Chapter

Comparing Different PV Module Types and Brands Under Working Conditions in the United Kingdom

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Abstract

The present work demonstrates the performance evaluation and economic analysis of different PV module types and brands at the working conditions of Padiham (53.5 N, 2.3 W) in the UK. The total area of PV plant was assumed to be 100 square meters. The simulations were carried out for modules installed on the roof and on the south-facing façade of a residential building. The comparison study is carried out to define the most suitable module type and brands for the considered place in the current study. The energy and economic performance of the grid-connected PV system are analyzed under the meteorological conditions of Padiham. The modules were characterized by evaluating their annual electrical energy generation and different figures of merit of the grid-connected PV systems such as the investment, annual profit, net present value, levelized cost of electricity, and the payback time. The simulations show that in this specific setup, monocrystalline modules have the best energy performance, while thin-film modules have the best economic performance.

Keywords: PV system, simulations, different PV brands, potential

1. Introduction

Today, most of the global energy comes from using fossil energy carrier. There is mounting evidence that global warming and, consequently, climate changes are anthropogenic and attributed to fossil-fuel consumption. The strong fossil-fuel dependence of our current energy system has resulted in daily fossil-fuel consumption of 98.2 million barrels of oil equivalent (Mbbl) in 2017 [1]. It is worth to mention that fossil fuel represents 75% of total global energy consumption, while renewable energy resources represent only 25% [2]. Consequently, about 36.8 billion tons of carbon dioxide emissions are emitted into the atmosphere annually for global energy production [3]. Observations provide evidence that atmospheric CO_2 levels caused by human activities have increased by 25% over the last century, which leads to rising global temperature [4].

In helping to face those challenges and achieving the EU targets for 2020 and 2050, in addition to improving the performance of the existing energy conversion systems, utilizing the available local renewable energy resources is needed as well. Although the current efficiency of such systems is still relatively low and the capital cost is still high, the abundance of solar energy that strikes our planet makes the use of solar panel economically viable [5, 6]. It is worth mentioning that the growing demand for renewable energy sources in recent years led to advancing the manufacturing of solar cells. The fast decrease in system prices combined with the increases in the performance make it economically feasible, and, consequently, increased amount installed globally [7]. Regarding the worldwide installed capacity, solar photovoltaic is now the third largest renewable energy source with annual capacity additions reaching 93.7 GW and 94.3 GW in 2017 and 2018, respectively [2, 8]. By the end of 2018, the total accumulated capacity is 480 GW [8]. Because they have no moving parts, PVs are stable over time, with typical durability of 25 years, and low maintenance is required during their operation [9].

Indeed, many different PV module types and brands are available in the market. The performance of each type and brand varies from one to another and strongly depends on the meteorological and working conditions. Current work, therefore, presents a comparison between different module types and brands under the meteorological conditions of Padiham (53.5 N, 2.3 W) in the UK.

2. Photovoltaic system overview

Photovoltaic (PV) system is a technology that converts solar energy into electricity. Because no moving parts, such systems are reliable, and low maintenance is required during the operation. In addition to the fact that PV systems do not emit any greenhouse gases during operation, manufacturing such systems results in very low emissions. In average, less than 2 years is needed for a PV module to generate the same amount of energy that has been used to fabricate the module—depending on the type of module [10].

Recently, the PV module has been integrated to building external envelope. Such a system is the so-called building-integrated photovoltaics (BIPV). The most advantage of BIPV is that such a system generates the electricity at the place where it is demanded, as well as PV modules can replace some parts of the building envelope components. This can result in reducing the initial costs of BIPV due to lowering the costs of conventional envelope materials. PV modules can be integrated into different parts of the envelope such as roof (flat or slope), façade, and shading devices for windows.

