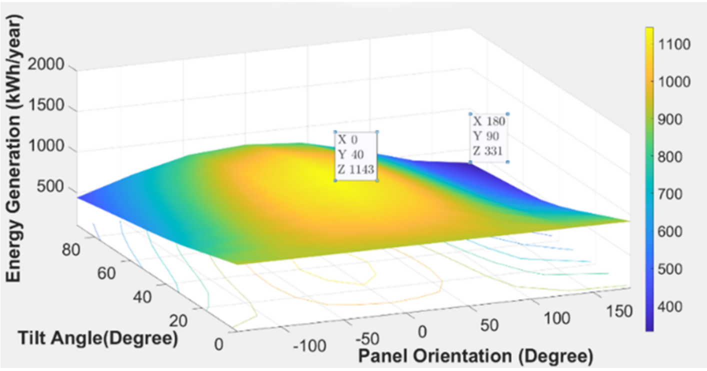

Figure 6 Kirkwall Annual Energy Generated

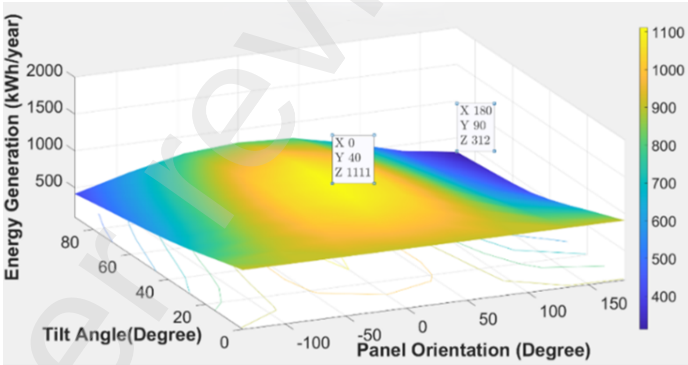

Figure 7 Portree Annual Energy Generated

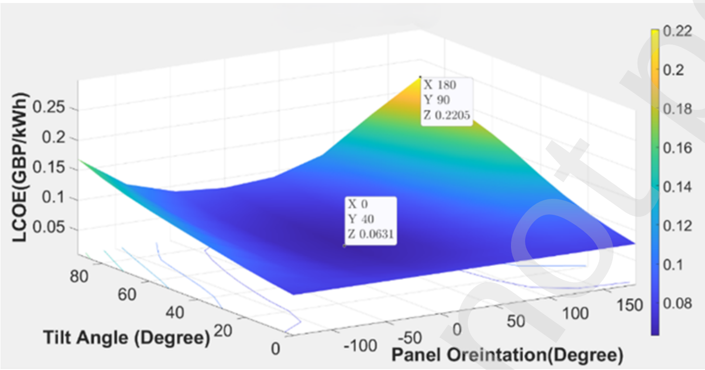

Figure 8 LCOE Assessment for Edinburgh BIPV System

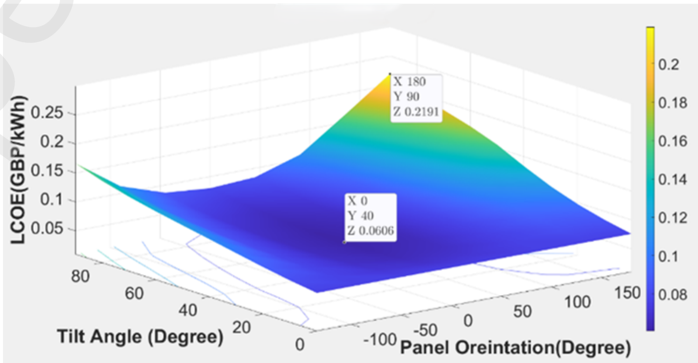

Figure 9 LCOE Assessment for Aberdeen BIPV System

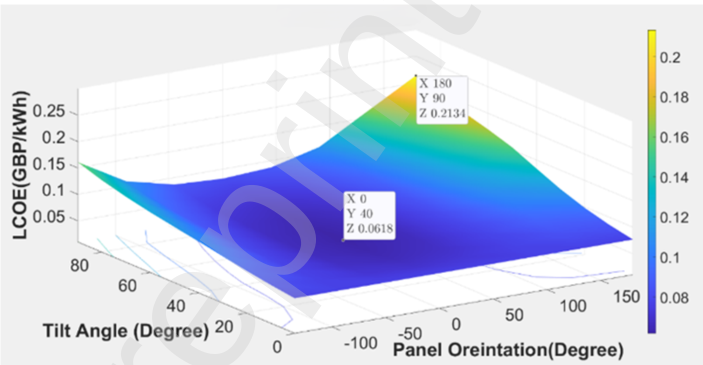

Figure 10 LCOE Assessment for Kirkwall BIPV System

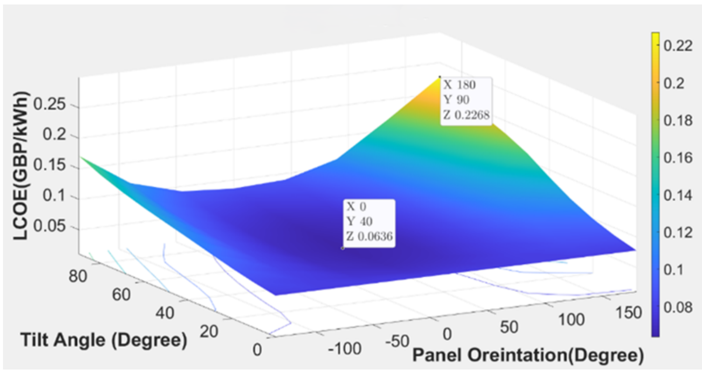

Figure 11 LCOE Assessment for Portree BIPV System

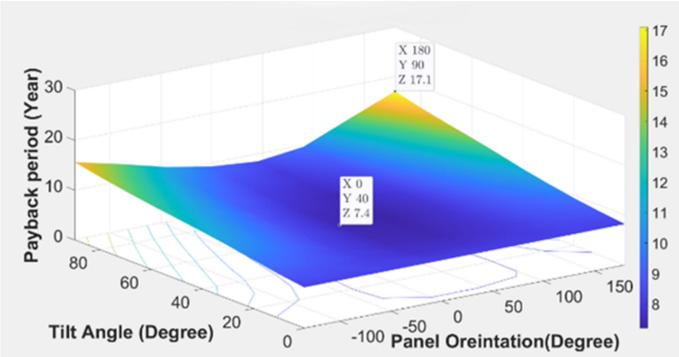

Figure 12 Payback Period Analysis for Edinburgh's BIPV System

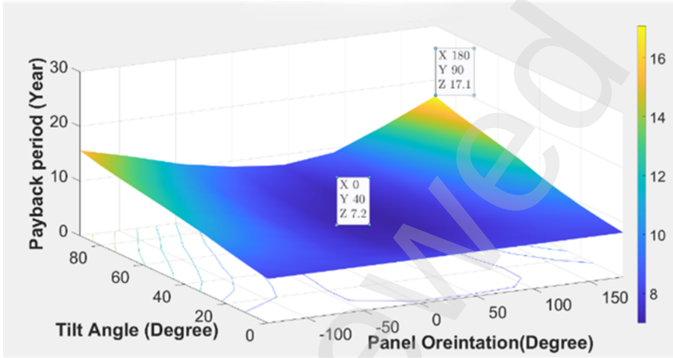

Figure 13 Payback Period Analysis for Aberdeen's BIPV System

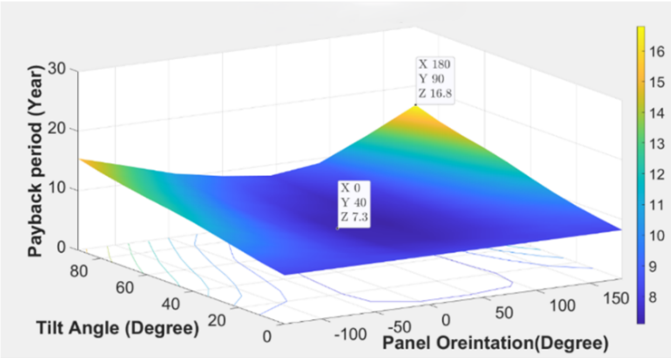

Figure 14 Payback Period Analysis for Kirkwall's BIPV System

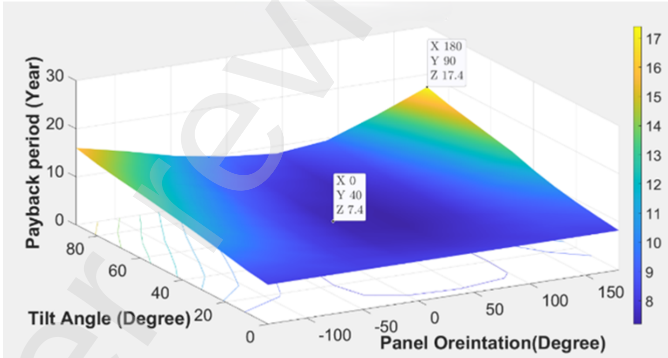

Figure 15 Payback Period Analysis for Portree's BIPV System

Additionally, This study places significant emphasis on the geographical characteristics and meteorological conditions of various locations in Scotland. As shown by the results presented in Table 2, the south-facing building façades at (0° azimuth and 40° tilt) exhibit greater economic feasibility compared to other orientations at (180° azimuth and 90° tilt). This is primarily attributed to higher solar irradiation on the south-facing façades, which enhances electricity generation and improves the overall profitability of BIPV systems in these configurations.

