THE UNIVERSITY *of* EDINBURGH
School of Engineering

Solar Energy Group Report – GROUP 2

Comparative study of Building Integrated PV and Large PV Farm in China and the United Kingdom

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Abstract: This comparative study investigates the technical and economic performance of building-integrated photovoltaic (BIPV), large-scale photovoltaic (PV) farms and solar thermal applications in China and the United Kingdom. PV system designs are optimised through PVsyst simulations, considering site-specific solar resources, local policies, and economic frameworks. The study also explores the role of solar thermal technologies—including solar water heating and concentrated solar power (CSP)—in diversifying energy strategies and enhancing renewable energy integration. Results indicate superior economic performance and energy efficiency for Chinese installations due to favourable irradiation conditions and supportive governmental policies. The analysis provides insights into system optimisation strategies and highlights key factors affecting the deployment and profitability of photovoltaic projects in different geographical and regulatory contexts.

Keywords: Photovoltaics; BIPV; Large-scale PV farm; Solar energy; Economic analysis; Performance ratio; PVsyst simulation; China; United Kingdom; Renewable energy policy; Solar thermal energy.

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1. Introduction

The global energy sector is undergoing a significant transition towards renewable energy sources, driven primarily by the need to reduce greenhouse gas emissions and mitigate climate change [1]. Among various renewable technologies, photovoltaic (PV) systems have emerged as one of the most effective solutions due to their scalability, declining costs, and adaptability to diverse geographic conditions.

This comparative study examines the technical and economic performance of building-integrated photovoltaic (BIPV) and large-scale photovoltaic farm installations in the United Kingdom and China, two countries with distinct solar resources, climatic conditions, and policy frameworks. Despite both nations significantly increasing their renewable energy portfolios, there remains considerable variation in the performance and economic viability of PV systems driven by local environmental conditions, technology choices, and supportive policies.

Previous studies have explored individual country analyses but lack detailed comparative assessments addressing both BIPV and large-scale solar farms within diverse climatic and policy contexts. This research aims to fill that gap by systematically comparing system designs, energy yield, performance ratios, and economic returns using rigorous simulation analyses with PVsyst software.

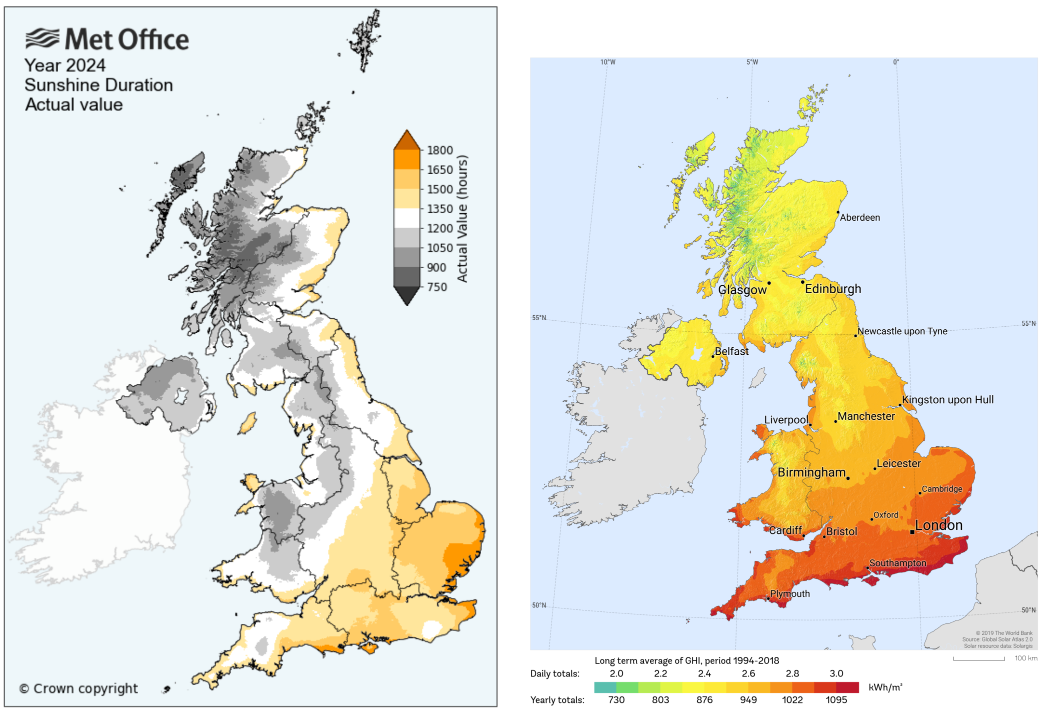
While the focus of this study is on photovoltaic systems, it is also important to recognize the role of solar thermal applications in the broader landscape of solar energy utilization. Solar thermal technologies—including solar water heating and concentrated solar power (CSP)—offer valuable contributions to decarbonization, particularly in the heating and industrial sectors. Although differing in operational principles from PV, these systems complement photovoltaic deployment and expand the potential for solar integration across various climatic and infrastructural settings. A comparative overview of solar thermal adoption in the UK and China is therefore included to contextualize their respective energy strategies and highlight potential synergies.

Ultimately, this study seeks to identify best practices and strategic insights that can inform policy-making, system design optimization, and investment decisions, thereby facilitating broader adoption and efficient deployment of solar energy technologies in varied global contexts.

2. The Solar Resource in the UK and China

2.1. Solar Resource in the UK

The United Kingdom, spanning latitudes 49°N to 61°N, possesses a relatively modest solar resource compared to sun-rich regions. Its oceanic climate and extensive north-south span contribute to frequent cloud cover, pronounced seasonal variability, and regional disparities in solar irradiance, all of which influence the performance and design of photovoltaic (PV) systems across the nation.



(a) 2024 UK Sunshine Hours [2]

(b) Average UK Solar Irradiation from 1994 to 2018 [3]

Figure 1. UK Solar Resource

In 2024, the UK recorded between 750 and 1,600 hours of effective sunlight per year, with significant geographic variations as reported by the Met Office[2]. The southeast experiences the highest sunshine hours, while the northern and western regions typically receive fewer hours due to persistent cloud cover and rain. Despite the limited direct sunlight, modern PV panels are designed to efficiently convert diffused light into electricity.

Spatially, solar irradiance in the UK is influenced by both latitude and local weather patterns. Southeastern regions benefit from a higher solar altitude during summer, contributing to an annual direct irradiance of about 1,095 kWh/m². In contrast, the north and west experience frequent rain and overcast skies, bringing total irradiation down to roughly

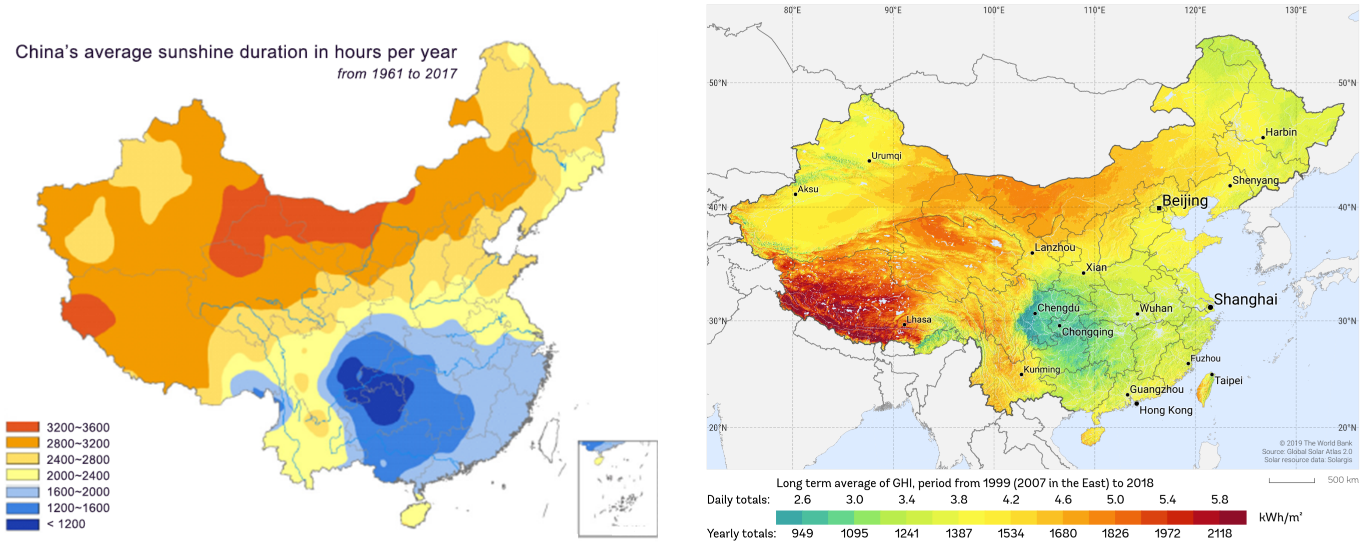
730 kWh/m²[4] and thus relying more on diffuse radiation. Even so, modern photovoltaic technology can effectively convert this diffuse light into a significant amount of electricity.

A major challenge is the seasonal variability in solar resources[3], with long, bright summer days and short, overcast winters causing fluctuations in energy production. This variability calls for integrating energy storage and smart grid management to ensure a stable power supply. Advances in battery technology and grid systems are helping to maximize the utilization of solar energy despite these fluctuations.

