

Article

Feasibility of Bifacial Photovoltaics in Transport Infrastructure

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Abstract: Around the world, large-scale bifacial photovoltaics (BPV) modules are increasingly being used to generate clean electricity, given the cost of manufacturing is becoming comparable to conventional monofacial PV modules. BPV, when installed vertically, can still produce high levels of electricity by collecting radiation on the front as well as on the rear side. This paper assessed the renewable energy generation potential of vertical BPV plants along the central reservation of UK motorways. These installations maximize the utility of road space while minimizing land consumption. The feasibility of BPV systems for different segments of a motorway case study in the UK were modelled to calculate energy yield, the levelized cost of electricity (LCOE), payback period, and net present value. The LCOE of a medium to large-scale system was 10–11 p/kWh, 60% less than that of a small-scale system. The payback period for medium to large-scale systems was found to be 6 years, whereas for small systems, it was 10 years. The paper further discussed the challenges and opportunities associated with installing BPV panels on motorways with guidance on the types of locations which are likely to be most successful for future full-scale installations.

Keywords: bifacial PV; transport infrastructure; LCOE; net present value



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1. Introduction

The UK Government aims to achieve net zero and position itself as a global leader in clean energy. This is driven by international commitments to reducing global warming and national priorities such as enhancing energy security, improving quality of life, fostering job security, developing skills, and boosting economic growth. Solar Photovoltaic (PV) is currently the most cost-effective source of electricity, adaptable for various scales of deployment, and essential in achieving global climate action goals. To meet the UK 2050 target of net zero emissions, the government aims to achieve 70 GW of solar power by 2035 [1]. The cumulative installed solar power capacity in the UK had reached 15.8 GW by March 2024.

Zero-carbon communities play a crucial role in driving the transition to carbon-neutral urban energy systems. This largely relies on retrofitting existing buildings to lower energy use, incorporating PV into rooftops and windows, and offering financial support to property owners and tenants to implement these upgrades [2]. The development of low-carbon infrastructure, such as solar farms, is also a critical national priority [1]. However, it faces several challenges, including increased land use, environmental and biodiversity impacts, water consumption, and emissions from indirect land use changes—particularly in densely populated areas with limited agricultural land availability [3]. The national

policy statement for renewable energy infrastructure therefore advises solar farms to be installed on pre-developed and non-agricultural land [1].

EU market trends suggest that total installed capacity could reach 1 TWp by 2030, equating to 2246 Wp per capita [4]. While the land requirement for conventional ground-mounted PV is relatively small—around 0.1% of the EU's total land area—availability remains restricted due to the prioritization of agricultural land for food production and the preservation of nature and landscapes. Additionally, in some instances, the distance from electricity network infrastructure presents a significant barrier.

Denholm and Margolis [5] claim that if the US should be entirely powered by photovoltaic energy, around 180 m² per person of land area would be needed which corresponds to about 0.6% of the total U.S. land area—a size comparable to the total area of the Netherlands, and roughly one-fifth the area of the UK. This land use equates with housing, transportation, and more critically with the agriculture sector. Hence, high deployment of conventional PV systems might raise a future conflict between the agriculture and sustainable energy sectors [6]. Consequently, alternative PV deployment methods are becoming increasingly popular, including building-integrated PV, floating PV, and agrivoltaics, which support sector growth even in areas with limited land availability. Additionally, transport infrastructure presents another viable option for accommodating PV systems [7]. Motorways are shade-free structures and could be an ideal solution for the surface problem of photovoltaics. In the Netherlands, vertical BPV have been utilized as a noise barrier, running either side of a motorway, where in an eight-month period, 163 MWh of electricity was produced [8]. The project demonstrated that traffic has a minimal impact on PV yield, reducing output by only 3%. Additionally, solar road installations could supply up to 5% of the Netherlands' electricity consumption, highlighting the substantial potential of road surfaces in cutting CO₂ emissions [7]. They have also been used in Dirmingen, Germany for agriculture and livestock farming where they produce electricity for up to 700 homes [9]. The recently amended National Roads Ordinance allows Switzerland to generate renewable energy along major highways where the potential for electricity generation is 55 GWh per year [10]. The German Transport Ministry has highlighted the vast potential of installing solar panels along motorways, estimating that by 2030, up to 200 TWh of solar power could be generated annually across Germany's autobahn network [11]. According to the Altes Neuland Foundation, a major advantage of this system is that electricity would be distributed at the point of production, ensuring efficient routing to the necessary locations. Since motorways connect key areas such as metropolitan hubs, industrial zones, and airports, they also serve as an avenue for charging infrastructure for electric vehicles, allowing electricity to be produced close to where it is needed.

Whilst there are numerous studies on infrastructure-integrated PV potential in urban areas [7–9], the literature and results on solar road potential modelling is currently lacking [12,13]. This article provides a unique contribution by providing guidance and prediction methods for modelling bifacial PV (BPV) on the UK roads. Using a motorway case study, this article proposes a novel business case for the installation of BPV plants along the central reservation of a motorway to enhance renewable energy generation whilst utilizing underutilized road infrastructure. This type of installation enables the efficient use of road space, minimizing land consumption and overcoming a common limitation of solar arrays that are not roof-mounted, integrated into buildings, or placed on green spaces. The feasibility of bifacial PV (BPV) systems for different segments of a motorway case study in the UK was studied by the following ways:

- Calculating the energy yield of a small (2.8 kW), medium (4 kW), and large (5.6 kW) scale BPV system to determine the levelized cost of electricity;

- Calculating the economic feasibility in terms of the payback period and net present value to suggest the most effective system;
- Highlighting power generation integration challenges and opportunities associated with BPV deployment.

2. Background

2.1. Solar PV Development in UK

Within the United Kingdom the uptake of solar energy conversion to electricity has been rather slow. Successive Governments have not been expressly supportive. In this respect, quotes from the two immediate past Prime Ministers are referred herein. Rishi Sunak has been reported to have said, “sure our fields are used for food production and not solar panels” [14]. Likewise, Liz Truss was quoted to have said, “I am somebody who wants to see farmers producing food, not filling in forms”. The latter quotes have also been cited by Frankopan [15]. However, the following analysis will show that the UK is now catching up fast with countries such as China in the exploitation of solar PV on a large scale.