Table 2: Summary of the overall study's main outcomes

Scotland BIPV projects	Optimum Annual Energy Generated (kWh/year)	Minimum Annual Energy Generated (kWh/year)	Payback Period (PP) at optimum orientation (Years)	Payback Period (PP) Payback at worse orientation (Years)	LCOE at optimum orientation (GBP/ kWh)	LCOE at worse orientation (GBP/ kWh)
Edinburgh	1121	321	7.4	17.1	0.0631	0.2205
Aberdeen	1167	323	7.2	17.2	0.0606	0.2191
Kirkwall	1143	331	7.3	16.8	0.0618	0.2134
Portree	1111	312	7.4	17.4	0.0636	0.2268

Another suggestion applied considered to Edinburgh as the vibrant capital of Scotland is shown in Figure 16, It provides a pictorial representation aimed at architects and BIPV system developers in Edinburgh. This visualization illustrates all possible orientations of a building for the installation of BIPV façades and highlights the associated profitability rates when installed at their optimal tilt angles (30–40°). By applying this approach to economic assessment, the graphical representation serves as a practical tool for stakeholders to evaluate the impact of building façade orientation on energy generation and economic feasibility. Furthermore, this visualization facilitates broader accessibility, enabling even non-specialists to comprehend the significance of façade orientation in planning and designing cost-effective and environmentally sustainable buildings. Such tools are essential in promoting the integration of BIPV systems in urban development and supporting informed decision-making for energy-efficient building practices.

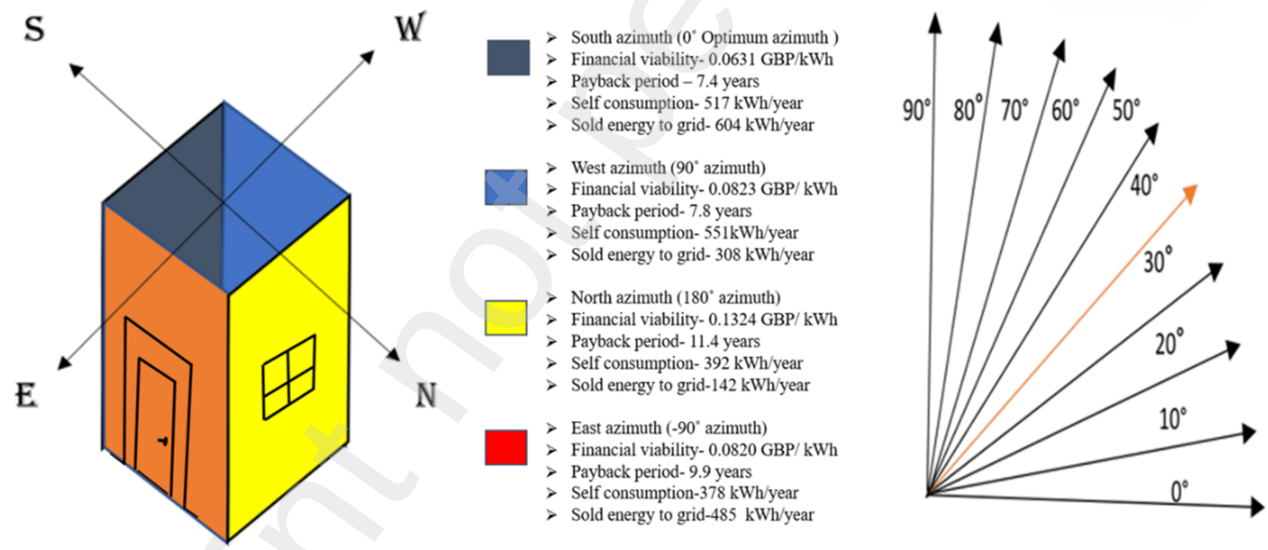

Figure 16 Pictorial representation of a BIPV system orientation-based economic viability in Edinburgh

5. Conclusion

The primary objective of this study was to assess the viability of BIPV systems as an envelope material for the entire exterior of the building with various orientations across four urban areas in Scotland. The study incorporated both the social and environmental benefits of BIPV systems into the economic analysis, aiming to enhance the understanding of BIPV economic feasibility and their potential as a building envelope solution. The findings showed that

Aberdeen achieved the best techno-economic performance, with an Annual Energy Generated (AEG) of 1167 kWh/year, Levelized Cost of Energy (LCOE) of 0.0606 GBP/kWh and a Payback Period (PP) of 7.2 years at the optimal orientation at (0° azimuth and 40° tilt) angles. However, Portree showed the lowest results at (180° azimuth and 90° tilt) angles, with AEG, LCOE, and PP of 312 kWh/year, 0.2268 GBP/kWh and 17.4 years respectively. A key conclusion of the study is that, in the context of Scotland, the construction of south-facing façades utilizing BIPV systems is economically viable when the full range of social and environmental benefits is considered. Furthermore, the findings suggest that the implementation of BIPV systems as a comprehensive building envelope could not only offset the initial investment but may also generate revenue for the building over time. The given analysis has the potential to assist end users and architects in seeing the BIPV system as a viable solution for building an envelope in Scotland or UK countries and direct governments and decision-makers in promoting this technology through logical subsidies and incentives.

It is now clear that the perception of BIPV technology as a useless solution for building envelope must shift. Instead, BIPV systems should be recognized as a viable and effective choice for building envelopes, regardless of orientation or direction. In other words, when architects are selecting building envelope materials to meet the demands of clients seeking environmentally friendly, energy-efficient structures, BIPV should be viewed as a competitive option that offers distinct advantages. Not only does BIPV contribute to green energy production, but it also has the potential to transform building façades into sources of revenue.

For future research, exploring advanced technologies to further enhance the economic viability of buildings is strongly recommended. One promising approach involves integrating concentrated photovoltaic (CPV) technologies into BIPV systems. CPV systems have the capability to focus both diffuse and direct sunlight onto the solar cells, potentially increasing energy output. This is particularly relevant for regions like Scotland, where direct sunlight is limited during non-summer months. By harnessing CPV technology, it may be possible to ensure more consistent energy production throughout the year, thereby improving the reliability and efficiency of BIPV systems. Future investigations should focus on optimizing CPV integration within BIPV systems, evaluating long-term performance, and assessing economic feasibility under varying climatic and geographic conditions.