In summary, although the UK's solar resource is characterized by modest irradiance and considerable variability, it still offers significant potential for sustainable energy generation. Through strategic system design, technological innovation, and integrated energy management, the challenges of the local climate can be effectively addressed, supporting national goals of energy diversification, carbon reduction, enhanced energy security, and economic growth in the renewable sector.

2.2. Solar Resource in China

China's solar energy potential varies widely due to its large geographic span (18°N to 53°N), diverse climates, and terrain. As a global leader in solar deployment, the country utilizes solar resources ranging from 1,000 to 2,200 kWh/m² annually (China Meteorological Administration). The highest irradiance occurs in northwestern arid regions like Tibet and Xinjiang (Figure 2b), where global horizontal irradiance (GHI) exceeds 1,800 kWh/m² due to high elevation, minimal clouds, and dry air[5][6]. These areas are ideal for large-scale solar farms and CSP plants, with over 2,000 hours of annual sunlight. In contrast, southeastern provinces such as Guizhou and Jiangsu face lower irradiance (1,000–1,400 kWh/m²) due to frequent clouds and humidity, requiring designs optimized for diffuse light.



(a) 2024 China mainland Sunshine Hours map

(b) Average China Global Horizontal Irradiance from 1994 to 2018

Figure 2. China Solar Resource

Seasonal impacts are strong in northern China, where winter sunlight hours and angles decrease similarly to the UK, Southern regions like Yunnan and Guangdong. however, maintain stable solar exposure year-round[7], supporting distributed PV systems. To manage regional differences, China employs smart grids, grid-scale storage, and cross-region power networks to stabilize energy supply despite solar variability.

In summary, China's strategy focuses on high-irradiance northwestern zones for centralized solar plants and southeastern regions for rooftop/distributed systems. Through infrastructure upgrades, policy support (e.g., feed-in tariffs), and technology innovation (e.g., bifacial panels), China advances its solar leadership while aligning with carbon neutrality goals.

2.3. Comparative Analysis

To provide a clear overview of these distinctions, Table 1 summarizes the key differences between the two countries' solar resource.

While the UK continues to expand solar development through innovation and policy support despite its relatively modest solar potential, China has established itself as a global leader in solar energy, capitalizing on its vast resource potential and scale advantages to drive its renewable energy transformation and carbon neutrality objectives.

In comparison to the global solar energy distribution, both the United Kingdom and China exhibit distinct characteristics. Globally, regions around the equator (20°N–20°S) receive the most consistent and intense solar irradiance, often exceeding 2,500 kWh/m² annually [8]. China, particularly in its northwestern regions, approaches this global benchmark with irradiance levels up to 2,200 kWh/m², making it highly favorable for large-scale PV deployment. The UK, on the other hand, falls below the global average with annual irradiance mostly between 730–1,095 kWh/m², placing it among the lower solar resource countries in Europe [9]. Nevertheless, advancements in technology and policy frameworks have enabled both nations to effectively utilize their respective solar potentials and contribute meaningfully to the global renewable energy transition.

Comparison Dimension	**United Kingdom**	**China**
Geographical Location	Latitude 49°N to 61°N	Latitude 18°N to 53°N
Annual Solar Irradiation (GHI)	Approx. 730 to 1,095 kWh/m²	Approx. 1,000 to 2,200 kWh/m²
Annual Sunshine Hours	750 to 1,600 hours	Over 2,000 hours in the best regions
Climate Characteristics	Oceanic climate, frequent cloud cover, high seasonal variability	Vast territory with diverse climates; northwest is dry and sunny, southeast is humid and cloudy
Resource-Rich Regions	Southeast regions have the highest irradiance; north and west are lower	Northwest (e.g., Xinjiang, Tibet) has the highest irradiance; southeast is lower
Radiation Type	Largely relies on diffuse radiation	High direct radiation in northwest; more diffuse in southeast
Seasonal Variation	Significant seasonal changes; long bright summers, short cloudy winters	Strong seasonal impact in the north; relatively stable in the south (e.g., Guangdong, Yunnan)
Technical Strategies	Emphasis on utilizing diffuse light, with energy storage and smart grid management	Centralized solar plants in the northwest; distributed systems and grid infrastructure in the east
Policy and Infrastructure Support	Focus on distributed systems with government subsidies and support	Government-led large-scale deployment with mature market mechanisms and multiple policy incentives

Table 1. Comparison of Solar Resources in the UK and China

3. Analysis of Solar Market and Relative Policies

The expansion of the global solar market, supported by favorable policies and incentives, has significantly driven the development of new solar energy projects. Following the Paris Agreement, renewable energy has emerged as a key focus for future development.

Both the UK and China have implemented a series of policies to support the development of clean energy technologies and facilitate structural economic shifts.

3.1. Analysis of UK

The UK's solar policy framework has evolved from mandates like the Renewables Obligation (RO) introduced in 2002, which required electricity suppliers to source a rising proportion of power from renewables, to more market-driven incentives such as the Smart Export Guarantee (SEG)[10,11]. The SEG ensures that small-scale solar generators (up to 5 MW) can monetize their excess power by selling it back to the grid, helping to sustain growth in the small-scale solar sector [11].

For large-scale solar farms, the UK utilizes Contracts for Difference (CfD), a competitive auction system that allows developers to bid for contracts, guaranteeing a fixed "strike price" for their electricity [12]. This mechanism stabilizes revenue for large solar projects without an open-ended subsidy, aligning with the UK's market-driven approach.

Apart from these direct incentives, the UK government has facilitated financing for solar deployment. Programs such as the Energy Company Obligation (ECO) have trialed free or discounted solar installations for low-income households to reduce electricity bills. Large-scale solar projects have benefited from low-cost capital via the UK Infrastructure Bank and the Green Investment Group. The government also offers tax incentives, including a zero VAT policy on solar installations, further lowering upfront costs for adopters.

The UK has established regulatory frameworks to ensure efficient grid integration for solar projects. Under G98/G99 regulations, small-scale solar generators can connect to the local distribution network via a fast-track notification process rather than requiring full prior approval [13]. This simplification has encouraged widespread rooftop solar adoption, particularly in commercial and industrial sectors. Additionally, net metering and "deemed export" arrangements under legacy FIT schemes provide additional incentives for solar users [14].

In England specifically, solar installations over 50 MW capacity are currently treated as Nationally Significant Infrastructure Projects (NSIPs), requiring a more stringent national-level approval (Development Consent Order) rather than local planning permission. The government has announced plans to raise this threshold to 100 MW for solar, aligning it with onshore wind. If enacted, projects up to 100 MW could be consented by local planning authorities, potentially simplifying and speeding up approval for mid-sized solar farms. Rooftop solar installations generally fall under permitted development rights, meaning they do not require planning permission in most cases across England [15]. This policy allows large commercial buildings, such as factories and warehouses, to install solar panels freely, unlocking significant rooftop solar capacity.

In contrast, ground-mounted solar farms face more rigorous planning requirements. Projects over 50 MW are classified as Nationally Significant Infrastructure Projects (NSIPs), requiring national-level approval via a Development Consent Order instead of local planning permission. However, the government has announced plans to raise this threshold to 100 MW, aligning it with onshore wind. If enacted, this change would allow mid-sized solar farms (50–100 MW) to be approved at the local level, streamlining the development process.

Collectively, these policies create a balanced regulatory and financial ecosystem, ensuring that the UK continues to expand its solar capacity through a combination of small-scale rooftop PV, mid-sized commercial solar, and large-scale solar farms.

3.2. Analysis of China

Unlike UK's policies have been market-oriented with government supports and consumer-driven, China's rapid solar power development are under instruction from government and public servants specialized in related technology.

Back in 2005, the National Development and Reform Commission (NDRC) formulated the *Renewable Energy Law of P.R.China* and it passed in the same year [16]. Functioning as a basic law, the Renewable Energy Law of P.R.China addressed the the necessity of developing renewable energy with supports on policy, academics and finance, including guidance on the development direction of photovoltaic industry, management of prices and subsidies and market supervision with industry regulation. The National Energy Administration (NEA) which subordinated to NDRC, oversees responsibilities including examination on major photovoltaic projects and supervision of grid connection and grid adaptability. Driven by active policy, major solar power projects including the "National advanced technology photovoltaic demonstration base in Datong"[17] and "Shouhang Dunhuan 100 MW Molten Salt Solar Power Plant"[18] are completed with integration on both electricity production and scientific research. such as the China National Renewable Energy Center (CNREC) and North China Electric Power University (NCEPU). Non-government projects, including private sector investment and distributed solar, have also benefited from a range of policy incentives (Table 2).