The current deployment of solar farms in the UK has reached 13.3 GWp capacity, with a total of 469 farms feeding into the grid. However, as observed by Frankopan, 2023 [15], even if that capacity was to increase five-fold, the land area covered by solar farms would still be 0.5 per cent of the land that is currently used for farming. Even the UK golf courses would still have twice the amount of land as solar farms [16]. The latterly mentioned UK PV national installation of 13.3 GW may not look large in contrast to that of China and India, where their largest PV farms alone are, respectively, of 8.43 and 3.5 GW capacities. China’s and India’s largest PV farms are, respectively, the Gonghe Talatan Solar Park in Qinghai Province and Bhadla Solar Park in Rajasthan State.

The UK’s largest solar farm will be the ‘Longfield’ solar farm that is being built in Chelmsford, Essex. That project will cover an area of 380 hectares (ha) with a peak capacity of 500 MW. The farm, being developed by EDF Renewables, will include battery storage [17].

In the remainder of this section, a review of the six other largest UK solar farms is presented and key lessons drawn [18].

1. Presently, approval has been given for the development of Project Fortress 350 MW solar PV farm with an area of 364 ha at Cleve Hill, near Faversham in Kent, England.
2. Shotwick Solar Park is located in Flintshire, Wales. Completed in year 2016, it has a capacity of 72.2 MW and covers an area of 101 ha.
3. Lyneham Solar Farm is the First Military facility and is located in Bradenstoke, Wiltshire. The farm occupies an area of 86 ha and has a peak capacity of 69.8 MW. It started to generate electricity in 2015.
4. Wroughton Airfield Solar Park is built on a former airfield. It covers an area of 70 ha and has a peak capacity of 60.6 MW.
5. Owl’s Hatch Solar Park is located in Herne Bay, Kent. Commissioned in March 2015, the solar park has a capacity of 51.9 MW and covers an area of 86 ha.
6. West Raynham Solar Farm: The UK’s First Solar Farm on a Former RAF Base was commissioned in March 2015. It has a capacity of 49.9 MW and covers an area of 225 acres.

The land area-to-PV capacity ratio for the above seven, largest UK farms is summarized in Table 1. A comparison of PV farms development in China and UK is provided in Table 2. It can be seen that despite having a significantly smaller land area of 0.244 million km² as compared to China’s 9.597 million km², the UK’s land area-based index and available solar energy-based index are comparable with China. This demonstrates that the PV installation

trend is increasing in the UK, and it is of utmost importance to prove the feasibility of solar projects on surfaces that do not damage agricultural land such as solar powered highways [19].

Table 1. The largest seven solar PV farms in UK.

Location	Area, ha	Peak Capacity, MW	Footprint Index, m ² /kW
West Raynham, Norfolk	91	49.9	18.2
Herne Bay, Kent	86	51.9	16.6
Wroughton Airfield	70	60.6	11.5
Bradenstoke, Wiltshire	86	69.8	12.4
Flintshire, Wales	101	72.2	14
Project Fortress, Kent	364	350	10.4
Chelmsford, Essex	380	500	7.6

Table 2. Comparison of solar PV farm developments in China and UK.

China	UK	Comparative Indices	
609.49	15.6	Installed PV capacity, GW	
1412	66.97	Population, Million	
9220	267	Annual electricity consumption, TWh	
9.597	0.244	Land area, million km ²	
3.965	2.43	Solar radiation income, kWh/m ² -day	
882.1	13.8	Potential solar electrical generation, TWh	
431.7	232.9	Per capita installed PV, W	Human population-based index
63.5	64	Installed PV, kW/km ²	Land area-based index
0.096	0.052	Solar fraction	Available solar energy-based index
108.9	95.9	Specific per capita installation, W/kWh/m ² -day	Population factor
16	26.4	Specific PV installation, kW/km ² /kWh/m ² -day	Land area factor
0.024	0.021	Specific solar fraction	Solar fraction factor

2.2. Bifacial PV

Installation of PV on roads is generally considered to be safe and relatively low-maintenance with a high potential for energy generation when considered cumulatively across a country [20]. The state-of-the-art glass–glass bifacial PV (BPV) are ideally suited under this scenario in contrast to conventional monofacial PV (MPV). BPV can be installed vertically and still produce high levels of electricity by collecting radiation on the front as well as on the rear side [21,22]. Since the solar cells are double-sided, when installed in the upright position, they face east and west, allowing them to capture sunlight efficiently as the sun rises in the east. Throughout the day, as the sun moves westward, direct sunlight diminishes around noon when it shines parallel to the panels. In the evening, at sunset, the west-facing side receives full exposure again. Figure 1 given below shows how this distinct setup produces an irradiation curve with two peaks—one in the morning and another in the evening—resulting in a unique energy output profile compared to traditional solar PVs [19].

BPV require minimal space, have little impact on vegetation, do not impact the mobility of farm animals, prevent snow from depositing, and help reduce the accumulation of dirt when installed vertically. Moreover, BPV are being manufactured at a cost that is only a fraction more than their monofacial counterparts [21]. BPV can be installed facing east to west, and have peak electricity generation during the morning and evening as opposed to the middle of the day, offering the advantage of supplementing electricity during peak demand hours. Moreover, the UK is in the temperate oceanic climate zone and receives

more diffuse solar irradiance which at the rear side causes more gain in the energy output than the conventional MPV.

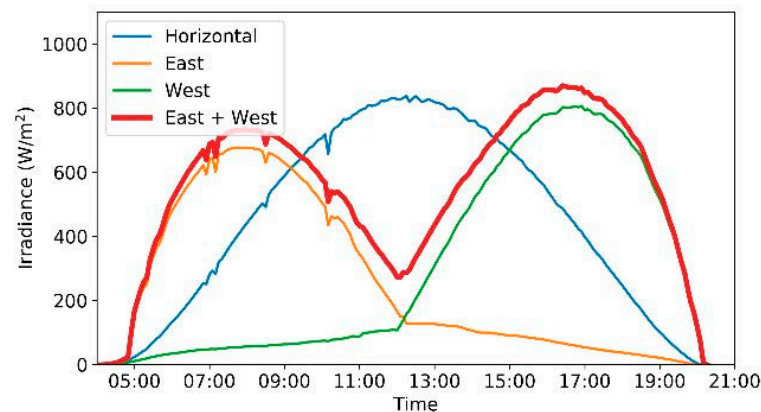


Figure 1. Irradiation cure for vertical BPV featuring a double peak structure [19].