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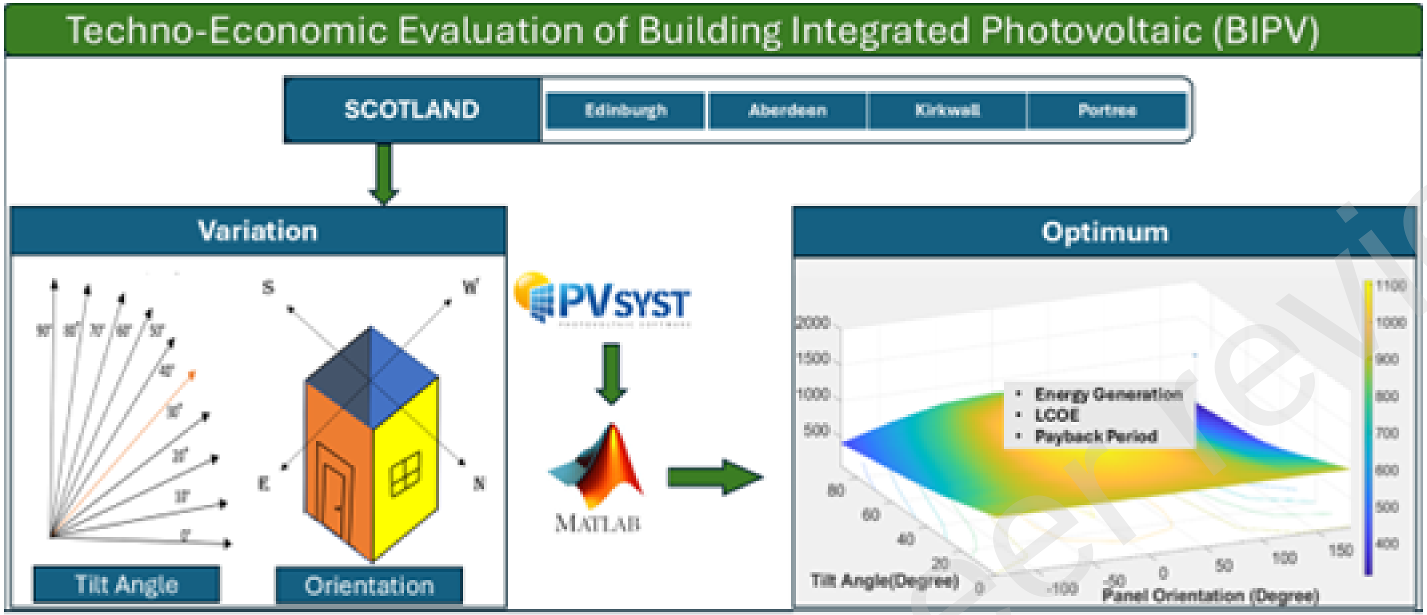
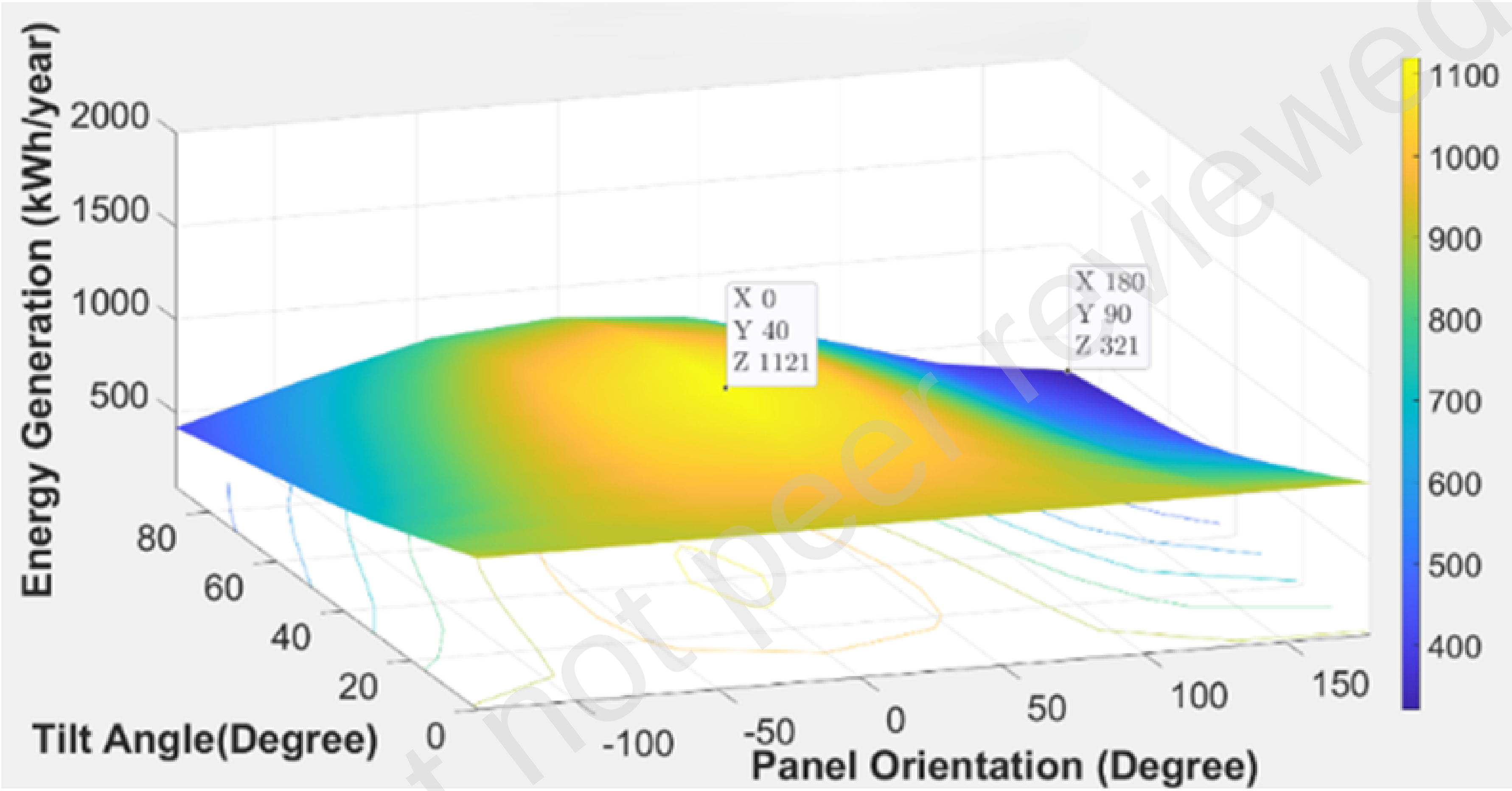
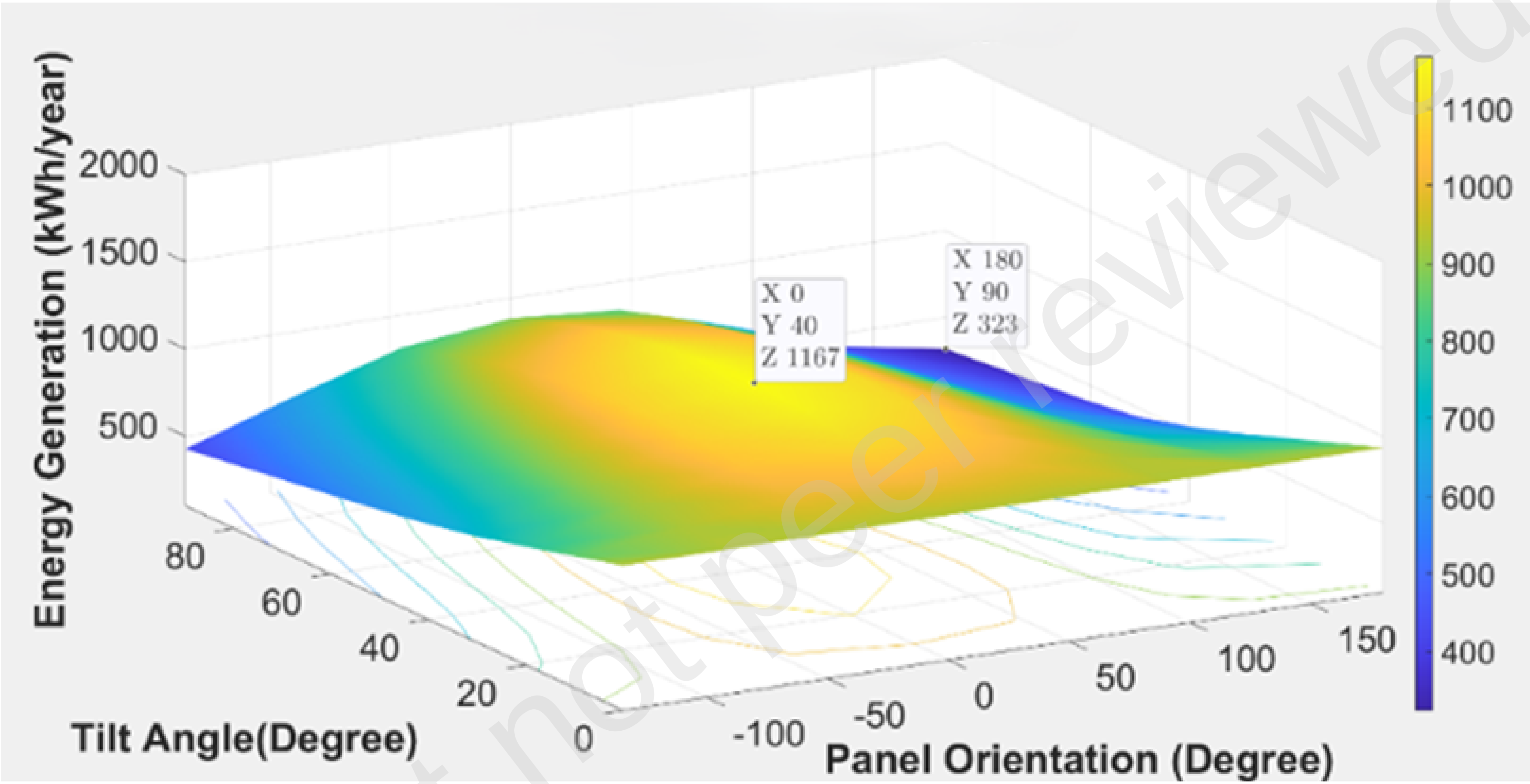
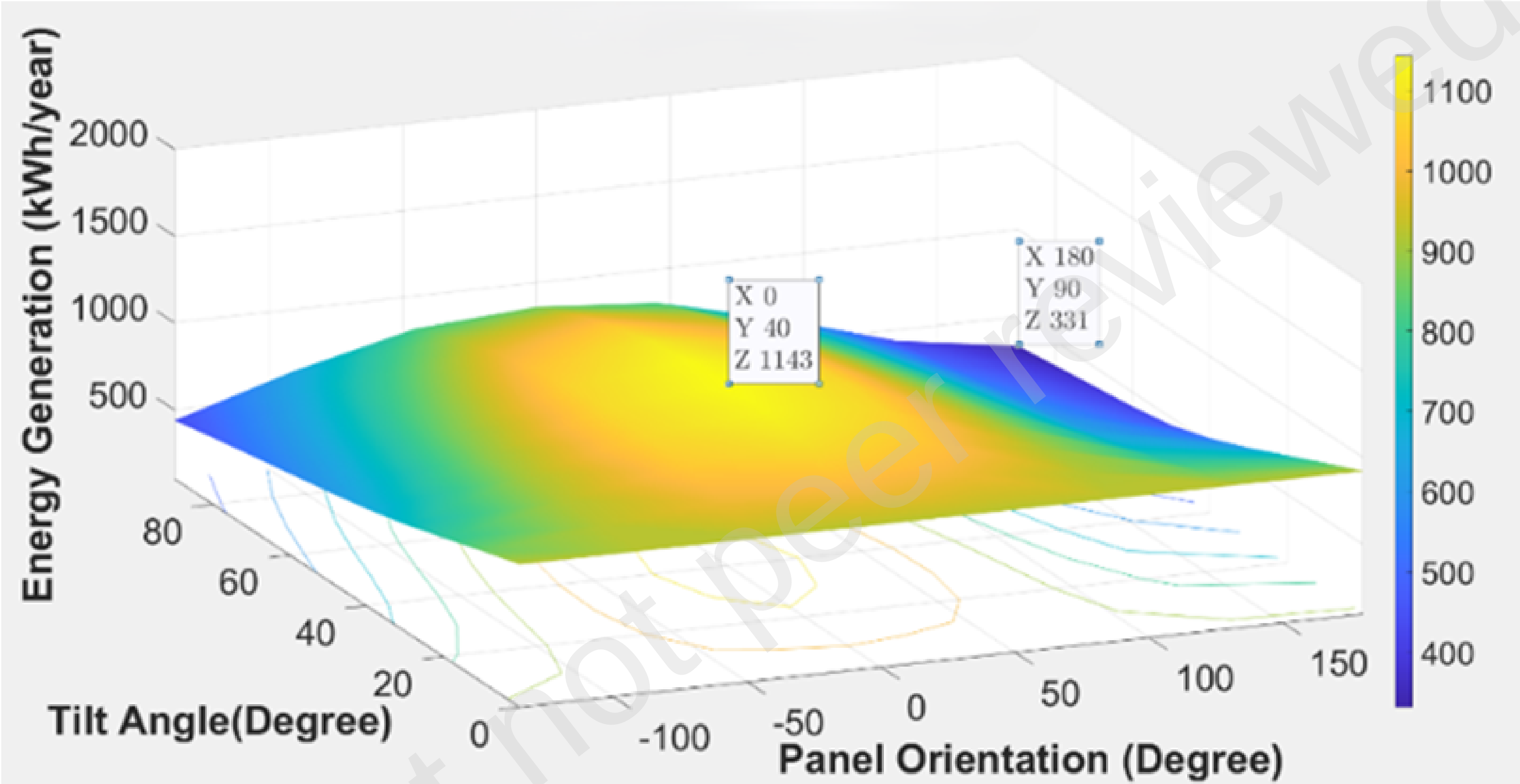