Policy Category	**Specific Measures**
Market Mechanisms	- **Grid Parity Policy**: 2021, subsidies have been removed, solar power pricing is market-driven. [19] - **Renewable Portfolio Standard (RPS)**: Requires power grid companies to purchase a fixed proportion of renewable energy, ensuring demand for solar power.[20]
Financial and Investment Support [21]	- **Green Finance Policy**: Encourages banks to offer low-interest loans, such as through carbon reduction support projects. - **Tax Incentives**: Provides VAT rebates and accelerated depreciation of fixed assets to reduce investment costs. - **Carbon Trading Market**: Allows solar power enterprises to generate additional revenue through "carbon credit" trading.
Distributed Solar Power Support	- **County-wide PV Initiative**: Encourages local governments and enterprises to advance rooftop solar installations. [22]
Technical and Standardization Support [23]	- **PV Product Quality and Grid Connection Standards**: Established by the NEA to ensure long-term stability and compliance of solar installations. - **Smart PV and Digitalization**: Encourages AI-driven optimization, energy storage integration, and microgrid development.

Table 2. Policy Support for Non-Government Solar Power Projects in China

China's photovoltaic industry was highly export-oriented, but following the U.S. and EU anti-dumping tariffs [24] in 2012 and 2018, the domestic market grew rapidly to absorb excess capacity. By 2023, China's cumulative solar capacity exceeded 500 GW, with over 70% of new installations consumed domestically [25]. This growth was supported by the Grid Parity Policy, which eliminated subsidies and encouraged competitive pricing, as well as the County-wide PV Initiative, which facilitated large-scale rooftop solar adoption.

In parallel, China has led advancements in solar cell efficiency and cost reduction. Traditional polycrystalline silicon (16-18%) has been largely replaced by PERC monocrystalline cells (22-23%), while TOPCon and HJT technologies (24-26%) are rapidly entering mass production [26,27]. Additionally, energy storage and AI-based smart PV systems are becoming essential to enhance grid stability and efficiency [28]. These technological improvements, combined with policy-driven market expansion, have reinforced China's global leadership in solar energy [29].

4. Photovoltaic System in the UK and China

In order to conduct a rigorous and equitable comparison between photovoltaic (PV) systems in China and the United Kingdom, representative case studies were selected based on comparable solar irradiation profiles, land availability conditions, and local economic and policy frameworks, as established in the preceding sections. As discussed in the previous chapter, the area of interest is chosen on the basis of solar resource analysis, available area and supported policies.

This work is dedicated to compare the feasibility and economic viability for different PV energy generation project in United King and China. With a fixed available area and employing uniform technologies across both countries, the study enables a systematic evaluation of location-specific impacts on energy yield, system efficiency, and financial viability.

4.1. Primary design criteria

In order to maximises efficiency for each PV system and ensures an equitable comparison, design procedures for each system were standardised by same design criteria to regulate parameter justification, including tilt angle, azimuth angle, PV module distance, DC/AC ratio and factors related to environment and economic consideration.

- **Tilt and Azimuth Optimization**
In all system configurations, tilt and azimuth angles were optimized using PVsyst to maximise annual global irradiation on the PV array. For BIPV systems, tilt was limited by architectural constraints, while azimuth was adjusted to reduce shading. Ground-mounted systems allowed greater flexibility in angle selection, based on site-specific solar potential and terrain. Azimuth orientations were generally aligned with geographic south, with minor deviations introduced to account for local shading or structural limitations.
- **Tracking System**
Solar tracking can significantly improve energy yield by aligning modules with the sun's path. However, rooftop (BIPV) systems are constrained by building structures and cannot accommodate tracking system. In the UK, high-latitude and predominantly diffuse irradiation reduce the benefit of trackers, making fixed-tilt systems more practical and economical. Meanwhile, restricted by local desert environment, solar tracking system is not applied due to challenges on installation and maintenance [30].
- **Module Layout and Shading Control**
To minimize inter-row shading and ensure an uniform irradiance distribution, module spacing and pitch distance were determined based on solar elevation angle analysis with assistant by PVsyst. The minimum distance between rows was calculated to prevent shading during critical low-sun periods, especially in winter. Detailed formulas and design parameters used for shading rate estimation are provided in Appendix J. Additional spacing was included where necessary to accommodate maintenance access and structural constraints.
- **DC/AC Ratio Selection and Inverter Sizing**
The DC/AC ratio was optimised in all systems using PVsyst to ensure a balance between inverter utilisation and energy clipping. Across the four system types, the ratio was maintained within the typical range of 1.1 to 1.3, a common practice to improve cost-effectiveness while limiting power losses during peak generation periods. Inverter quantities were selected based on string voltage compatibility, total DC capacity, and MPPT input flexibility. For rooftop installations, the Huawei SUN2000-330KTL-H1 inverter was chosen, offering six MPPT inputs per unit to mitigate the impact of partial shading and complex roof geometry. For large-scale open-field systems, a higher number of inverters was required to distribute the increased number of strings and ensure reliable operation under high irradiance conditions. Specific DC/AC ratios and inverter counts for each system are summarised in Appendix I.

4.2. Rooftop installation system

The selected rooftop photovoltaic (PV) systems for comparative analysis are sited in **Guiyang, Guizhou Province, China**, and **London, United Kingdom**. The primary criterion for choosing these locations was their similar annual irradiance levels(about 1000 kWh/kWp)[31], thereby facilitating a meaningful comparison of energy generation and performance between distinct geographic contexts. Specifically, the proposed Chinese installation is located on the rooftop of the Guizhou Provincial Museum(28,822.37m^2) in Guiyang, while the UK installation is situated atop the rooftop of a Lidl distribution warehouse(27,499m^2) in London. This comparative approach evaluates how differences in climate, shading conditions, and environmental factors influence overall system efficiency and electricity production despite analogous irradiance conditions.

For consistency and ease of comparative analysis, both rooftop PV systems employ identical PV modules and inverter technologies. The selected PV module is Yongkang Haoyu's monocrystalline silicon module (KPV-500M-132[32]), each rated at 500 Wp. The inverter chosen is the Huawei SUN2000-330KTL-H1[33], featuring six Maximum Power Point Tracking (MPPT) inputs. This MPPT technology allows each string of modules to operate independently, optimizing power extraction under varying irradiance conditions and partial shading caused by frequent fog, surrounding structures, or other site-specific obstructions. Consequently, the inverter significantly mitigates shading impacts and enhances system performance stability throughout the year[34]. Utilizing the same equipment across both locations ensures that differences in system performance can be directly attributed to site-specific environmental and climatic factors, rather than variations in technology.

4.2.1. UK

The Lidl Enfield Regional Distribution Centre (RDC) has been selected as the project site due to its extensive flat rooftop area, which provides advantageous conditions for the installation of a solar photovoltaic (PV) system. Given the building's orientation, the rooftop solar panels are designed and compactly arranged to conform to the roof layout, thereby maximizing power generation within the available space.

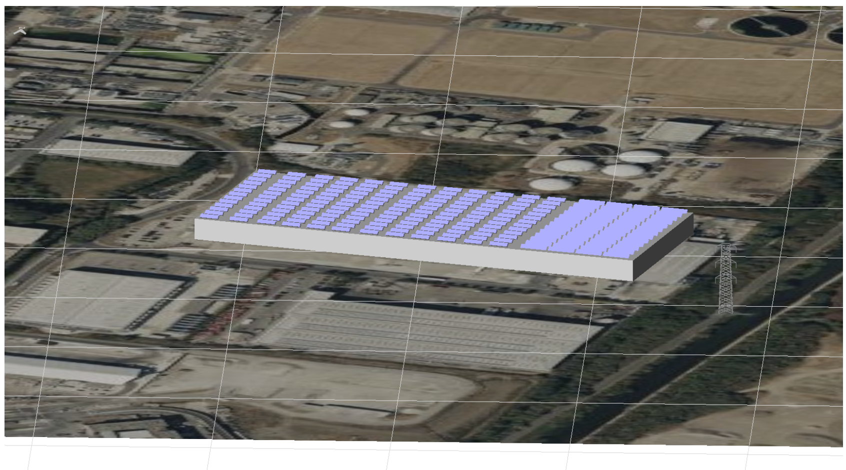
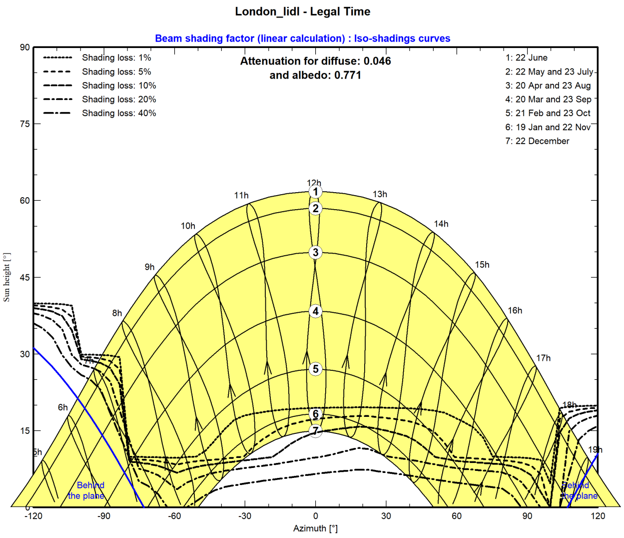


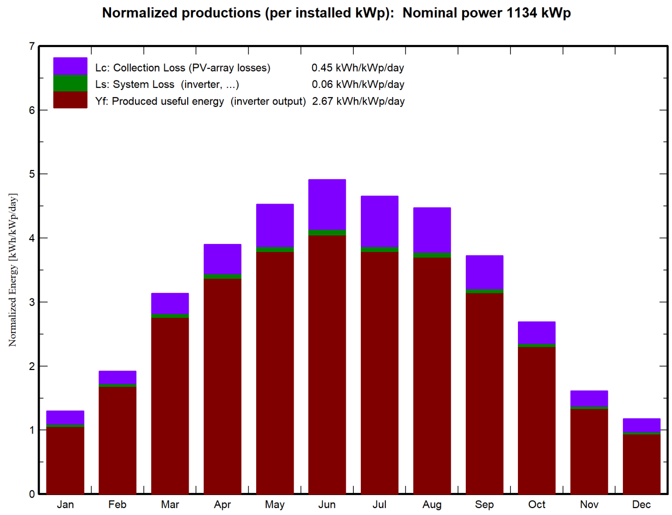
Figure 3. PV Design Layout for Lidl

According to the software simulation results, the loss of system's energy yield compared to the optimum orientation is limited to only 0.9%, with the azimuth and tilt angles configured at 17° and 39.4° respectively for optimised space usage on rooftop. The total nominal power of the system is 1134 kWp, using same PV panels and inverter models as for the same rooftop system proposed in China. In the simulation, the DC/AC ratio (PNom Ratio) is 1.26, which is within the commonly recommended range for optimizing energy yield and economic performance. As a result, the overload loss is limited to 0.1%, indicating that the system design achieves a good balance between investment cost and energy production potential under real operating conditions.