The electric output of a PV system depends on different factors such as:

- The availability of and accessibility to solar radiation, which in turn is influenced by the climate, the inclination, and orientation of the modules
- The PV technology is related to facts such as efficiency and its decline with time and the cell temperature
- The over shading in some areas of the modules

3. Objective

This work aim is to evaluate the performance of a photovoltaic (PV) system installed on the roof or integrated to the south-facing façade of residential apartments in Padiham (53.5 N, 2.3 E), UK. Moreover, the work presents a comparison

	Type		
Brands	Monocrystalline	Polycrystalline	Thin film
	Motech XS72D3-320	Hanwha Solar One 310	Stion STO-150
	Panasonic N330	JA Solar 48-225/4BB	Solar Frontier SF170-S
	Silevo 310	Trina 315	Stion STN-125
	Sunpreme 360	SunTech 320	SolTech Energy 80
	Solar World SW350 XL	Jinko Solar JKM270	
	Silevo 220	Motech IM72C3-310	
	Optimus 60 OPT280	Canadian Solar CS6X-320P	
	LG Solar 320	Solar World SW260	
	Jinko Solar JKM275M	Yingli Solar YL305P	
	Solar World SW325 XL	PEAK BLK 255	
	JA Solar 72-315/SI	Gintech 240	
	Hyundai HiS-S265MG	Hyundai HiS-S250MG	
	Mitsubishi PV-MLE265HD2	Kyocera KD220GH-4FB2	

Table 1.
Considered PV module types and brands [11].

between the energy and economic performance of the most common PV module types, which are:

1. Polycrystalline module

2. Monocrystalline module

3. Thin-film module

Of course, a tremendous number of companies are making different brands of PV modules. Therefore, in order to identify the suitable module type and brand, performances of different module type and brands are compared under the meteorological conditions of Padiham, UK. The present work considers only the brands that were mentioned in the report prepared by the Fraunhofer Institute for Solar Energy Systems, ISE [11] (see **Table 1**). The electricity generation profiles of the installed PV system will be identified. Annual electricity generation profile, energy efficiency, and different figures of merit of economic performance of different module types and brands will be illustrated at the working conditions of the considered city.

4. Determination of available solar energy

The first and most important step before designing a photovoltaic system is the determination of the available solar energy (ASE) on an inclined surface in the considered site. ASE can be either measured or simulated. Solar radiation simulations have advantages over measurements and are more reliable over the years [12]. Unlike measured solar radiation, simulated solar radiation can account for universal climate variations over many years, without having the burden of having to process decades of field data. Also, the actual measurements of the ASE are

January	February	March	April	May	June	July	August	September	October	November	December
0.32	0.34	0.37	0.39	0.41	0.39	0.41	0.41	0.38	0.34	0.30	0.30

Table 2.
Clearness index in Padiham, UK [18].

Input Data								
Latitude	55.871254	N	degree	Month	Clearness KT	PV Specification		
Longitude	12.826451	e	degree	Jan	0.33	fill factor	0.77	-
Standard Longitude	15	degrees		Feb	0.39	derating factor	0.90	
Slop angle β	50.0	degrees		Mar	0.44	short circuit current	9.09	A
Surface azimuth	180.0	degrees		Apr	0.48	open circuit voltage	45.73	V
Avilable area	100	m^2		May	0.5	voltage temp. coefficient	340.00	%/C
Inflation rate	0.7%	%		Jun	0.48	NOCT (nominal operating cell temperature)	45.00	C
Real interest rate	3.4%			Jul	0.49			
Electrical price escalation rate	1.0%			Aug	0.49	nomional capacity	320.00	W
				Sep	0.45	module price	480.00	$
Electricity price	0.207	$/kWh		Oct	0.38	Area	1.64	m^2
				Nov	0.39	module degradation rate	1.0%	%
				Dec	0.35			

Figure 1.
Input data interface of the developed excel-based model to simulate the PV system.

costly due to the high price of the required instruments. Therefore, simulation is a common method to calculate the available solar energy at a particular location.
In this work, a computational model was built to estimate the available solar energy, with the resolution of 1 hour, per square meter of surface considering different slopes and azimuth angles. The model can be used to determine the optimal azimuth and slope angles of the PV modules. The optimum angles are defined as the angles that result in maximum annual electricity generation. More details about the model can be found in Ref [13].