Techno-Economic Evaluation of Building Integrated Photovoltaic (BIPV)
SCOTLAND
Edinburgh
Aberdeen
Kirkwall
Portree
Variation
Optimum
PVSYST
MATLAB
S
W
E
N
Tilt Angle
Orientation
Energy Generation
LCOE
Payback Period
Tilt Angle(Degree)
Panel Orientation (Degree)

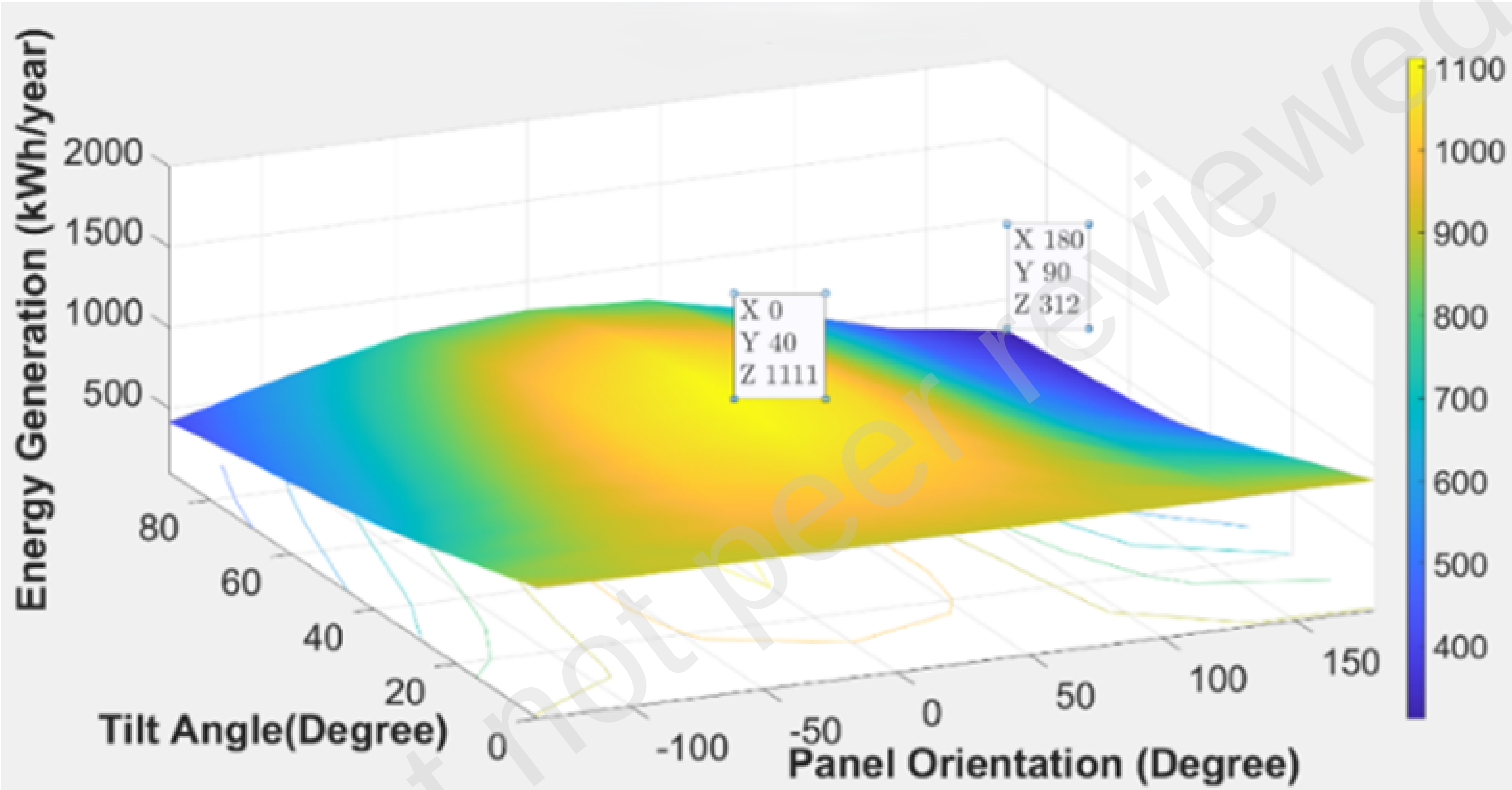


Energy Generation (kWh/year)
2000
1500
1000
500
80
60
40
20
0
Tilt Angle(Degree)
-100
-50
0
50
100
150
Panel Orientation (Degree)
X 0
Y 40
Z 1121
X 180
Y 90
Z 321
1100
1000
900
800
700
600
500
400