The design layout of the solar system on the roof is shown in Figure 3. Due to London's geographical location, its solar height angle remains relatively low throughout the year. As a result, shading losses are primarily concentrated during the early morning and late afternoon hours, and are particularly significant in winter. Figure 4a illustrates



(a) London shading loss diagram

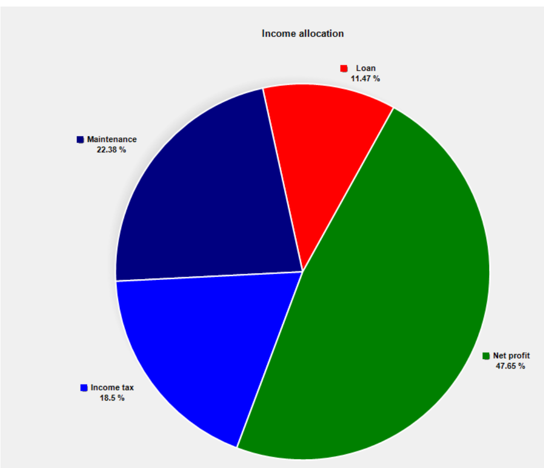


(b) Normalised Production graph in London

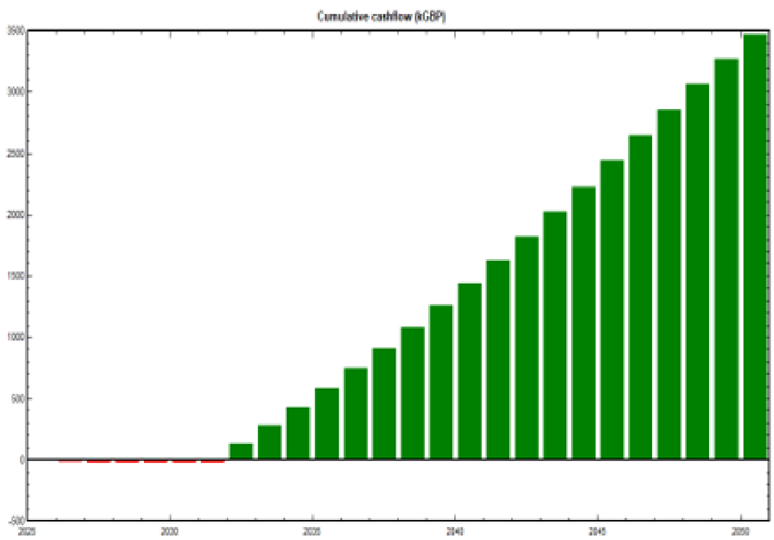
Figure 4. UK rooftop system Simulation results

the relationship between shading loss and solar altitude angle, indicating that shading loss contours cover only a limited area.

To further minimize potential shading losses, a pitch distance of 8 meters is recommended based on research findings. Additionally, a spacing of 1 meter is maintained between certain rows to allow for equipment maintenance, while the remaining tables' longer spacing is determined according to the structural characteristics of the rooftop and the need to avoid existing obstacles. Under clear sky conditions, the linear shading loss of direct beam irradiance is estimated at only 6% of the total incident irradiance. This level of loss is considered acceptable and does not compromise the overall feasibility or performance of the PV system. Figure 4b describes the simulation results of energy yield for a complete system. Taking into account the potential losses, the system's annual production is 1,112 MWh, with a performance ratio of 0.846. This means that the useful energy produced accounts for 84.6% of the reference incident energy.



(a) Income allocation for Rooftop in London



(b) Cumulative cash-flow for Rooftop in London

Figure 5. UK rooftop system Simulation results

The economic analysis supports the extensive conclusion of the system efficiency. The total installation cost of £699,412.45 is fully financed through a loan with a 6-year term and an interest rate of 4.5%. The project has an operational lifetime of 25 years, with total annual operating costs of £96,025.64. The system benefits from a fixed Feed-in Tariff of £0.179/kWh, with an inflation rate of 2.5% and a discount rate of 4%. Given by Figure 5a, the configuration of the income allocation reveals that the net profit is dominant.

The financial assessment indicates that the project's Levelized Cost of Energy (LCOE) is £0.0953/kWh, significantly lower than the guaranteed tariff rate. Key financial metrics show a strong economic performance, with an Internal Rate of Return (IRR) of 62.52%, a Return on Investment (ROI) of 255.3%, and a payback period of 6.3 years which is well below the project's lifetime.

Overall, the economic analysis demonstrates that the project delivers stable cash flows with low financial risk. Even under sensitivity scenarios such as increased O&M costs or tariff reductions, the project maintains a solid profitability margin. It can be concluded that this is a financially viable, high-return, and low-risk distributed renewable energy investment.

4.2.2. China

The rooftop photovoltaic (PV) system located on the Guizhou Provincial Museum in Guiyang was designed considering site-specific architectural and environmental characteristics. Given the existing structural configuration, comprising multiple flat-roofed buildings, PV modules were strategically arranged across several rooftops to maximize exposure to solar irradiance. The module selected was Yongkang Haoyou KPV-500M-132 (monocrystalline silicon, 500 W)[32], integrated with thirteen Huawei SUN2000-330KTL-H1 inverters[33], each equipped with six Maximum Power Point Tracking (MPPT) inputs to mitigate potential shading impacts. The array is mounted at a tilt angle of 19.9°, near-optimum to enhance annual energy generation while aligning with existing building orientations (detailed layout and precise technical specifications are provided in Appendix I).

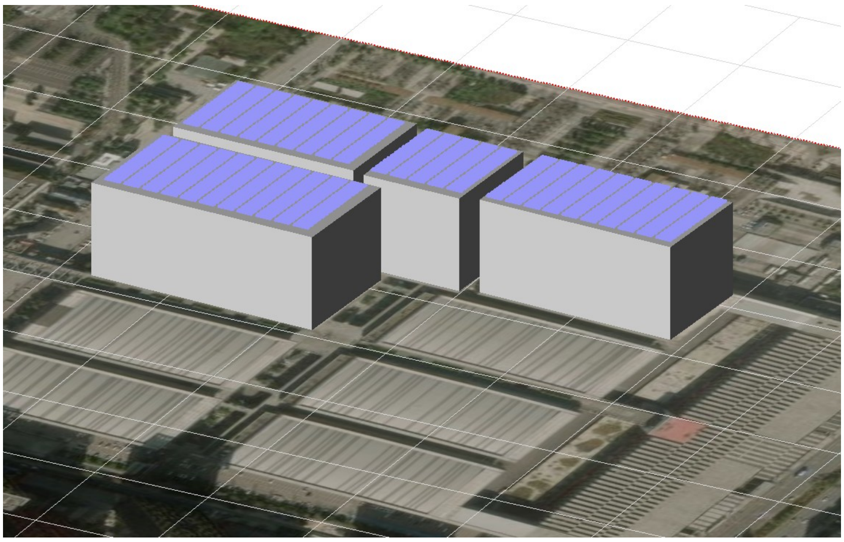
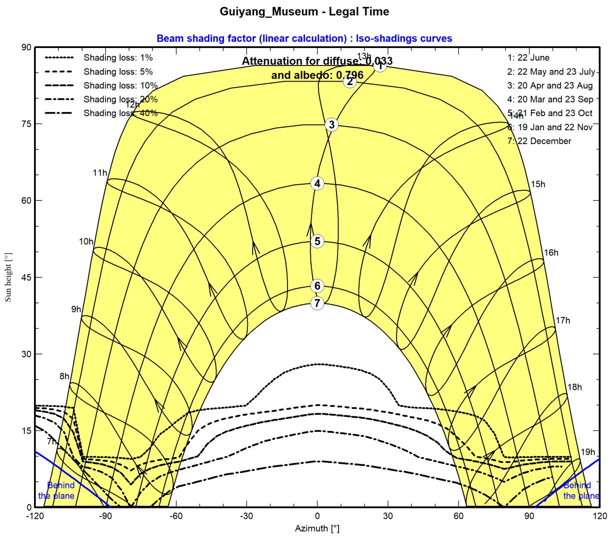
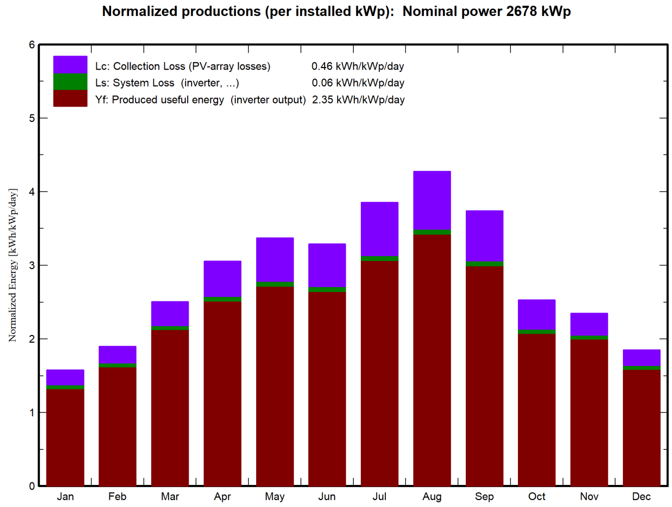