It should be noted that the model was built based on well-known theoretical relations for calculating available solar energy. These relations have been tested by a number of studies [14, 15]; the reader is recommended to consult Section 2 in Refs. [16, 17]. It is also worth noting that in the current study, the cloudy day approach was taken in the calculation of the available solar energy. The clearness index of the city of Padiham, which was taken from [18], is tabulated in **Table 2**. The specifications of the considered PV module, which appear in **Figure 1** as input data, were collected from the technical brochure of each module, which was provided by the factory of each considered module. Some of the specifications of the PV module are certain wattage, voltage, and amperage which are called electrical characteristics of the module. These characteristics of the module are defined under specific conditions which are called standard test conditions (STC). STC, which is the universal standard, is a set of laboratory test conditions including irradiance of 1000 W/m^2, air mass of AM1.5, and cell temperature of 25°C [16].

5. Simulation PV system

Because an electric grid is available in Padiham, a grid-connected system will be considered in the current work. In such a system, the electric grid acts as a virtual storage system, which in turn can reduce the net costs of PV systems. However, these systems require an inverter to convert the DC (direct current) voltage into AC voltage. Also, to reduce the initial cost of the system, grid-connected PV systems have another advantage. Indeed, the electricity consumption of a building is not constant over the day and varies depending on the occupancy of the building, user behavior, and used equipment. On another side, the electricity output of the PV system varies during the day with the position of the sun in the sky.

Consequently, there might be periods when the output of the PV system exceeds the electricity demand of the building or vice versa. Therefore, in a grid-connected system, the electricity demand of the building is met by a combination of solar energy and grid electricity. In other words, when the output of the PV system exceeds the demand of the building, the system will export the exceeded energy to the grid and vice versa. Namely, when the output of the PV system is not enough to cover the demand of the building, the system will import electricity from the grid.

In current work, an Excel-based model has been built to simulate hour-by-hour energy and economic performance of a grid-connected PV system for different slope angle. As mentioned above the model can be used to determine the optimal inclination angle so that the annual generation of PV module can be maximized. The model can also simulate a PV system installed on south-facing façade or a vertical wall of any azimuth angle. Furthermore, the model was built using well-known theoretical relations for calculating the electricity generation of the PV system. For more details, the reader is recommended to consult Refs. [19, 20]. In order to be able to simulate the energy and economic performance of the PV system, assumptions had to be made. In the current study, the assumptions are based on realistic current conditions in the UK and data collected from literature review (see **Table 3**)[1] [21–33].

5.1 Component and installation costs

The price PV module was taken based on the price given by different suppliers. According to the component price collected from literature review, the replacement of the inverter (which takes place every 8th year) and the installation cost were assumed to be 322 $/kW and 0.018 $/W, respectively [23–25].

5.2 Operation and maintenance costs

Operation and maintenance (O&M) represent expenses on equipment and services that occur after the system is installed. Fortunately, solar panels have 25 years

Factor	Value	Factor	Value
Inflation rate	0.1%	Labor cost	18 $/kW
Real interest rate	0.6%	Operation	10 $/kW·y
Elect. price	20.1 ₵/kWh	Inverter lifetime	8 y
Feed-in tariff	6.7 ₵/kWh	Wire efficiency	98%
Elect. price escalation	1%/y	Lifetime of the project	25 y
Degradation rate	1%/y	Inverter price	322 $/kW
Cell temperature	$T_C = T_a + 1.25 \bullet (NOCT - 20) \bullet G_s$		

Table 3.
Assumptions made in the present work.