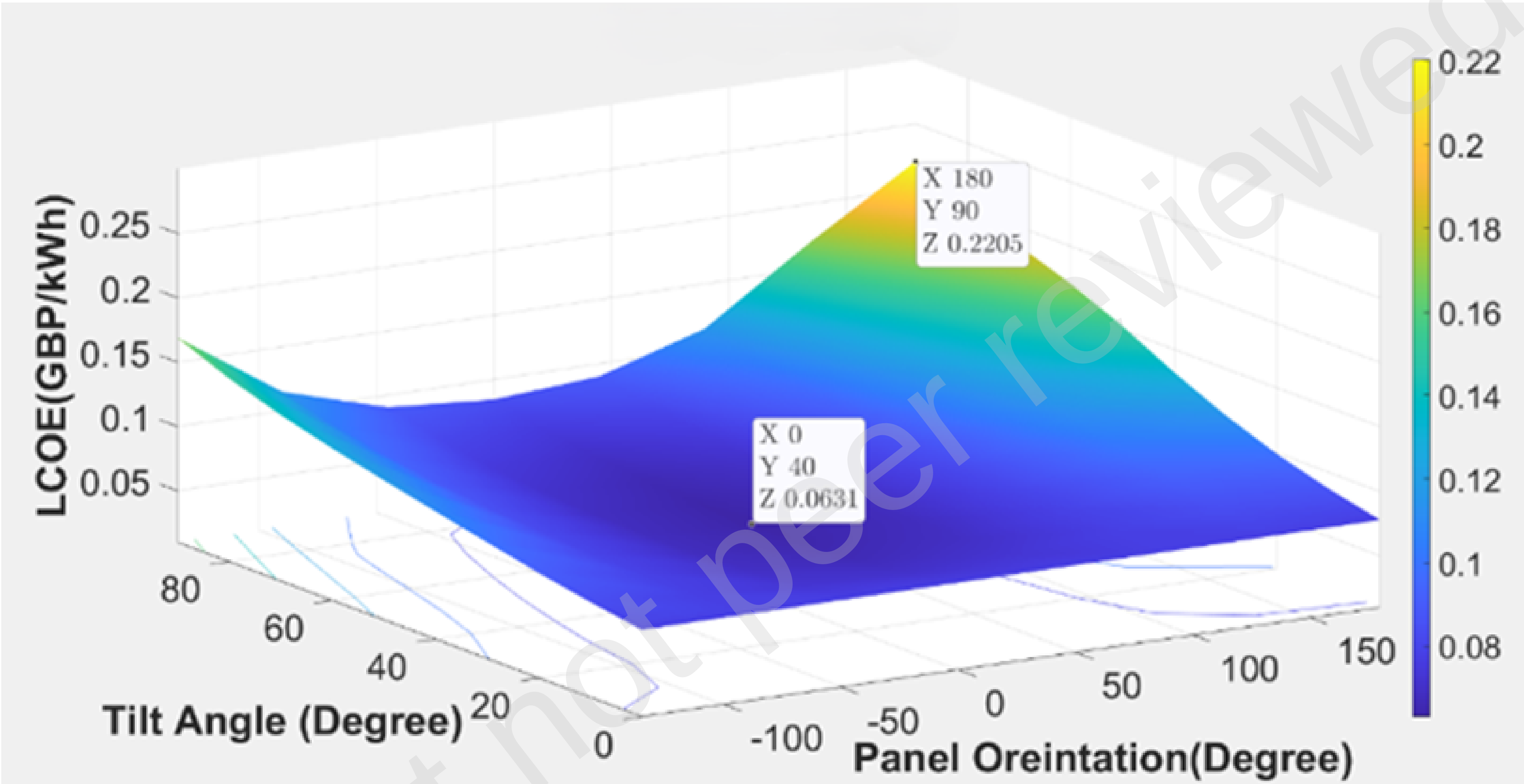

Energy Generation (kWh/year)
2000
1500
1000
500
X 0
Y 40
Z 1167
X 180
Y 90
Z 323
80
60
40
20
0
Tilt Angle(Degree)
-100
-50
0
50
100
150
Panel Orientation (Degree)
1100
1000
900
800
700
600
500
400



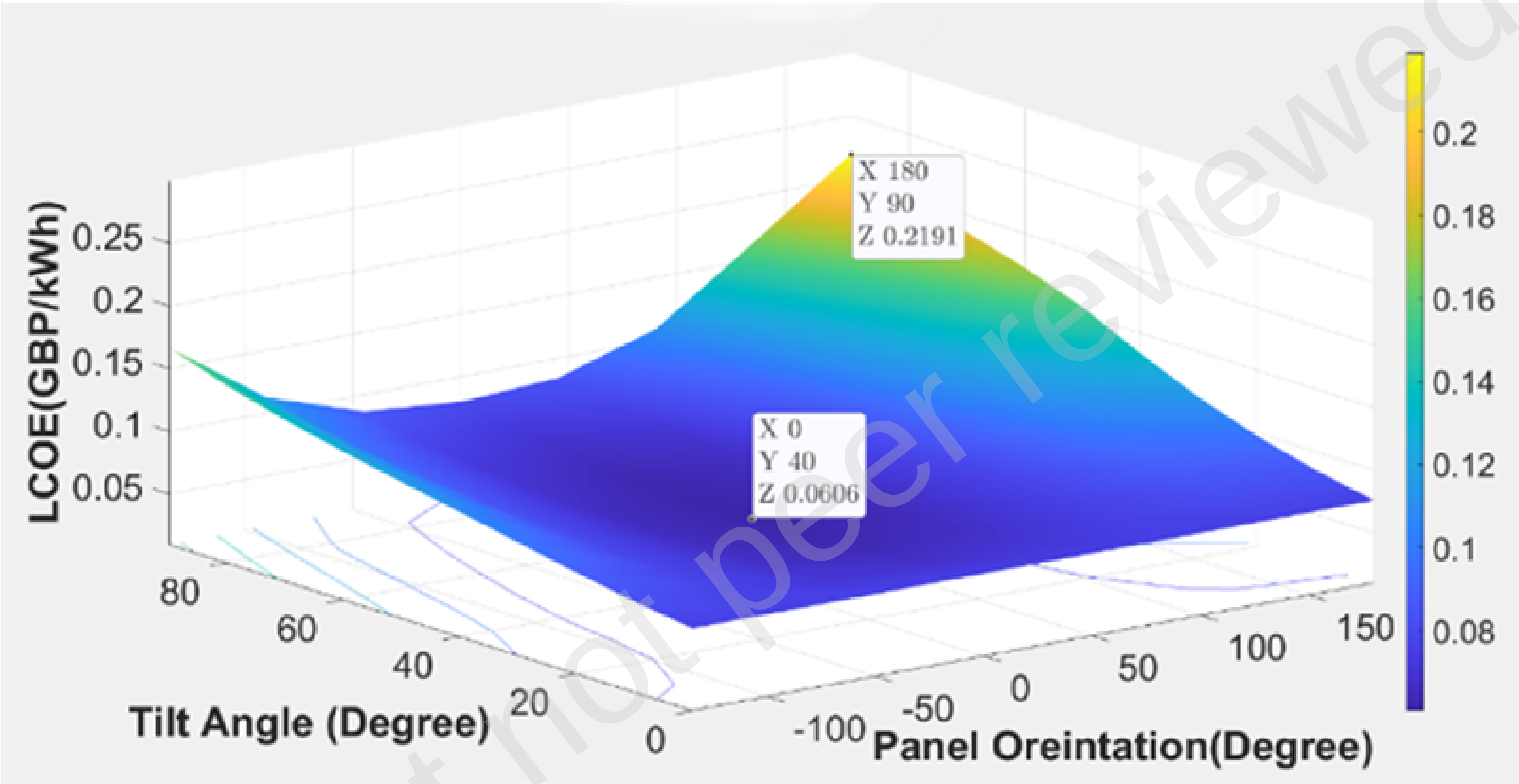
Energy Generation (kWh/year)
2000
1500
1000
500
X 0
Y 40
Z 1143
X 180
Y 90
Z 331
80
60
40
20
0
Tilt Angle(Degree)
-100
-50
0
50
100
150
Panel Orientation (Degree)
1100
1000
900
800
700
600
500
400



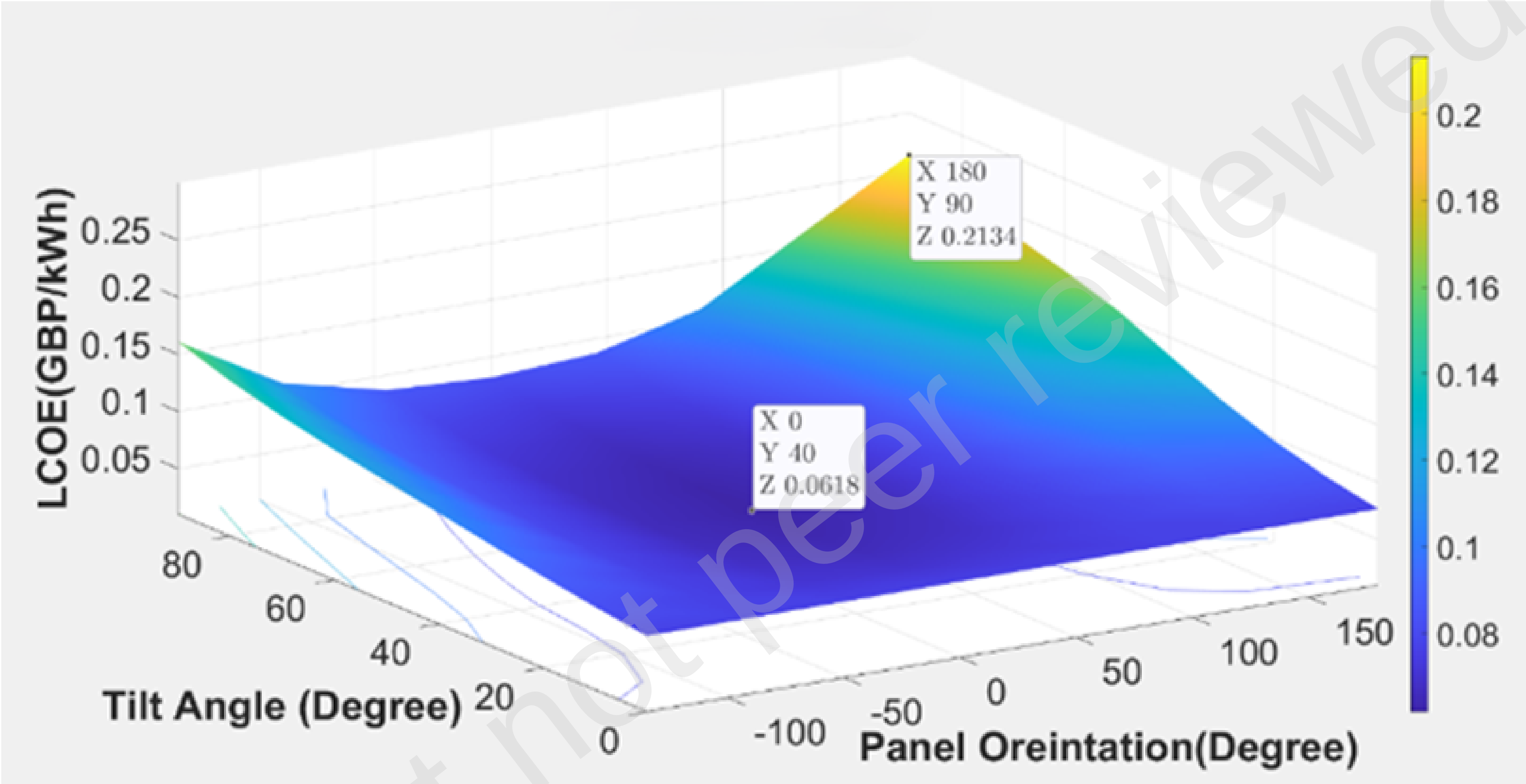
Energy Generation (kWh/year)
2000
1500
1000
500
X 0
Y 40
Z 1111
X 180
Y 90
Z 312
80
60
40
20
0
Tilt Angle(Degree)
-100
-50
0
50
100
150
Panel Orientation (Degree)
1100
1000
900
800
700
600
500
400