Figure 6. : PV Design Layout for GuiZhou museum

The shading losses in the Guiyang rooftop system significantly impact energy generation, primarily due to the city's climatic conditions, which include frequent fog and mist, especially during the cooler months. These environmental factors lead to reduced irradiance and increased shading throughout the day[35]. The shading analysis shown in the provided iso-shading diagram (figure Figure 7a) highlights the angular and temporal variations in shading, with marked intensity during the morning and late afternoon hours, especially around winter solstice (December), when the sun's altitude is lower. Shading





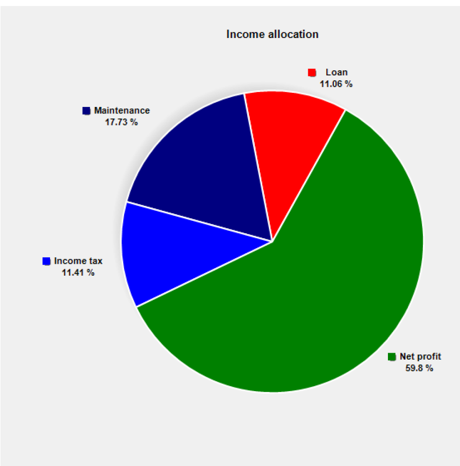
(a) Guiyang Museum Shading Loss Diagram

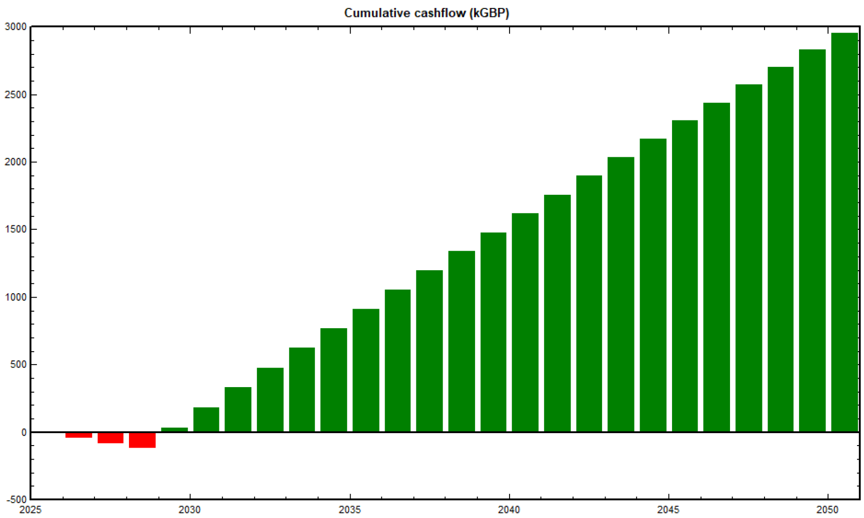
(b) Normalized Production graph in Guiyang

Figure 7. Guiyang Simulation results

losses are particularly noticeable during specific times of the day, leading to a reduction in potential energy generation.

However, the inverter system ensures a more consistent and stable performance throughout the day by effectively managing these losses, as shown in the figure Figure 7b. Simulation results for the Guiyang rooftop installation demonstrate an annual energy yield of approximately 2,294 MWh/year, with an overall performance ratio (PR) averaging around 0.819, and Nominal power achieved 2,678 kWp. A notable factor influencing system performance is the relatively high shading loss, calculated at approximately 0.4%. This substantial shading effect arises primarily from the complex rooftop geometry, characterized by multiple adjacent building structures and significant height differences.





(a) Income allocation for Rooftop in Guiyang

(b) Cumulative caseflow for Rooftop in Guiyang

Figure 8. Guiyang Simulation results

The economic analysis for the rooftop photovoltaic (PV) system installed on the Guizhou Provincial Museum demonstrates favourable financial viability. Based on local economic conditions in Guiyang, the system incurs an initial installation cost of approximately 664,380 GBP. With annual operating and maintenance expenditures estimated around 74,790 GBP/year, the system's calculated levelized cost of electricity (LCOE) stands at 0.0296 GBP/kWh. Considering local tariff rates and available incentives or subsidies supporting renewable energy investments, the project exhibits a payback period of approximately 3.7 years, indicative of strong economic attractiveness.

The cumulative cash flow analysis projects positive returns after the fourth year of operation (around 2029), showing steady annual net profit accumulation and reaching approximately 4 million GBP by the end of the project's life cycle in 2050. Income distribution for the system shows approximately 59.8% net profit, with operational maintenance costs consuming about 17.73%, loan repayments accounting for 11.06%, and income taxes at approximately 11.41%. These results highlight the economic robustness of rooftop PV projects under current market conditions and renewable energy policies in Guiyang. Additional financial details and assumptions underlying this analysis are included in Appendix A4.

4.3. Large solar array system

The locations selected for the large-scale solar arrays are **Pembroke, Wales** and **Dunhuang, China**—both known for receiving some of the highest solar irradiation levels in their respective countries. Each project covers an identical area of 560 000 m^2 and employs the same PV modules (JinkoSolar JKM585M-7RL4-V) and inverters (SUN2000-100KTL-M1), albeit configured with different system layouts. Due to variations in solar irradiation levels, associated costs, and differing numbers of PV modules and inverters required, the resulting power generation capacities and economic outcomes will significantly differ. A detailed analysis of these aspects will be presented in the subsequent subsections.

4.3.1. UK

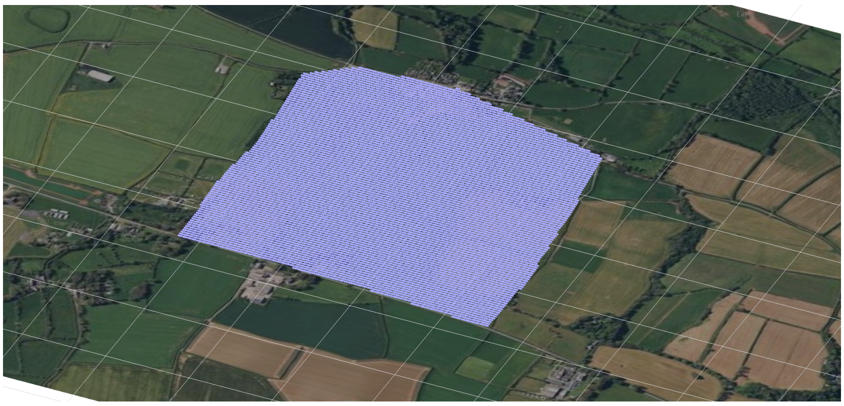
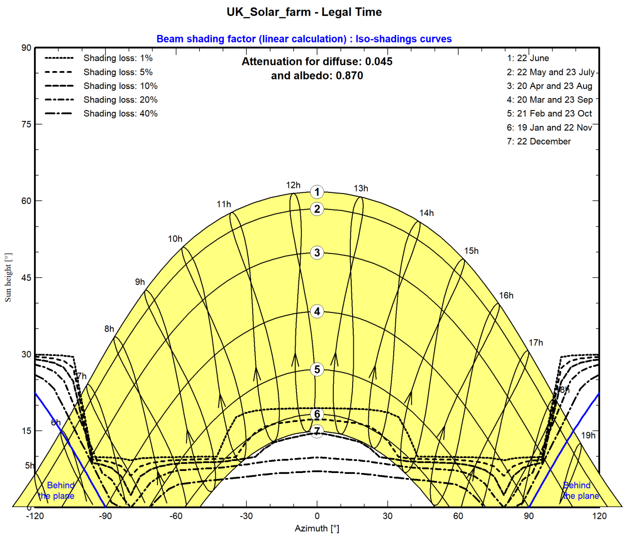