The authors are currently engaged in researching vertical BPV performance and have conducted tests at the Heriot-Watt University test site [23,24]. Results demonstrate that the energy gain of BPV using a non-traditional reflective surface was up to 40%, which implies that it is possible to produce up to 40% extra energy from BPV than from conventional MPV.

3. Materials and Methods

The UK is a moderately high latitude country representing a diffuse climate with a low to average clearness index 0.28–0.42, respectively, and average ambient temperature ranging from 4–18 °C. The M6 is the UK's longest motorway, which is 236 miles long (380 km) passing through several regions, as shown in Figure 2. M6 was chosen as the motorway case study for this analysis due to it running north–south, from the Scottish border to the Midlands, making it ideal for the installation of BPV.

Using Google Earth, 20 sections of M6, that approximately run in north–south direction, were selected for BPV installation along the central reservation. The latitude and longitude of the 20 locations are provided in Table 3. The length of each considered section was 10 m, where a grid-connected system comprising of 10 monocrystalline 280 Wp BPV was installed.

North–south running BPV tend to suffer more from shadows from traffic than installations facing south, because these systems generate most of the electricity in the morning and evening hours, when the sun has a low position. On average, the annual irradiation and direct current yield reduction caused by traffic was found to be around 3%. This indicates that traffic shading does not drastically impact the potential of solar roads. However, these percentage losses are comparable to inverter losses and should therefore be taken into consideration [6]. To avoid the effect of traffic and dynamic shading on the performance of BPVs, this study proposes a high placement of PV modules at a height of 1.5 m from the ground [19].

The installation set-up is shown in Figure 3 below. To quantify the energy production, several simulations of grid-collected PV systems were run in PVSol Premium 2024 for each location. Meteonorm 8.0 typical meteorological year (TMY) data were used for simulation with a bifaciality factor of 0.8, which describes the ratio of the PV module's rear and front side efficiencies. The 5% factor allows determining how much additional energy yield can be produced by the rear irradiance receiving capability of the modules. It depends on temperature and irradiance level and its value can be in the range of 60% to 90%.

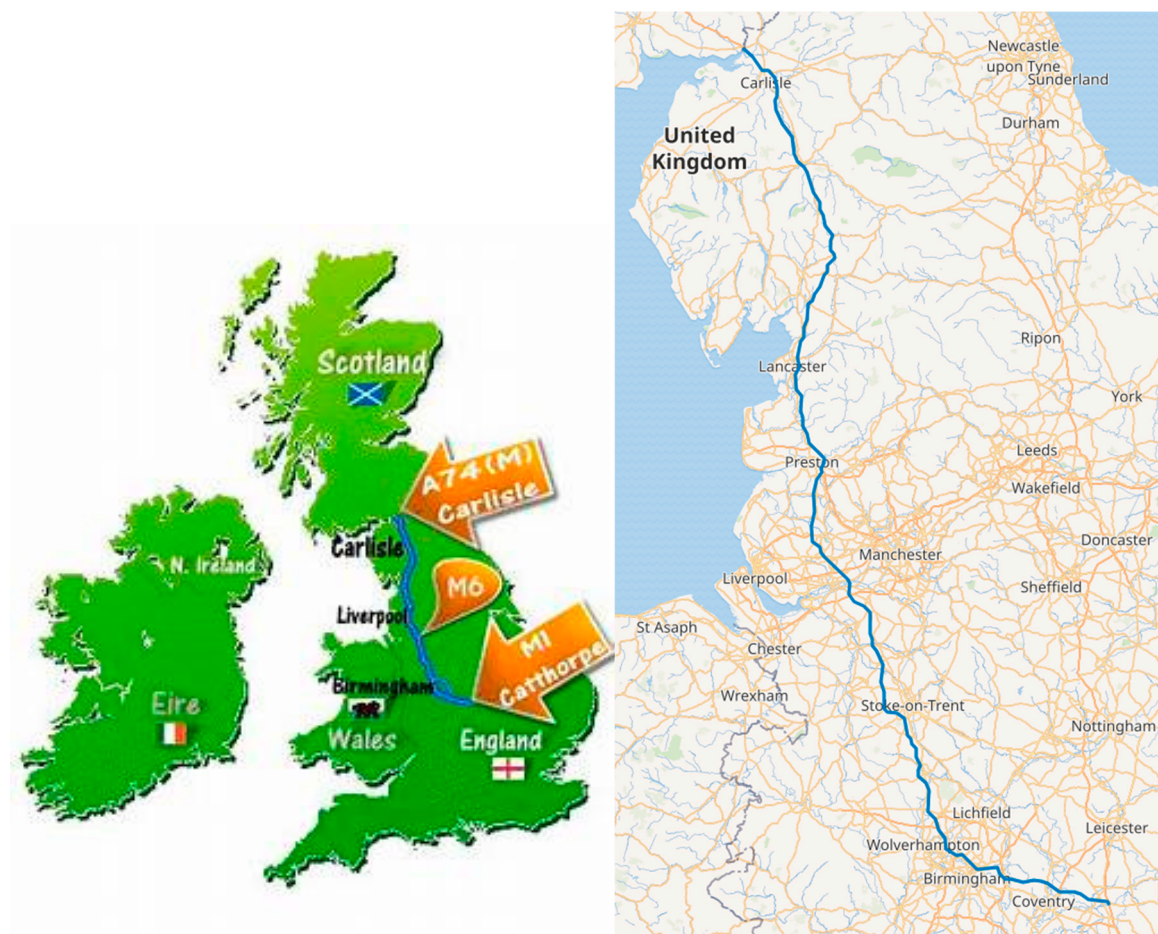


Figure 2. M6 from the Scottish border to the Midlands.

Table 3. Latitudes and longitudes of 20 sites on M6.