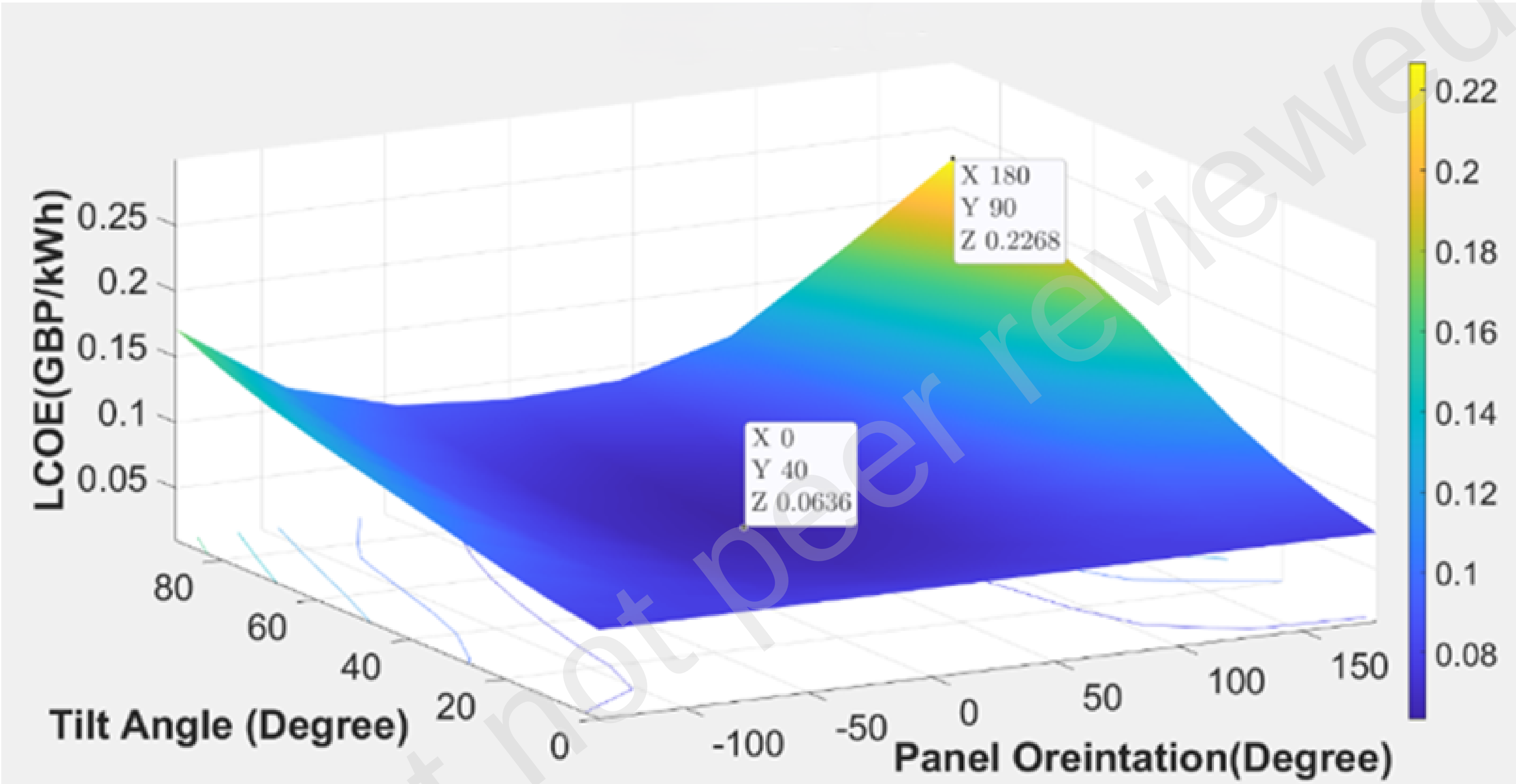
X 180
Y 90
Z 0.2205
X 0
Y 40
Z 0.0631
LCOE(GBP/kWh)
0.25
0.2
0.15
0.1
0.05
80
60
40
20
0
Tilt Angle (Degree)
-100
-50
0
50
100
150
Panel Oreintation(Degree)
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08



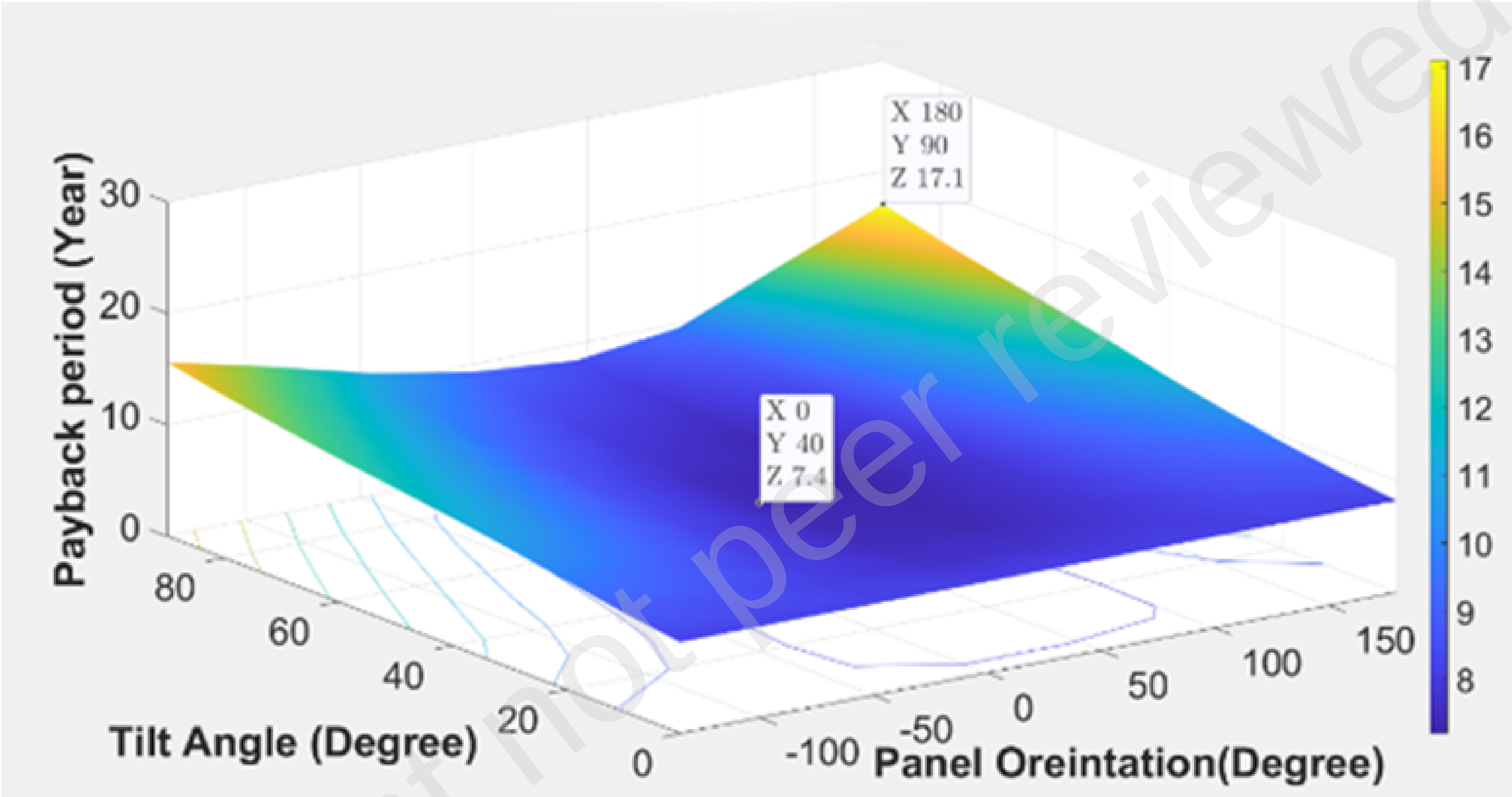
LCOE(GBP/kWh)
0.25
0.2
0.15
0.1
0.05
X 180
Y 90
Z 0.2191
X 0
Y 40
Z 0.0606
80
60
40
20
0
Tilt Angle (Degree)
-100
-50
0
50
100
150
Panel Oreintation(Degree)
0.2
0.18
0.16
0.14
0.12
0.1
0.08