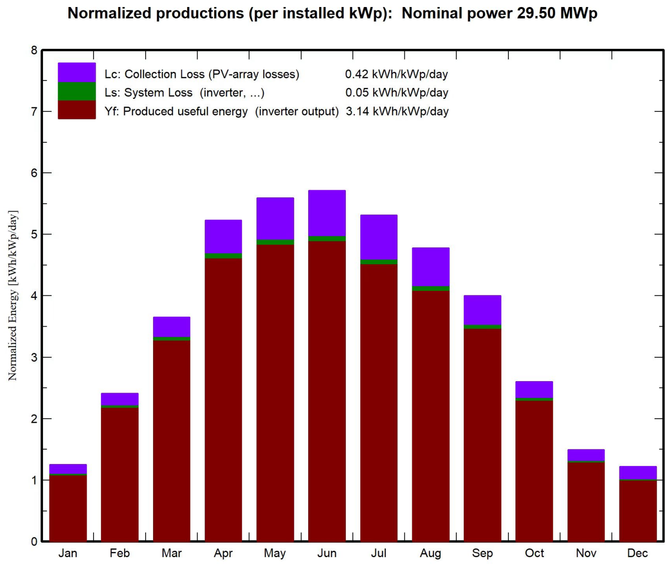
Figure 9. : PV Design Layout for UK Solar Farm

The UK-based photovoltaic (PV) system comprises 50430 modules, configured into 3362 strings of 15 modules connected in series to meet the inverter's input voltage specifications. The module tables follow a standard arrangement of 4 modules in length and 2 modules in height, resulting in 8 modules per table. As a profit-oriented project, the system is designed to maximize annual energy yield while minimizing expenses. Given the relatively low solar irradiation in the UK, only fixed and tilted panels will be used, as tracking systems are not considered cost-effective. Software simulations indicate that a tilt angle of 39.5° provides optimal performance and profitability. The pitch has been set to be 8 m, and the table spacing has been set to 1.5 m.

The selected site is agricultural land with some variation in elevation, which may lead to shading and reduce the performance of PV modules. The optimal solution is to level the terrain so that the entire area lies on a uniform plane. Although this increases the initial construction cost, it enhances energy efficiency and reduces long-term maintenance expenses.



(a) Pembroke Solar Farm Shading Loss Diagram



(b) Normalised Production graph in Pembroke

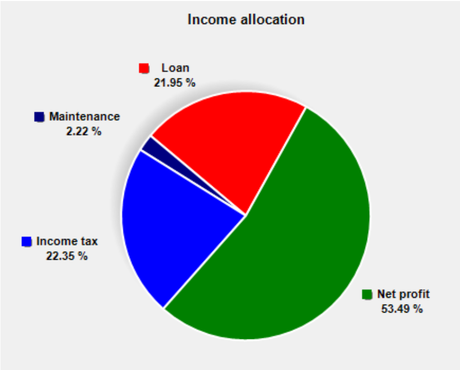
Figure 10. Pembroke simulation results.

Located at approximately 51°N in Pembroke, UK, this project experiences pronounced seasonal variation in both solar elevation angle and daylight duration. Conversely, during the summer period (around June), the solar altitude is higher and daylight hours are significantly extended, resulting in minimal shading during midday. The selected fixed tilt angle of 39.5°, oriented due south (azimuth 0°), is optimized for annual performance by enhancing the incidence angle of solar irradiance throughout the majority of the year. However, this configuration limits energy capture during sunrise and sunset, particularly in winter, when the sun's position behind the array reduces available irradiation—further accentuating the seasonal performance disparity inherent to higher latitudes.

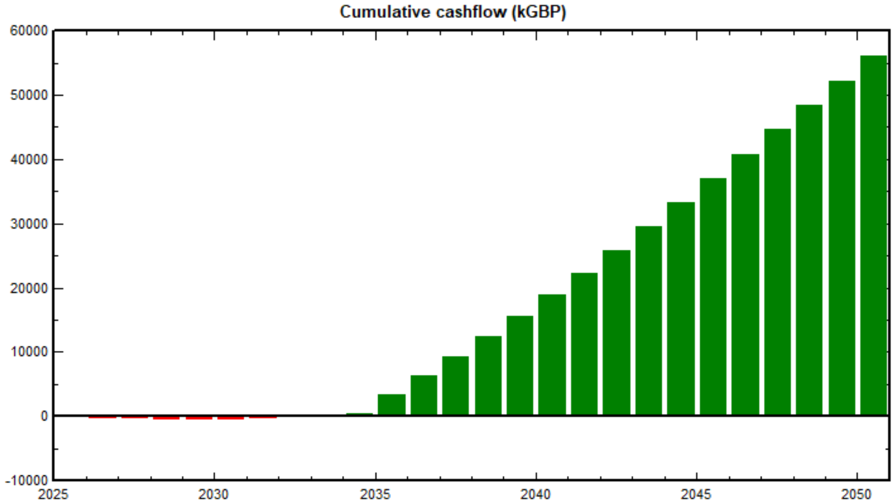
The monthly normalized energy output data exhibit a clear seasonal trend, with lower yields in winter and higher yields in summer—typical of systems located at higher latitudes. Between May and August, daily yields range from approximately 5 to 7 kWh/kWp, while during the winter months (November to January), yields decline to around 1–2 kWh/kWp. Collection losses (L_c) and system-level inverter losses (L_s) remain relatively stable at approximately 0.42 kWh/kWp/day and 0.05 kWh/kWp/day, respectively, indicating that the impacts of temperature coefficients, wiring losses, and inverter efficiency are within expected operational limits. Under these site-specific conditions and fixed-tilt configuration, the system achieves an annual average specific yield of approximately 3.14 kWh/kWp/day. This value reflects both the climatic constraints of the region and a commendable level of overall system performance.

The economic analysis for the large-scale photovoltaic (PV) system installed in Pembroke, United Kingdom, illustrates robust long-term financial performance. The system, with a total installed capacity of 29.5 MWp, incurs an initial investment cost of approximately £18.58 million. Annual operational and maintenance costs, including provisions for inverter replacement and inflation, amount to approximately £93,058.

Simulation results indicate an annual energy production of 33,809 MWh, with a levelized cost of electricity (LCOE) of £0.0504/kWh. Based on feed-in tariff rates and a 25-year project lifetime, the system achieves a payback period of approximately 9 years. Over this period, the project accumulates a net present value (NPV) of £11.17 million, with an internal rate of return (IRR) of 53.57%, and a return on investment (ROI) of 60.1%.



(a) Income allocation for Rooftop in Pembroke



(b) Cumulative caseflow for Rooftop in Pembroke

Figure 11. Pembroke simulation results.

Cumulative cashflow (Figure 11b) turns positive in year 9 and steadily increases, surpassing £56 million by the end of the simulation period in 2050. This financial trajectory reflects consistent energy production and favorable tariff conditions.

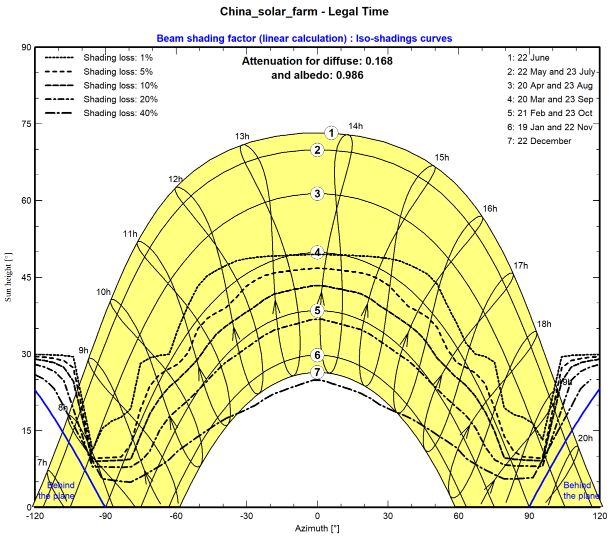
As shown in the income allocation pie chart (Figure 11a), the system's total income is primarily allocated to net profit 53.49%, with loan repayments constituting 21.95%, income tax at 22.35%, and maintenance costs at a modest 2.22%. This distribution underscores the system's financial efficiency and its potential as a viable model for future large-scale solar deployments in the UK.

4.3.2. China

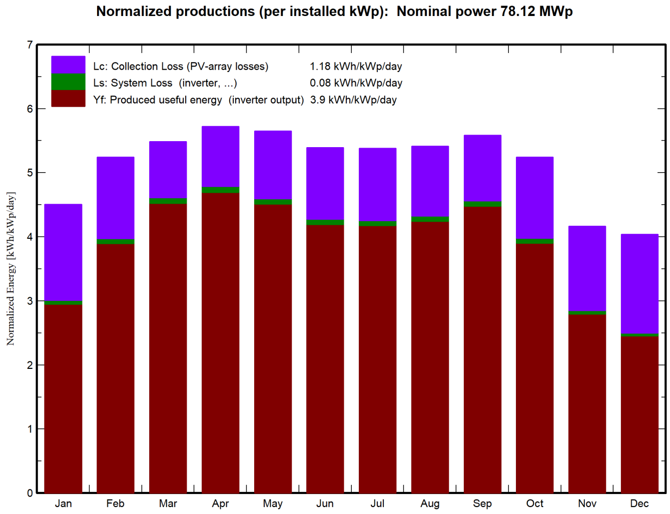
With carefully calculation and scaling, the planned large PV system in China employs 153062 modules arranged into 10933 strings with 14 modules in one series. The system is located in Dunhuang, Gansu Province, offering one of the highest solar resource potentials in China by high annual direct normal irradiance (DNI) and minimal cloud cover throughout the year. The flat desert terrain provides an unobstructed environment for solar exposure with zero surrounding shading, but also presents challenges for maintenance due to sand accumulation, limited water availability, and increased wind wear on mechanical components.