Location	Latitude, North	Longitude, West
1	54.20	−2.72
2	54.84	−2.89
3	54.72	−2.80
4	54.62	−2.72
5	54.16	−2.74
6	54.10	−2.77
7	54.00	−2.78
8	53.88	−2.74
9	53.70	−2.68
10	53.64	−2.69
11	53.53	−2.70
12	53.13	−2.33
13	53.05	−2.33
14	52.95	−2.22
15	52.86	−2.16
16	52.81	−2.15
17	52.74	−2.10
18	52.65	−2.06
19	52.59	−2.01
20	53.83	−2.72

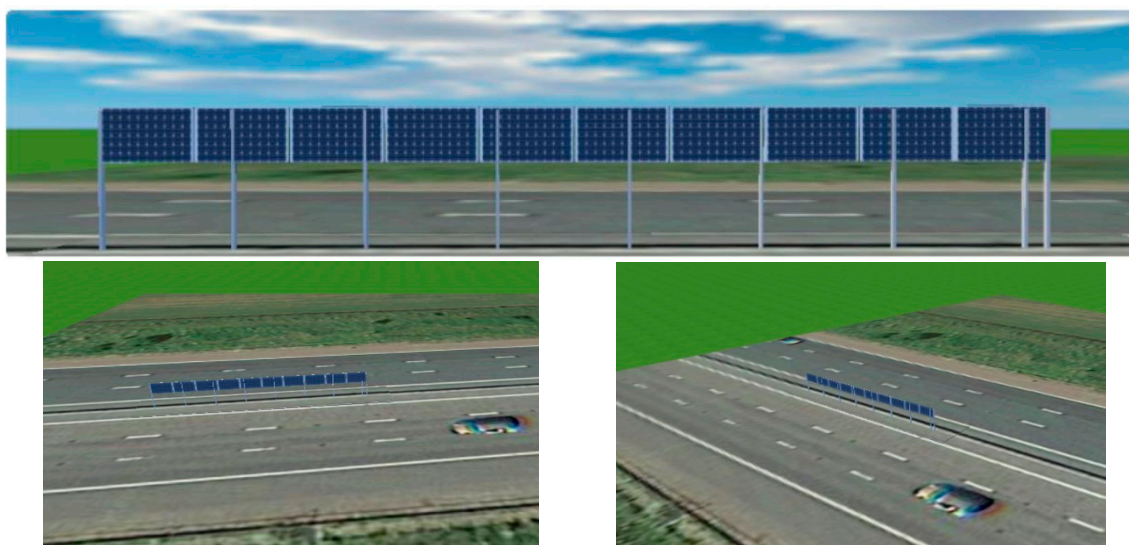


Figure 3. Vertical installation of BPV (top), east view (bottom left) and northeast view (bottom right).

To observe the annual solar energy potential of the location, an hourly irradiance mapping was carried out using NASA API in Python 3.7 environment. The solar irradiance data was downloaded using NASA API, and based on the data the hourly irradiance was mapped using heatmapping in Python. Wind speed mapping, essential to assess the effect of wind loading on the PV array, was also performed. Vertical installation of BPV was deemed the most appropriate as it would utilize the space effectively on the central reservation. Moreover, vertical BPV have the highest bifacial energy gain from 22% to 47% when compared with conventional monofacial PV, as explained in Section 2.2 and discussed in detail by the authors [24]. The bifacial energy gain can be calculated from the difference between the energy produced from the bifacial and the reference monofacial PV, provided that identical modules are used. Factors that effect bifacial energy gain are module type, height, ground reflectivity, and shading. During simulation, Meteornorm typical meteorological year (TMY) data was used, which provides hourly data at 4–6% annual variability that may lead to uncertainty in the energy output generated result.

The higher energy gain of vertical BPV makes it an appropriate choice for motorway applications. Yearly energy generation of equivalent monofacial and bifacial PV was compared for 20 sites. The “Levelized Cost of Energy” (LCOE) was calculated for the site with the maximum energy yield for a range of PV system sizes (small, medium, and large). LCOE [25,26] represents the minimum electricity price required for a specific energy source to cover its capital and operating costs throughout the project’s lifespan. Assessing the cost efficiency of a PV project involves evaluating both capital expenditure (CAPEX) and operational expenditure (OPEX), including fixed operational and maintenance expenses, such as preventive and reactive maintenance, consumables, and spare parts. Typically, CAPEX is higher than OPEX, and once installed, PV systems demand minimal maintenance compared to other renewable sources.

A complete LCOE assessment was performed using PVSyst 7.4 with the net present value (NPV) calculation factored in. For the present analysis, two standard measures have been considered as follows:

1. Net present value (NPV);
2. Levelized cost of electricity (LCOE).

$$LCOE = \frac{CAPEX + \sum_{n=1}^N \frac{OPEX}{(1+r)^n}}{\sum_{n=1}^N \frac{E_0(1-D)^n}{(1+r)^n}} \quad (1)$$

Here, CAPEX = total investment cost, OPEX = annual operation and maintenance cost, r = discount factor, D = degradation rate, E = energy yield, and N = project lifetime.

Net present value (NPV) denotes the total discounted benefit of a project over its lifetime. For a project to be financially viable, its discounted benefits must surpass its discounted costs. The LCOE is determined by the ratio of the total discounted cost to the total discounted energy production over the project's duration. With the project lifetime of 30 years, a 5% discount rate was considered [26].

4. Results

The hourly irradiance mapping results are provided in Figure 4. It can be clearly seen from Figure 4a that the maximum solar intensity occurs during summer months, reaching an hourly peak of 561 W/m². The peak sunshine is 3–4 h, where the irradiance ranges between 250–570 W/m² during the peak sunshine hour period. However, from November to March, the irradiance remains less than 300 W/m². Regardless, the period for maximum solar generation is March–October, indicating that a backup energy generation plan will be required during the low irradiance period. Figure 4b shows the average wind speed distribution along the M6 at site 7. Wind speeds are relatively low from April to October, peaking at 15.5 m/s in December.