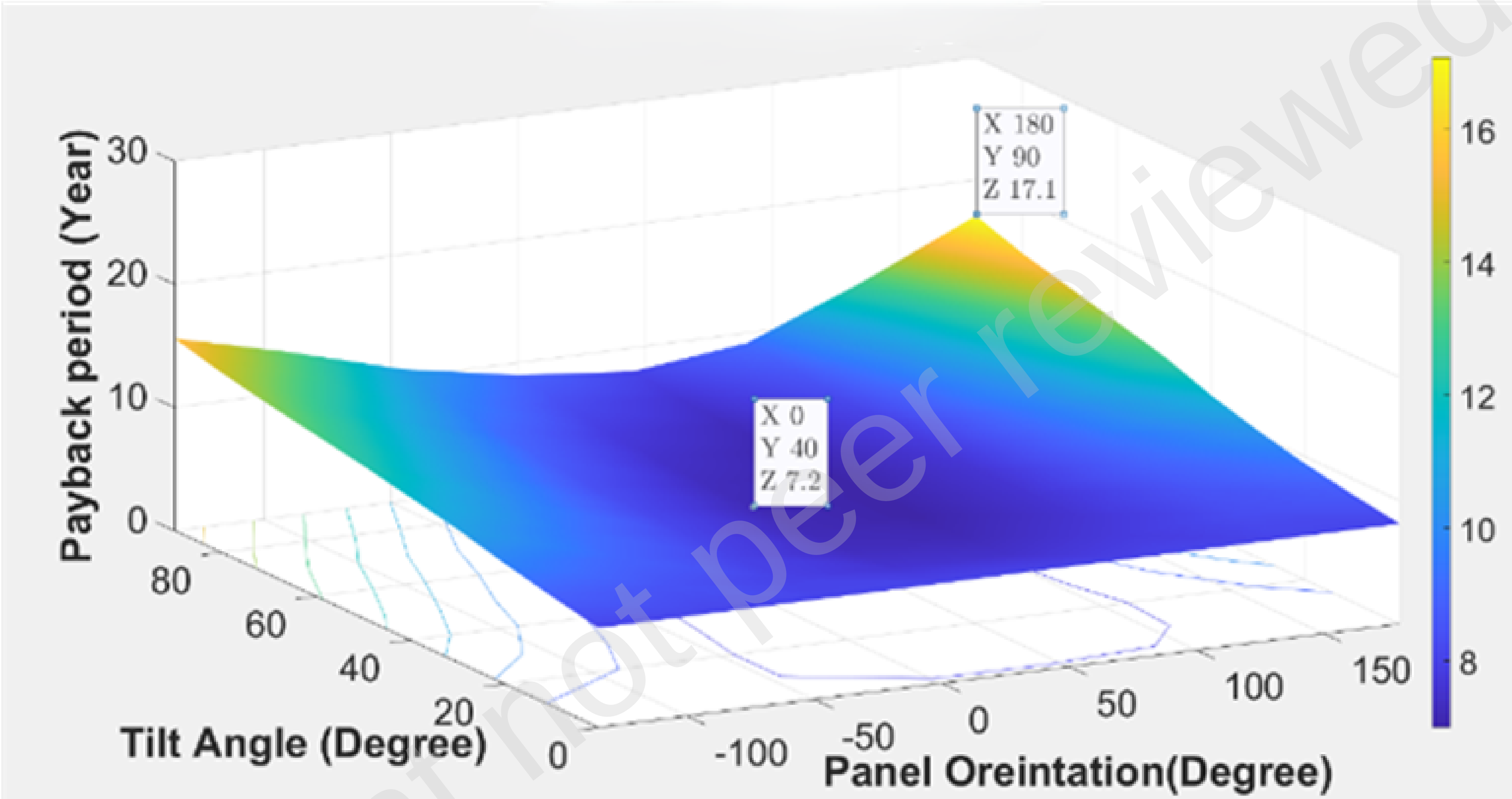


LCOE(GBP/kWh)
0.25
0.2
0.15
0.1
0.05
X 180
Y 90
Z 0.2134
X 0
Y 40
Z 0.0618
80
60
40
20
0
Tilt Angle (Degree)
-100
-50
0
50
100
150
Panel Oreintation(Degree)
0.2
0.18
0.16
0.14
0.12
0.1
0.08

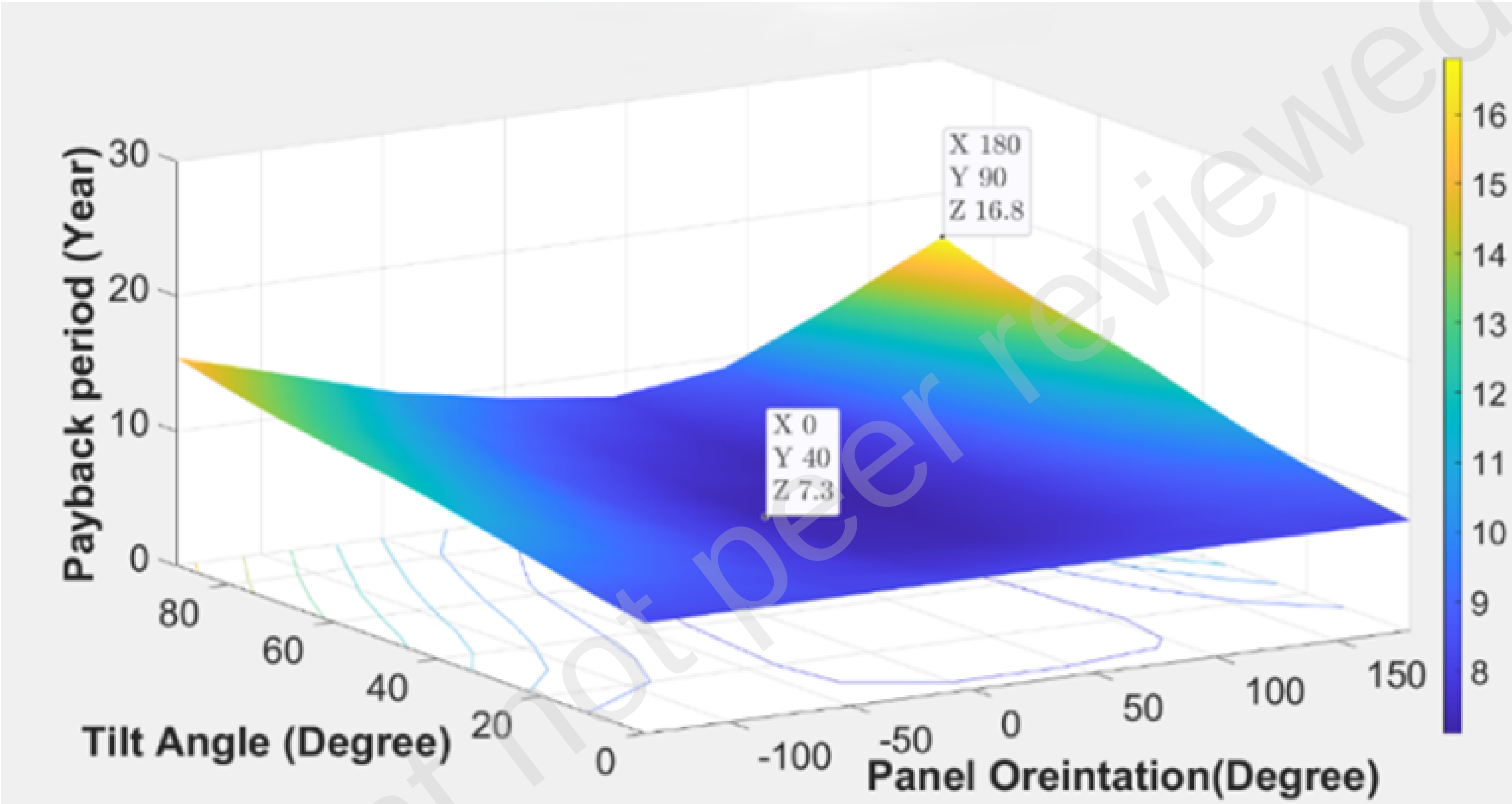


LCOE(GBP/kWh)
0.25
0.2
0.15
0.1
0.05
X 180
Y 90
Z 0.2268
X 0
Y 40
Z 0.0636
80
60
40
20
0
Tilt Angle (Degree)
-100
-50
0
50
100
150
Panel Oreintation(Degree)
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08