Unlike the tracking system previously considered, the Dunhuang installation utilizes a fixed-tilt configuration with a tilt angle of 40.9°, oriented due south (azimuth 0°). This fixed-tilt strategy simplifies the structural design and reduces maintenance requirements, particularly advantageous given the harsh desert environment.

Simulation results from PVsyst indicate a total annual electricity generation of approximately 135,153 MWh, supported by the favourable solar resource in Dunhuang. Despite the use of a tracking system, the overall performance ratio (PR) remains at 0.695, slightly lower than that of the UK system. This is attributed to higher collection losses from soiling, tracking inaccuracies, and elevated module temperatures in desert conditions. The sun path diagram (Figure 12a) confirms a wide unobstructed horizon, allowing full utilisation of direct normal irradiance (DNI) throughout the day. The tracking system significantly improves early morning and late afternoon energy yield, compensating for the flat solar altitude angles typical in high-latitude winter months. The monthly energy output demonstrates relatively stable performance across the year, with less seasonal variation compared to the UK system. Loss breakdowns reveal that collection losses account for



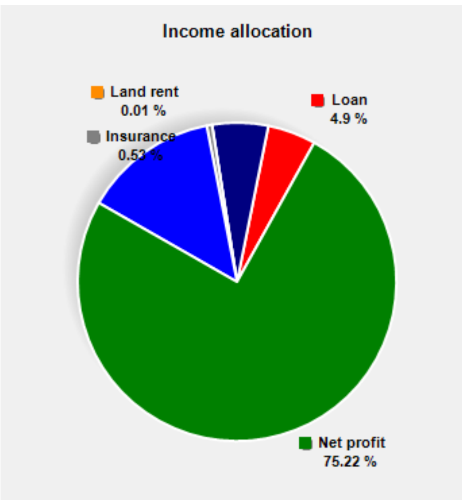
(a) Dunhuang Solar Farm System Shading Loss Diagram



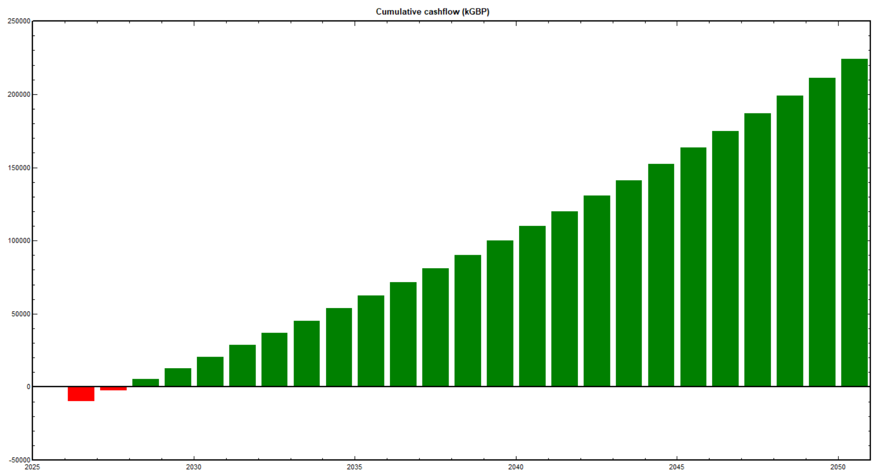
(b) Normalised Production graph in Dunhuang

Figure 12. Dunhuang solar farm system simulation results

29.2% of total potential production, while system losses from inverters and wiring are relatively low at 1.4%, as shown in Figure 12b.



(a) Dunhuang Solar Farm System Income Allocation



(b) Cumulative cashflow for Rooftop in Dunhuang

Figure 13. Dunhuang solar farm system economic analysis

Economic analysis of the Dunhuang solar farm reveals exceptional financial performance. With a total initial capital investment of approximately £17.38 million, the project benefits from both scale and solar resource advantages. Operational and maintenance costs are estimated at around £613,740 per year, while revenue is supported by a feed-in tariff of £0.08/kWh. The levelised cost of electricity (LCOE) is projected to be £0.0166/kWh, significantly lower than that of the UK system. Financial metrics demonstrate high profitability: a net profit margin of 75.22%, a payback period of just 2.1 years, a return on investment (ROI) of 911.3%, and an internal rate of return (IRR) of 97.93%. These values are summarised from PVsyst financial outputs and illustrated in Figure 13a, which shows income allocation with minimal contributions to land rent, insurance, or debt servicing. The cumulative cash flow chart (Figure 13b) shows a steep positive trajectory, with the break-even point reached before year 2028. By 2050, the system is projected to generate a net cumulative cash flow exceeding £270 million, reinforcing the long-term financial sustainability of the project.

5. Thermal applications

Solar thermal technology takes advantage of solar energy in the way of generating heat for directly use other than the solar photovoltaic technology. Common solar thermal system types including solar water heaters, solar air heaters, and solar concentrators present a significant opportunity to diversify its renewable energy portfolio and reduce carbon emissions [36]. Moreover, for further development, emerging technologies that enhance efficiency and integration capabilities are likely to attract greater market attention.

1. It is important to have high efficiency for collecting energy, so researches focusing on the advanced materials for heat absorption bring benefit to minimize thermal losses [37].
2. Enhancing heat transfer plays a vital role in boosting energy yield efficiency. Several studies have explored methods such as using nano-fluids, microchannel heat exchangers, and advanced surface coatings to improve system efficiency [38].
3. The combinations with other kinds of energy systems such as PVT, CHP and energy storage systems offers additional opportunities for optimization and efficiency gains [39].

This chapter explores the potential of solar thermal applications in the two selected countries, examines the current market landscape, highlights notable projects, and discusses emerging technologies in the sector.

5.1. Solar thermal application in UK

Solar thermal systems can provide a substantial portion of a building's heating and hot water needs, thereby decreasing the reliance on fossil fuels and lowering energy bills. The solar thermal installations solves 40% to 60% of the heating and hot water needs of a household [40].

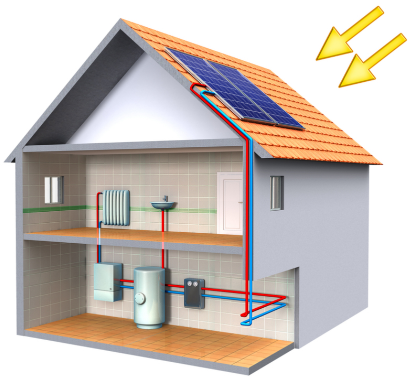


Figure 14. :Solar thermal collectors

The UK market for solar thermal systems like figure 14 has seen fluctuating growth, influenced by policy changes and the availability of financial incentives. The closure of policy Renewable Heat Incentive (RHI) in March 2021 has impacted market dynamics [41]. Subsequently, one potential mechanism to support the deployment of solar thermal, designed to replace RHI,is the Clean Heat Grant (CHG), delivers upfront grants to help homeowners pay for low carbon heating technologies. The government's continued attention and policy adjustments prove that there is room for future development in this field [42].

The 23/24 Solar Thermal Outlook given by Solar Heat Europe states 4 main market segments in this field: residential buildings, tertiary buildings, district heating, and industry. There is 96% of solar thermal volume installed on buildings, with 71.9% of which is selected as flat plate collector type [43]. From the perspective of annual overview in 2023, the UK has grow its annual evolution new installed capacity by 69 %, indicating a new market is in growth [43].

The integration of solar thermal systems with other technologies, such as heat pumps and combined heat and power (CHP) systems, continues to present opportunities for market expansion. While large-scale solar thermal power plants can demonstrate the potential of concentrated solar power (CSP) technologies, the UK has primarily focused on smaller-scale installations due to its climate and geographic constraints.

A project worthy to be concerned in the UK is the largest solar thermal project installed by Naked Energy across the roof of the British Library in London in 2024 [44]. 950 solar collectors with a hybrid technology combining both PV and thermal are expected to yield 216 MWh of energy per year, while the solar collectors used from its Virtu range will save up to four times the amount of carbon as standard solar photovoltaic (PV) panels [45]. The technology was also funded by The Public Sector Decarbonisation Scheme, run by the Department for Energy Security and Net Zero, and it is expected to play an important role for leading other sectors to join the energy transition [44].

Similar researches on innovative projects integrating hybrid photovoltaic-thermal (PVT) collectors with CHP systems have been explored. For instance, a proposed micro-CHP system combining PVT collectors, a Stirling engine, and energy storage demonstrated an annual electricity self-sufficiency of 87% and met 99% of thermal energy demand for a typical London household [46]. However, economic analyses indicate a discounted payback period of 28 years, highlighting the need for cost reductions in PVT and CHP technologies.

To conclude, solar thermal applications in the UK hold significant potential for contributing to sustainable heat generation. However, their widespread adoption depends on economic competitiveness, which can be enhanced through financial incentives and technological advancements. Integrating solar thermal systems with other energy technologies and continuing research into emerging solutions will be a crucial part for their future role in the UK's energy landscape.