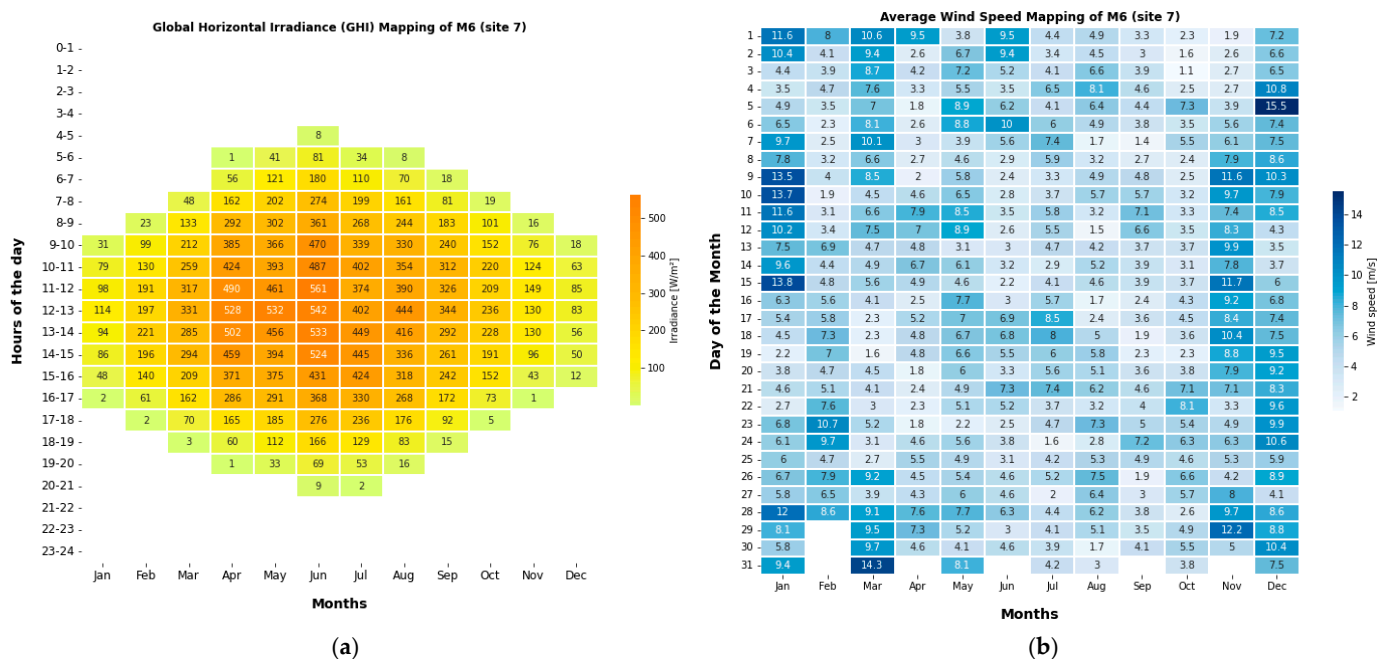


Figure 4. (a) Global horizontal irradiance and (b) average wind speed mapping of M6 (Site 7).

The Pearson correlation between solar and wind energy density is -0.7 , which shows a highly complementary relation between solar and wind: high wind speed during low solar months and vice versa. This suggests that at the time of higher solar gain in summer, wind loading impact might be lower, which is favourable for the vertical BPV.

The energy yield over a one-year period for 20 sites on the M6 is presented in Figure 5 below. The lowest energy production on sites 3 and 4 is around 3000 kWh, and the maximum yield is noted on site 7, with the generation of 3174 kWh. Figure 6 shows that for site 7, the peak generation occurs from May to July and is over 450 kWh. The overall generation in winter is negligible, with less than 100 kWh.

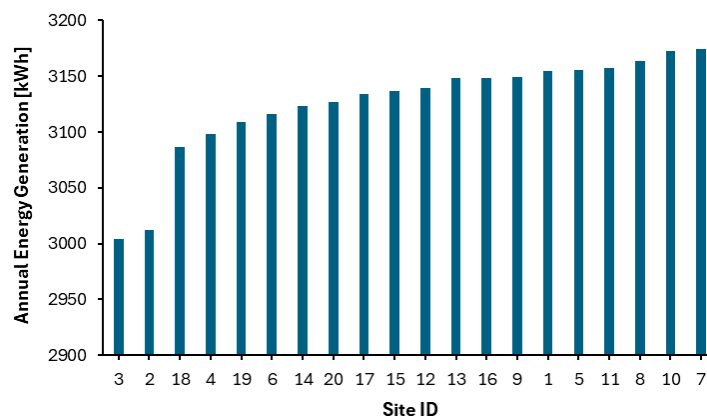


Figure 5. Energy generation for 20 sites.

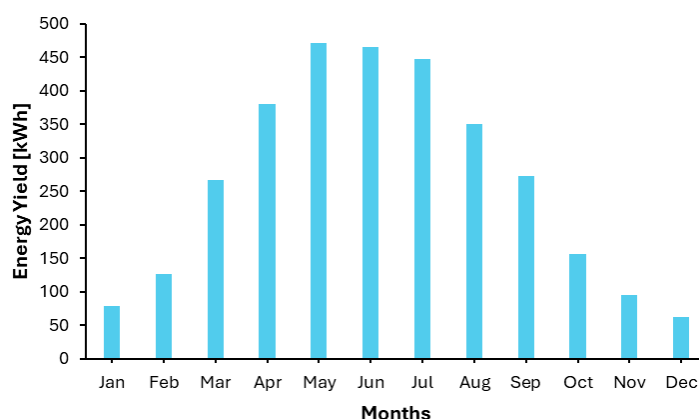


Figure 6. Site 7 energy generation curve.

A more precise representation of energy yield distribution would be the probability of energy generation within a 2-sigma confidence interval. Figure 7 shows that the likelihood of the yield at a 95% confidence level falls between 3032 and 3218 kWh. The probability density function shows the mean generation is 3125 kWh. Considering 5% of the length of the total M6 (i.e., 5% of 373.7 km = 18.65 km), a total energy generation potential of 58 MWh annually can be achieved if vertical BP is used. We selected 5% of the length of the motorway to capture the variation in local solar climate. The chosen segments are representative of the range of solar radiation received along the entire motorway, where latitude and longitude do not vary significantly from start to finish (Table 3). To illustrate further potential of BPV, it will be justified to demonstrate the energy gain that could be achieved in comparison to conventional monofacial technology. It can be seen in Figure 8 that the energy produced from BPV consistently exceeds the energy yield from MPV. This is due to the benefit of BPV energy capturing both diffuse and reflected irradiance from the rear side, leading to more energy generation, whereas the MPV only produces from the front side.