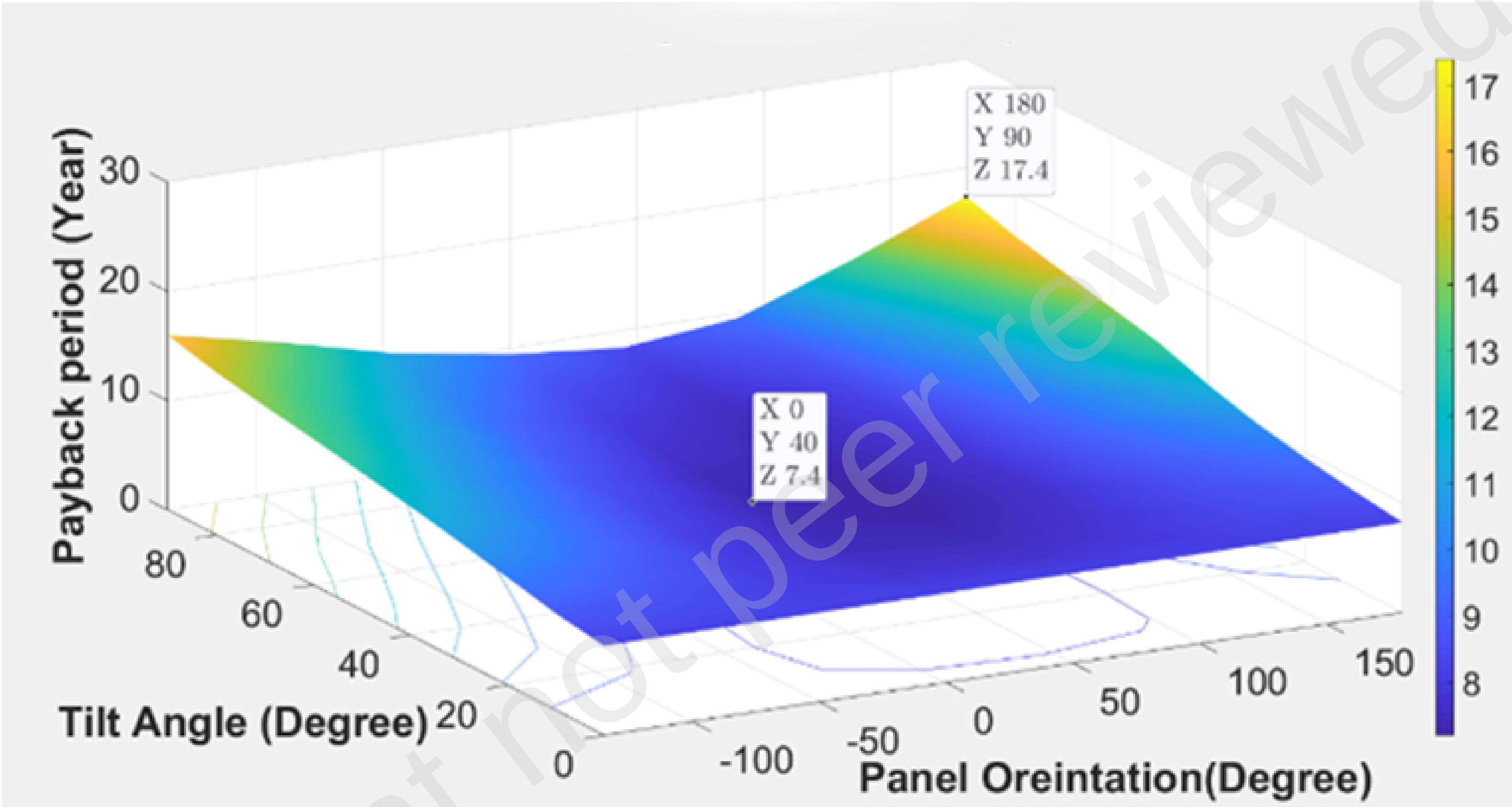

X 180
Y 90
Z 17.1
X 0
Y 40
Z 7.4
Payback period (Year)
Tilt Angle (Degree)
Panel Oreintation(Degree)



Payback period (Year)
30
20
10
0
80
60
40
20
0
Tilt Angle (Degree)
-100
-50
0
50
100
150
Panel Oreintation(Degree)
X 180
Y 90
Z 17.1
X 0
Y 40
Z 7.2
16
14
12
10
8



Payback period (Year)
30
20
10
0
80
60
40
20
0
Tilt Angle (Degree)
-100
-50
0
50
100
150
Panel Oreintation(Degree)
X 180
Y 90
Z 16.8
X 0
Y 40
Z 7.3
16
15
14
13
12
11
10
9
8



Payback period (Year)
30
20
10
0
80
60
40
20
0
Tilt Angle (Degree)
-100
-50
0
50
100
150
Panel Oreintation(Degree)
X 180
Y 90
Z 17.4
X 0
Y 40
Z 7.4
17
16
15
14
13
12
11
10
9
8

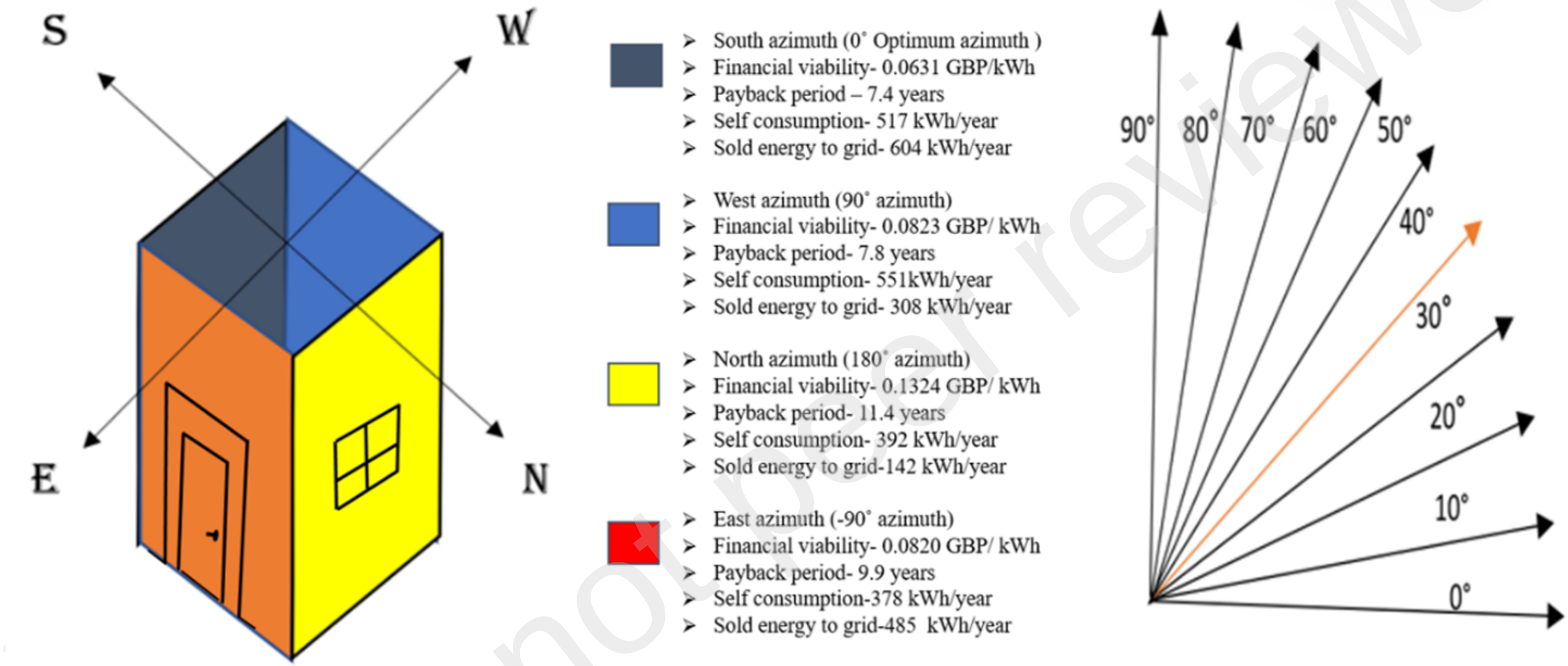

S
W
E
N
South azimuth (0˚ Optimum azimuth)
Financial viability- 0.0631 GBP/kWh
Payback period – 7.4 years
Self consumption- 517 kWh/year
Sold energy to grid- 604 kWh/year
West azimuth (90˚ azimuth)
Financial viability- 0.0823 GBP/ kWh
Payback period- 7.8 years
Self consumption- 551kWh/year
Sold energy to grid- 308 kWh/year
North azimuth (180˚ azimuth)
Financial viability- 0.1324 GBP/ kWh
Payback period- 11.4 years
Self consumption- 392 kWh/year
Sold energy to grid-142 kWh/year
East azimuth (-90˚ azimuth)
Financial viability- 0.0820 GBP/ kWh
Payback period- 9.9 years
Self consumption-378 kWh/year
Sold energy to grid-485 kWh/year
90°
80°
70°
60°
50°
40°
30°
20°
10°
0°

Table 1: Financial parameters for Scotland BIPV projects

Financial parameters	Unit	values
Total installation cost	(GBP/ kWp)	1650
Project lifetime	(Years)	25
Inflation variation per year	(% / Year)	1.5
Discount rate variation	(% / Year)	1
Production variation (degradation)	(% / Year)	-0.50
Fixed feed-in tariff (SEG)	(GBP / kWh)	0.075
Annual tariff variation	(% / Year)	2.16
Duration of tariff warranty	(Years)	25
Fixed consumption tariff	(GBP / kWh)	0.34
Annual tariff variation	(% / Year)	0.69
Average annual consumption per household	(kWh/year)	1802
Start Year	2022	

Table 1: Summary of the overall study's main outcomes

Scotland BIPV projects	Optimum Annual Energy Generated (kWh/year)	Minimum Annual Energy Generated (kWh/year)	Payback Period (PP) at optimum orientation (Years)	Payback Period (PP) Payback at worse orientation (Years)	LCOE at optimum orientation (GBP/ kWh)	LCOE at worse orientation (GBP/ kWh)
Edinburgh	1121	321	7.4	17.1	0.0631	0.2205
Aberdeen	1167	323	7.2	17.2	0.0606	0.2191
Kirkwall	1143	331	7.3	16.8	0.0618	0.2134
Portree	1111	312	7.4	17.4	0.0636	0.2268