[1] T_c is the cell temperature, T_a is the ambient air temperature, NOCT is the nominal operating temperature, and Gs is the available solar radiation (W/m^2).

of warranty. Product warranties usually cover major maintenance. Therefore, O&M costs during the first 25 years (which was assumed to be the project economic life) will be only for surface cleaning of PV modules and supervising. In 2013 in the USA, the cost of supervision and twice a year cleaning of the panels was reported to be 8.3 $/kW per year [22]. Therefore, in current work, the annual O&M cost of the project will be assumed 10 $/kW·y.

6. Results and discussions

The developed model was used to simulate the performance of grid-connected PV system. As mentioned above, different brands of PV modules were tested in the present work, see **Table 1**.

6.1 Thin-film module type

Among the brands of the thin film mentioned in the report prepared by the Fraunhofer Institute for Solar Energy Systems, ISE [11], only the price of four brands was collected so far.

The electrical output of the PV module per square meter of different brands of thin-film PV module installed on the roof is shown in **Figure 2**. As shown, the annual electrical output per square meter of selected modules varies from a minimum of 127 to a maximum of 151 kWh/m2·y. The optimal slope angle of the module was found to be 49° facing the south. From an energy viewpoint, the results illustrated in **Figure 2** show that Stion STO-150 thin film is the best among the considered thin-film module brands.

Energy performance of PV modules strongly depends on the module temperature variations. Therefore, as expected, simulations show that the efficiency of the PV modules during colder months is higher than those during the warmer months. **Figure 3** shows that the efficiency of the thin-film PV module ranged from 9.6% (SolTech Energy 80 in August) to 12% (Stion STO-150 in January).

In order to compare the different brands from the economic point of view, the levelized cost of electricity and the accumulative cash flow were determined for each brand. As shown in **Figure 4**, the levelized cost of electricity varies from a

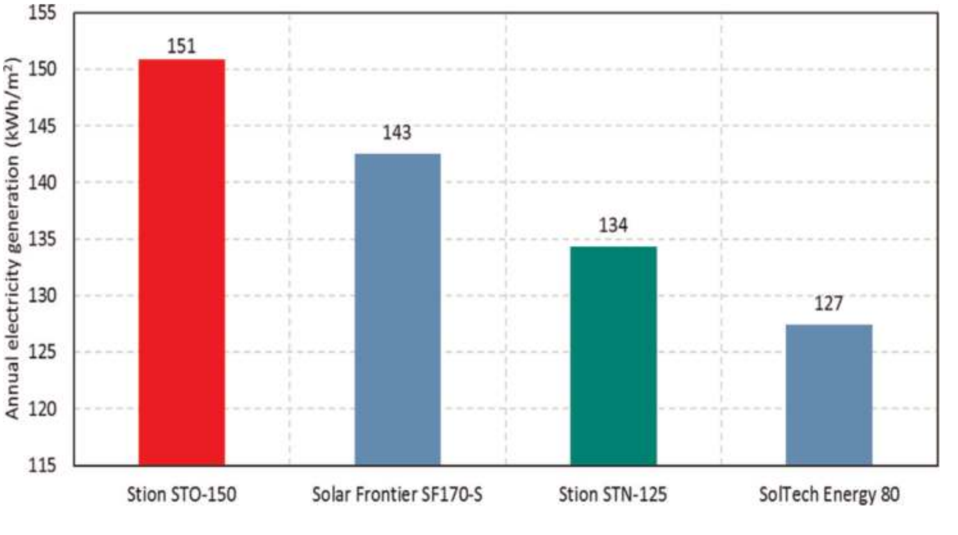

Figure 2.
Electricity output per square meter of thin-film PV module installed on the roof. The optimal slope angle of the module was found to be 49 facing the south.

minimum of 7.5 (Stion STN-125) to a maximum of 15.3 ₵/kWh (SolTech Energy 80). Thus, from the levelized cost of electricity viewpoint, Stion STN-125 is the best among the considered brands.

Figure 5 shows the accumulative cash flow of Stion STO-150 (of the best energy performance) and Stion STN-125 (of the best economic performance). Apparently, the installation cost of Stion STO-150 is 39% more than the initial cost of Stion STN-125 for the same available area of PV cells (which is in our case 100 m^2).