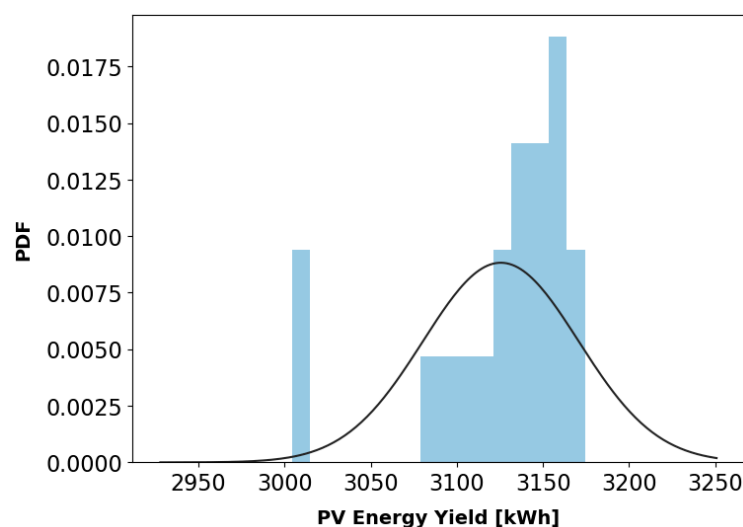


Figure 7. Site 7 energy yield distribution curve.

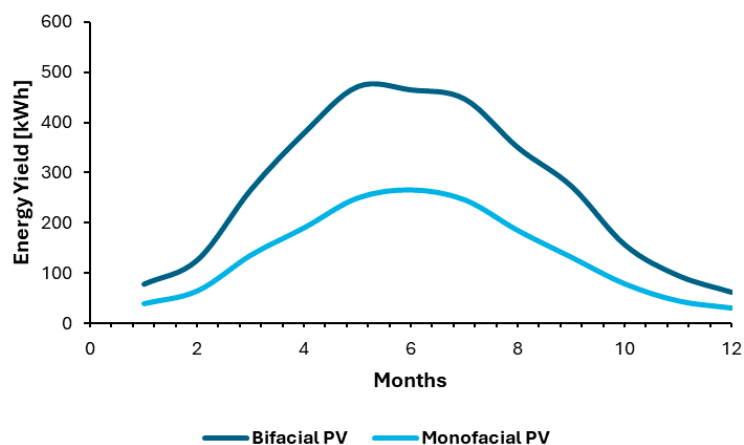


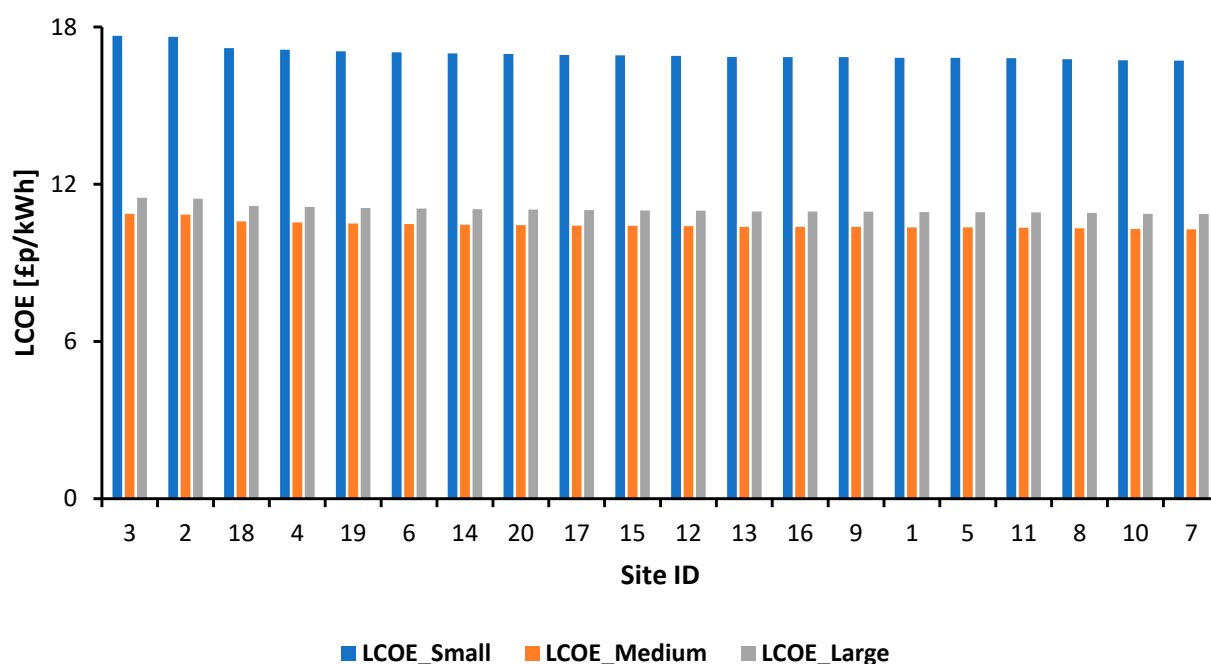
Figure 8. Site 7 energy generation of monofacial and bifacial PV.

Table 4 presents the LCOE calculated for three categories of systems: small, medium, and large, with capacities of 2.8 kW, 4 kW, and 5.6 kW, respectively. The economic analysis took into account the cost saving for grid electricity purchase. The CAPEX for small, medium, and large systems was considered as £2/Wp, £1.23/Wp, and £1.3/Wp, respectively [27]. The OPEX was assumed to be at 2% of the CAPEX with an annual increment of 2%, and the discount factor was 5%. For site 7, based on the LCOE study, a medium- and large-scale system would be economically feasible compared to a small-scale system. The LCOE of a medium to large-scale system is about 10–11 p/kWh, 60% less than that of a small-scale system. Moreover, the payback period for medium to large-scale systems is 6 years, whereas for small systems, it is 10 years. The net present value is two to three-fold higher for a medium- and large-scale system. Hence, considering the time value of money, medium–large scale system indicates economic viability of the BPV project that is more likely to be profitable by generating higher returns on investment. The sensitivity to key parameter for the economic analysis has been discussed in detail by the authors elsewhere [24].