5.2. Solar thermal application in China

China exhibits significant potential for solar thermal applications, benefiting from extensive solar resource availability, particularly in its western and northern regions. According to the China Solar Thermal Industry Federation, the annual solar radiation in China's western provinces, such as Tibet, Xinjiang, and Inner Mongolia, frequently exceeds 1,800 kWh/m^2[47], making these regions particularly suitable for large-scale solar thermal installations.

The current solar thermal market in China is primarily dominated by solar water heating systems, with a cumulative installed area exceeding 500 million square meters as of 2024, accounting for approximately 70% of the global capacity. These systems are predominantly utilized in residential sectors for domestic hot water, contributing substantially to reducing dependence on conventional fuels and cutting carbon emissions significantly across urban and rural areas.

Notable projects include the Shouhang Dunhuang 100 MW molten salt tower solar thermal plant show in figure 15, operational since 2018, located in Gansu Province. It represents one of China's flagship concentrated solar power (CSP) projects and demonstrates the viability of CSP technology in delivering dispatchable renewable energy at scale. Another significant project is the Delingha 50 MW parabolic trough CSP plant in Qinghai Province, which has effectively showcased the integration of thermal storage capabilities, enabling electricity generation beyond daylight hours[18].

Emerging technologies within China's solar thermal sector focus primarily on improving system efficiency and integration capabilities. Research on advanced heat transfer fluids, such as molten salts with enhanced thermal properties, has gained momentum due to their ability to increase operational efficiency and storage capacities. Additionally, solar thermal integration with photovoltaic (PV) systems, known as photovoltaic-thermal (PVT)

Figure 15. :Shouhang Dunhuang 100 MW molten salt tower solar thermal plant

hybrid technology, is rapidly advancing. These hybrid systems offer dual functionality, simultaneously generating heat and electricity, which significantly enhances overall system efficiency and economic viability. Recent developments in nano-coatings for absorptive surfaces have also demonstrated substantial improvements in thermal capture efficiency, marking a progressive step towards more efficient and compact solar thermal systems[48].

In conclusion, solar thermal applications in China show considerable promise, driven by substantial market scale, governmental support, and ongoing technological advancements. Continued innovation in CSP technologies, storage solutions, and hybrid system integrations will likely play a crucial role in achieving China's long-term renewable energy and carbon neutrality objectives.

6. Discussion

The comparative analysis of photovoltaic (PV) systems between the United Kingdom and China provides significant insights into how geographic, climatic, and policy differences influence PV system performance, economic viability, and energy strategy implementation.

In the rooftop PV installations, despite similar annual irradiance levels (1000 kWh/kWp), Guiyang, China exhibited notably higher energy production (2,294 MWh/year) compared to London, UK (1,104 MWh/year). This disparity can primarily be attributed to effective inverter management systems minimizing shading impacts in Guiyang's complex urban layout, as well as optimized tilt angles tailored to local solar conditions. Additionally, economic analyses revealed that rooftop installations in China presented a significantly lower levelized cost of electricity (LCOE) and shorter payback periods than the UK, highlighting the substantial impact of China's favourable economic incentives and reduced operational costs. These findings corroborate previous studies emphasizing the critical role of localized design optimization in achieving superior PV performance.

For open-field installations, the system located in Dunhuang, China, significantly outperformed its counterpart in Pembroke, UK, generating approximately 135,153 MWh/year compared to 33,809 MWh/year. This substantial difference is primarily attributed to the superior solar resource in Dunhuang, combined with a higher density of PV tables, which enhances overall energy output despite a lower performance ratio. In contrast, the fixed-tilt system in Pembroke, while less densely configured and more cost-effective in terms of installation, exhibited lower annual energy yield. However, it achieved a higher performance ratio due to reduced mutual shading between tables. From an economic perspective, the

Dunhuang project delivered outstanding financial returns, characterized by a significantly shorter payback period and higher internal rate of return (IRR), highlighting the economic benefits of abundant solar irradiation and robust renewable energy policies in China.

The results from this comparative analysis align with existing literature, reinforcing that strategic system design choices such as layout strategy (Efficiency-driven Layout and Yield-driven Layout) and localized policy frameworks significantly enhance solar PV performance and financial viability. Future research should explore advanced integrated systems that incorporate energy storage and adaptive management technologies to further improve energy resilience against climatic variability. Moreover, investigating emerging PV technologies, such as bifacial and tandem cells, could further enhance energy yields and economic returns, particularly beneficial in regions with moderate to lower irradiation. This approach would support broader adoption of solar energy technologies in varied geographic contexts.

7. Conclusions

This comparative study between photovoltaic (PV) systems in the United Kingdom and China has highlighted substantial variations in system performance and economic viability driven by geographic, climatic, and policy differences. Rooftop PV installations in China, specifically in Guiyang, showed significantly higher annual energy yields and superior economic returns compared to those in London, mainly due to optimized inverter management, reduced shading losses, and effective local policy incentives. For large-scale PV farms, the Dunhuang system, employing a fixed-tilt configuration (40.9°), markedly outperformed the Pembroke system in the UK, demonstrating higher energy output and better economic metrics, including shorter payback periods and higher internal rates of return. These findings underscore the importance of tailored system design, appropriate technology selection, and supportive governmental policies in enhancing the adoption and financial success of PV projects across diverse geographical contexts.

8. Further Study

Future research should explore advanced integrated photovoltaic systems incorporating energy storage and adaptive management technologies to enhance grid stability and energy reliability. Additionally, evaluating emerging PV technologies such as bifacial modules, tandem cells, and perovskite-based photovoltaics could reveal further efficiency improvements and cost reductions. Comparative studies on policy frameworks and their impact on renewable energy development can also provide valuable insights for global policy formulation and strategic investment planning.

Appendix I System Design Parameters

Appendix J Shading rate and N-S pitch calculation

The shading rate us given by:

$$\text{Shading Rate} = \frac{L_{sh}}{H} = \frac{1}{\tan(h)} \tag{A1}$$

where L_{sh} is the length of the shadow on the ground, H is the vertical length of the PV panel, and h is the solar elevation angle, given by:

$$\sin(h) = \sin(\varphi) \cdot \sin(\delta) \; + \; \cos(\varphi) \cdot \cos(\delta) \cdot \cos(\omega) \tag{A2}$$

ω is the local latitude, and δ is the declination angle of the sun, and ω is the hour angle.

The vertical length of the PV panel H is given by:

$$H = L \cdot \sin(\beta) \tag{A3}$$

Where β is the tilt angle of the PV panel.

Table A3. Summary of PV System Design Parameters

Parameter	China Open Field	UK Open Field	China Rooftop	UK Rooftop
Location	40°09′08.0"N 94°29′29.5"E	1°38′11.2"N 4°57′41.2"W	26°38′50.3"N 106°37′48.7"E	51°37′14.2"N 0°2′14.5"W
Irradiance [kWh/kWp]	1816.5	1060.3	962.1	1026.4
PV modules	Jinkosolar JKM585M-7RL4-V		KPV-500M-132	
Inverter modules	SUN2000-100KTL_M1		SUN2000-330KTL-H1	
PV Mod. in series	14	15	26	28
No. of inverters	689	295	7	3
No. of strings	10933	3362	206	81
DC/AC Ratio	1.21	1.19	1.25	1.26
Mounting type	Tracker	Fixed	Fixed	Fixed
Tilt angle [°]	-60 60	39.5	19.9	40.9
Azimuth angle [°]	0	17	2	17
Shading loss [%]	15	5.10	0.4	6.00
Performance ratio	0.695	0.87	0.819	0.840
System production [MWh/year]	135,153	33,809	2,294	1,104

Table A4. Financial Parameters for Rooftop and Open Field PV Systems

Price List (GBP)	China Rooftop	UK Rooftop	China Open Field	UK Open Field
PV module /module	38.02	38.02	50.25	50.25
Tracker /module	NONE	NONE	0.68	NONE
Inverter /module	7025.07	7025.07	1252.13	1252.13
Electricity feed-in tariff /kWh	0.089	0.17	0.08	0.087
Payback period (years)	3.8	6.1	2.1	9
Total yearly cost	75,063.29	89,097.19	1,641,646.97	1,013,407.13
Maintenance / year	29,497.10	41,391	613,739.53	68,109.01
Project lifetime (years)	25	25	25	25
Inflation	2.50%	2.50%	2.50%	2.50%
Discount rate	4%	4%	3.30%	10%
Income tax	15%	25%	15%	25%
Loans	522,827.50	699,412.45	17,376,674.05	18,582,846.05
Interest rate	4.50%	4.50%	4.50%	4.50%
Net Present Value (NPV)	1,707,034	1,838,318	158,582,397	11,165,117
Internal Rate of Return (IRR)	70.29%	72%	97.93%	53.57%
Return on Investment (ROI)	326.50%	262.80%	911.3%	60.10%

From these, the length of the shadow on the ground L_{sh} can be given by:

$$L_{sh} = \frac{H}{\tan(h)} = \frac{L \cdot \sin(\beta)}{\tan(h)} \tag{A4}$$

In order to avoid shading between PV panels, it should be ensured that when the distance between PV panels is longer than the length of the shadow on the ground.

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