In other words, by using Stion STO-150, the annual electricity is increased by 12%, and the initial cost of such a system is increased by 39% in comparing to Stion STN-125 (see **Table 4**). Hence, the preference of the decision-maker should be considered in order to select the most suitable PV brand, namely, either the brand of the best energy performance or the brand of the best economic performance.

Repeating the simulation for the module installed on the south-facing façade leads to the same conclusion. Explicitly, from an energy viewpoint, the Stion STO-150 thin film is the best brand among the considered brands. While from the economic viewpoint, Stion STO-125 thin film is the best brand among the considered brands.

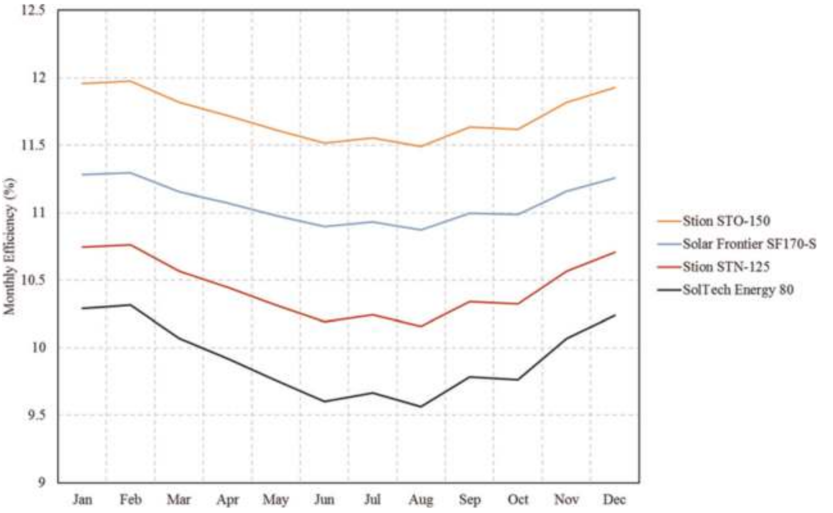

Figure 3.
Monthly average efficiency of different brands of thin-film module at working conditions of Padiham, UK.

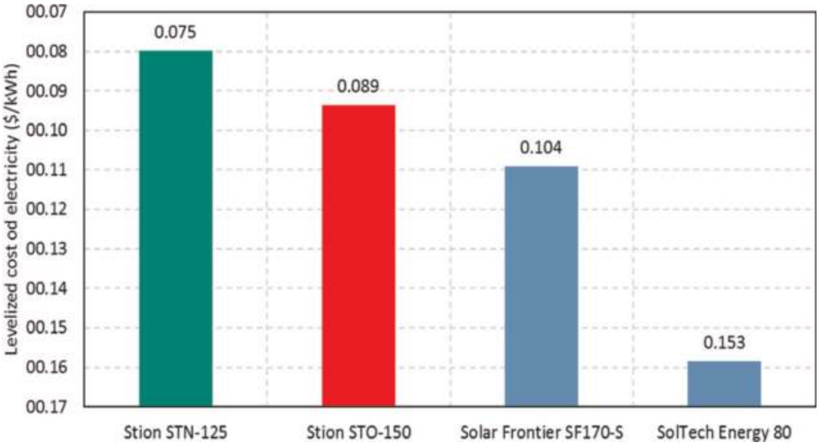

Figure 4.
The levelized cost of electricity of different brands of thin-film module at working conditions of Padiham, UK.

Table 5 shows the comparison between two different thin-film PV module brands that are installed on the roof of the building and installed on the southern façade. As shown, modules that are installed on the roof can generate up to 31% more annual electricity as compared with the same modules installed on the façade. This can be attributed to the fact that a module on the rood receives more solar energy than a module installed on the façade. On the other hand, the greater solar radiation on the roof makes the temperature of modules that are installed on the roof slightly higher. Consequently, the average annual efficiency of the system installed on the façade will be slightly higher. However, the abundant amount of the solar energy on the roof, as compared with the façade, overcomes the improvement in the efficiency. So, as it was expected, installing a PV system on the roof is better than on the southern wall.