Table 4. LCOE, net present value and payback period for site 7.

System Size kW	LCOE (p/kWh)	NPV (£)	PBP (yr)
2.8	17	7357	10
4	10	14,774	6
5.6	11	20,152	6

Figure 9 presents the LCOE across different sites, ranging from 10 p/kWh to 18 p/kWh, depending on the size of the system. However, for a system of the same capacity within various sites, there is a slight variation of about 1 p/kWh, which is mainly due to the geographical location of the sites and can be considered negligible.

**Figure 9.** LCOE for small (2.8 kW), medium (4 kW), and large (5.6 kW) BPV plants.

5. Discussion

The feasibility of BPV systems on the central reservation of motorways should involve addressing both the technical and practical aspects of integrating the technology into such environments. The central reservation (usually no wider than a single lane of traffic) can provide enough space for the installation of vertical BPV systems. Since BPV systems generate more power by capturing reflected light, motorways which normally have high reflective road surfaces (especially concrete or tarmac) and adjacent areas, could increase the amount of sunlight reflected from the ground. This could boost energy yield by a significant margin compared to MPV. The reflection from the road could provide an opportunity for bifacial gain, which is typically in the range of 5% to 30% more energy [22,24] compared to traditional monofacial systems, depending on the setup, the ground conditions, and the view-factor [23].

The M6 case study in this study demonstrated that utilizing the redundant central reservation area for vertical BPV could generate up to 58 MWh per year even when only 5% (18.65 km) of its total length was used. This output is on par with a number of solar farms that are provided in Table 1, but without the need for a lot of land coverage. Considering the total length of major motorways in Britain is 2300 miles, installing BPV systems on the central reservations are an exciting opportunity to utilize large, underused, areas for

renewable energy generation. These locations should provide easy access for installation and long-term maintenance while minimizing disruption to traffic.

The transition to a low carbon transport sector is expected to be achieved primarily by battery-powered electric vehicles (EVs), leading to increased high-power demand at service stations. As EVs become more common, incorporating the electricity generated by BPV systems on the motorways into charging stations can help reduce carbon emissions and enhance the sustainability of transportation [28]. There are several electrical substations located near the M6, primarily serving to step down or transform high-voltage electricity from the National Grid for local distribution. These substations are not directly on the M6 but are typically positioned nearby, connected through a network of pylons and underground cables. The electricity generated could be fed into the grid serving substations connected to the motorway services. This approach would address the rising demand for clean energy for EV charging without competing for land or overloading the power grid, as electricity is generated locally near service stations.

Despite its environmental benefits and rapidly declining costs, solar energy presents unique challenges for grid integration due to its intermittent and variable nature. To ensure a stable and reliable electricity supply, enhancing grid flexibility is essential. A combination of technological innovations such as integrating battery storage systems, improved forecasting of solar generation as well as infrastructure upgrades, and supportive policy frameworks, can ensure that solar becomes a stable and reliable component of the modern energy mix. The government could incentivize the installation of energy storage systems along motorways. To ensure that the generated solar power is integrated into the National Grid, the UK Government would need to assess and potentially upgrade its infrastructure to accommodate the additional electricity from these motorway-based PV systems. The National Grid's RIIO-T3 business plan aims to enhance the capacity of the current network and extend it to integrate new renewable energy sources [29]. This plan is driven by three key goals: expanding the network's capacity to accommodate the growing flow of renewable energy, rapidly connecting new customers to the grid, and ensuring network reliability and resilience during the system-wide transformation. The National Grid must accommodate a projected doubling in demand by 2050 as electrification expands across heating, transport, and industry.

In addition to feeding energy into the grid, some of the electricity generated can be used directly to power motorway infrastructure such as street lighting, traffic signals, or electric vehicle charging stations along the motorways.

Table 4 compared the cost-effectiveness of different BPV system sizes. The LCOE values for medium- and large-sized systems (10–11 p/kWh) demonstrated the economic feasibility of vertical BPV systems. These costs are relative where the variation within LCOE range depends on a number of factors such as the specific location, varying solar irradiation levels, ground conditions, and system configuration. The UK grid's ability to integrate solar energy can also influence the LCOE. With adequate storage solutions or grid balancing, solar power's value in the market may increase, lowering the overall LCOE for bifacial plants. Bifacial panels generally cost more than traditional monofacial systems, and the cost of integrating them into motorway infrastructure can increase upfront installation costs. While the energy yield from bifacial panels can be higher due to the reflected light, the return on investment (ROI) depends on factors such as panel cost, installation complexity, and expected performance. The additional costs related to motorway-specific installation could affect the financial attractiveness of the project.

For the social and regulatory feasibility, the system must comply with UK regulations and guidelines for infrastructure projects and must be designed to avoid obstructing sightlines or creating glare that could distract or harm drivers. Local communities and

stakeholders need to be engaged early in the planning process to address concerns about aesthetics, road safety, or disruptions during installation. This can help gain public support and ensure smoother project implementation. Motorways are high-traffic areas, which makes accessing panels for maintenance, cleaning, or repair potentially hazardous. Ensuring safe, timely access to solar panels while minimizing traffic disruptions would be crucial. It has been found that vertical PV panels accumulate minimal dust than conventional tilted PV panels while maintaining a comparable energy yield [30]. Stealing modules from the central reservation pose little or less risk as the installation is very difficult to reach.