6.2 Polycrystalline module type

In this section, a comparison between 13 different brands of the polycrystalline PV module is presented. Recall that the selected brands were chosen based on the report prepared by Fraunhofer Institute for Solar Energy Systems, ISE [5].

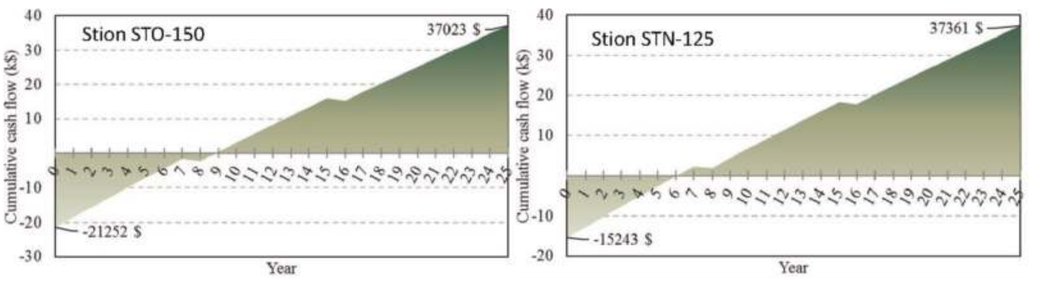

Figure 5.
Accumulative cash flow of Stion STO-150 (on the left) and Stion STN-125 (on the right) at the current conditions in the UK.

Brand	Annual elect. (kWh/m^2)	Annual efficiency (%)	LCOE (¢/kWh)	Initial cost ($/100 m^2)	Payback time (year)
Stion STO-150	151	11.7	8.9	21,252	9
Stion STN-125	134	10.4	7.5	15,243	6
Difference	12%	13%	19%	39%	50%

Table 4.
Comparing two thin-film modules of best energy and best economic performance.

	Annual elect. (kWh/m^2)			Avg. annual efficiency (%)			LCOE (¢/kWh)		
	Roof	Facade	Difference (%)	Roof	Facade	Difference (%)	Roof	Facade	Difference (%)
Stion STO-150	151	115	31	11.7	11.8	−1	8.9	11.6	23
Stion STN-125	134	103	30	10.4	10.6	−2	7.5	9.8	23

Table 5.
Comparison between installing modules on the roof and on the south-facing façade.

The annual electrical output per square meter of different brands of polycrystalline that are installed on the roof is illustrated in **Figure 6**. As shown, the annual electrical output per square meter of selected modules varies from a minimum of 162 to a maximum of 215 kWh/m^2 y. The optimal slope angle of the module was found to be 48° facing south.

As expected, simulations show that the efficiency of the polycrystalline PV modules during colder months is higher than those during the warmer months. The PV module voltage reduction causes efficiency reduction due to increasing the operating temperature of the module. **Figure 7** shows that the efficiency of polycrystalline PV module ranged from 11.7% (Kyocera KD220GH-4FB2 in August) to 17.6% (Hanwha Solar One 310 in February).

Hence, from the energy viewpoint, Hanwha Solar One 310 module seems to be the best among the considered polycrystalline module brands.