The potential visual impact and safety implications for drivers resulting from the integration of PV systems into roadways require comprehensive analysis. Specific concerns include glare, distraction, visibility under varying weather and lighting conditions, all of which could affect driver performance and overall road safety. By proactively addressing these issues, the integration of solar PV systems into roadways can be optimized to enhance both sustainability and safety. PV modules do not produce more glare than normal glass noise barriers. This, however, is still a cause of major concern when installing PV systems on or near motorways as the glare could affect drivers' visibility. BPV, in particular, could cause reflections from both the front and rear sides when installed vertically, which could be distracting or dangerous for drivers. BPV systems would need special design considerations to minimize glare and may need coatings to absorb or diffuse light that could cause reflection in the direction of traffic. If the panels are integrated into existing barriers, with appropriate design considerations, they could actually improve safety (e.g., by providing reflective surfaces that increase visibility for drivers at night or in foggy conditions). To further lessen the risks of glare for the drivers, only relatively straight sections of the roads should be selected for BPV installation to minimize the risk of reflections. A detailed sunlight angle analysis and simulation should be performed to ensure driver safety.

BPV panels on motorways are environmentally feasible as they allow for dual land-use, avoid competition for agricultural or natural land, and help achieve sustainability goals. This maximizes the use of available land whilst reducing the need for new land development for solar farms, which can be beneficial for the environment and local communities. Moreover, motorways are already developed areas, so adding solar PV would likely have a lower environmental impact compared to using agricultural or natural land for solar farms. The environmental feasibility would further need to consider how the system could affect local ecosystems. Projects would need to assess the potential impact on local wildlife and biodiversity, including the risk of birds or animals coming into contact with the infrastructure. The government could fund pilot projects to test the technical and economic viability of bifacial PV on motorways. These smaller-scale trials would help address issues such as durability, efficiency, and maintenance requirements. The data and insights gained from pilot projects can be used to refine the design and deployment strategy for larger-scale implementations. The success of these pilots could serve as proof of concept for wider deployment.

Installing BPV systems in the central reservation would not interfere with traffic flow or create safety hazards. The central reservation often features safety barriers or fences, which could be adapted to carry the solar panels. These systems could be mounted on barriers or dedicated frames, ensuring there is no obstruction to vehicles or emergency access. This would integrate renewable energy infrastructure into existing safety features, enhancing efficiency without requiring additional space. Central reservations can be strategically located for high exposure to sunlight. BPV could benefit from reflected sunlight from the road surface, improving energy generation. The UK, although not known for constant sunshine, has substantial potential for solar energy, particularly when considering the rise in solar irradiance during peak daylight hours.

Modern BPV are designed to withstand weather conditions such as wind, rain, and temperature extremes, making them suitable for motorway environments. Maintenance would be focused on cleaning the panels periodically, which could be done with minimal disruption to traffic. Panels must be placed securely, and not interfere with the safety of the motorway, including maintaining proper clearance for vehicles in case of an accident or if the panels are dislodged.

6. Conclusions

This study provided a methodology to quantify the energy yield potential of BPV installations on motorways which offer multiple uses of the same road space, thereby consuming a limited amount of land. Results of this study could form the basis of a much more in-depth projection of the BPV electricity generation potential of all of Britain's roads and railways. The recently amended National Roads Ordinance allows Switzerland to generate renewable energy along major highways where the potential for electricity generation along motorways is 55 GWh and railways is 46 GWh per year [10].

Using Google Earth, 20 sections of M6 that approximately run in the north–south direction were selected for BPV installation on the central reservation. It was shown that up to 58 MWh could be generated annually even when only 5% (18.65 km) of the motorway was used. The LCOE analysis showed that a medium- and large-scale system would be economically feasible as compared to a small-scale system. The LCOE of a medium to large-scale system was found to be 10 p/kWh with the payback period of 6 years. The net present value was twofold higher in a medium-scale system.

In addition to energy performance and economic viability, the feasibility of BPV systems must also address environmental and practical aspects of integrating the technology on the central reservation of motorways. There could be concerns about the esthetic impact, potential glare affecting drivers, and maintenance access. Installation may require additional safety measures to prevent accidents or obstruction of road operations.

Table 5 highlights the key considerations for integrating BPV in motorway environments. Installing BPV systems on UK motorways offer promising opportunities for renewable energy generation, but it also involves several planning challenges. Addressing safety concerns, obtaining planning permissions, ensuring cost-effectiveness, and mitigating environmental impacts will require careful consideration and thorough planning. Ultimately, successful implementation would rely on collaboration between local authorities, environmental regulators, highway agencies, and renewable energy developers to design solutions that are both safe and sustainable for the motorway network and surrounding communities.

Table 5. Key considerations for techno-socio-economic-environmental feasibility of BPV on motorways.

Category	Key Considerations	Assessment Criteria
Technical Feasibility	Site assessment, structural integrity, grid connectivity, bifacial PV performance	Road orientation, shading analysis, grid access, material durability
Social & Regulatory Feasibility	Public engagement, safety impact, planning permissions	Community acceptance, safety regulations, legal constraints
Economic Feasibility	Cost–benefit analysis, funding sources, ROI projections	CAPEX vs. OPEX, financial incentives, payback period
Environmental Feasibility	Impact on wildlife, carbon reduction, land use efficiency	Biodiversity impact, CO ₂ savings, sustainable integration

Systems will need to be set up to continuously monitor the performance of the installed bifacial PV systems. This includes tracking energy generation, efficiency, and operational status. Given the harsh environment of motorways (e.g., pollution, dust, and debris), regular cleaning and maintenance are essential to ensure that the panels operate at peak efficiency.

A key limitation of this study was the use of an existing simulation tool, which has constraints in shading analysis, accounting for weather variability, and incorporating site-specific conditions. The authors plan to develop a customized simulation tool tailored to the context, enabling more accurate analysis of the results. Future research work should involve smaller-scale trials to obtain data and insights to refine the design and deployment strategy for larger-scale implementations. The success of these pilots could serve as proof of concept for wider deployment.

The implementation of BPV systems on UK motorways represents a novel way to enhance renewable energy generation whilst utilizing underutilized road infrastructure. By ensuring regulatory compliance, leveraging financial support, and fostering collaboration between the public and private sectors, the government can facilitate the successful deployment of such projects. With proper planning, community engagement, and technological innovation, this initiative could significantly contribute to the UK's renewable energy goals whilst optimizing motorway spaces for sustainability.

The concept of using motorway infrastructure for solar generation, including bifacial systems, is still evolving, and further studies and pilot projects will help determine its long-term feasibility in the UK.

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