In order to compare the different brands from the economic point of view, the levelized cost of electricity and the accumulative cash flow were determined for

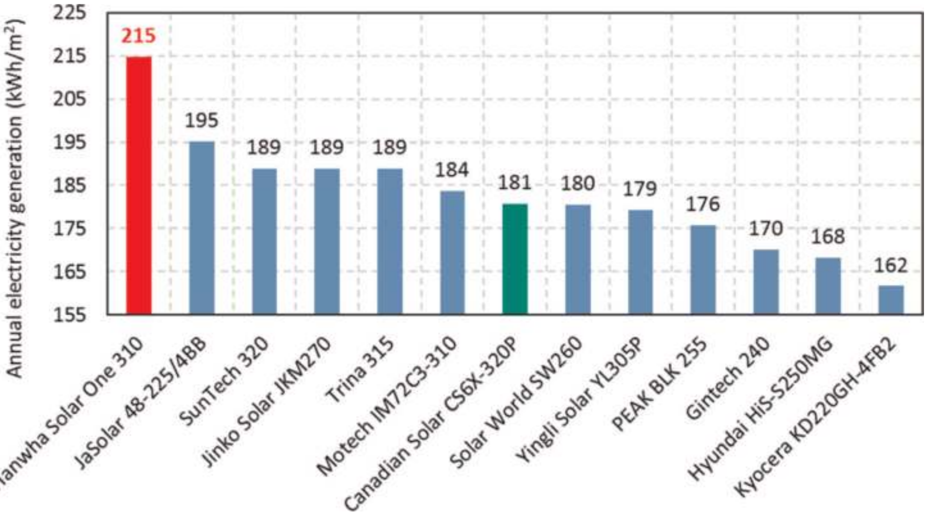

Figure 6.
Electrical output per square meter of polycrystalline PV module installed on the roof. The optimal slope angle of the module was found to be 48 facing south.

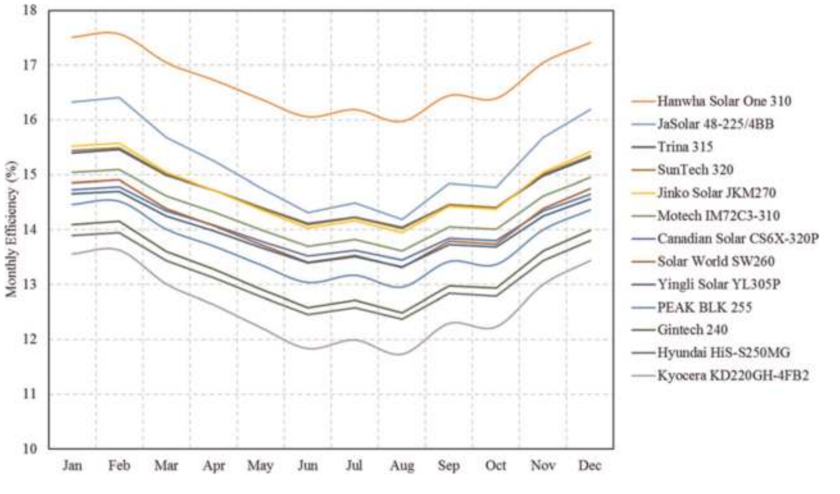

Figure 7.
Monthly average efficiency of different brands of the polycrystalline module at working conditions of Padiham, UK.

each brand taking into account the assumptions shown in **Table 3**. As shown in **Figure 8**, the levelized cost of electricity varies from a minimum of 7.8 (Canadian Solar CS6X-320P) to a maximum of 12.1 ₵/kWh (Kyocera KD220GH-4FB2).

Figure 9 shows the levelized cost of electricity versus the annual electricity generation per square meter of different polycrystalline brands. One can say that the annual electricity generation and levelized cost of electricity are somehow contradicting. As shown the Hanwha Solar One 310 seems to be the best from annual electricity generation viewpoint, while Canadian Solar CS6X-320P seems to be the best from levelized cost of electricity viewpoint.

Figure 10 shows the accumulative cash flow of Hanwha Solar One 310 (of the best energy performance) and Canadian Solar CS6X-320P (of the best economic performance). Apparently, the installation cost of Hanwha Solar One 310 is 61% more than the initial cost of Canadian Solar CS6X-320P for the same available area of PV cells (which is in our case assumed 100 m^2). In another word, by using Hanwha Solar One 310, the annual electricity is increased by 19%, and the initial cost of such system is increased by 61% in comparison to Canadian Solar

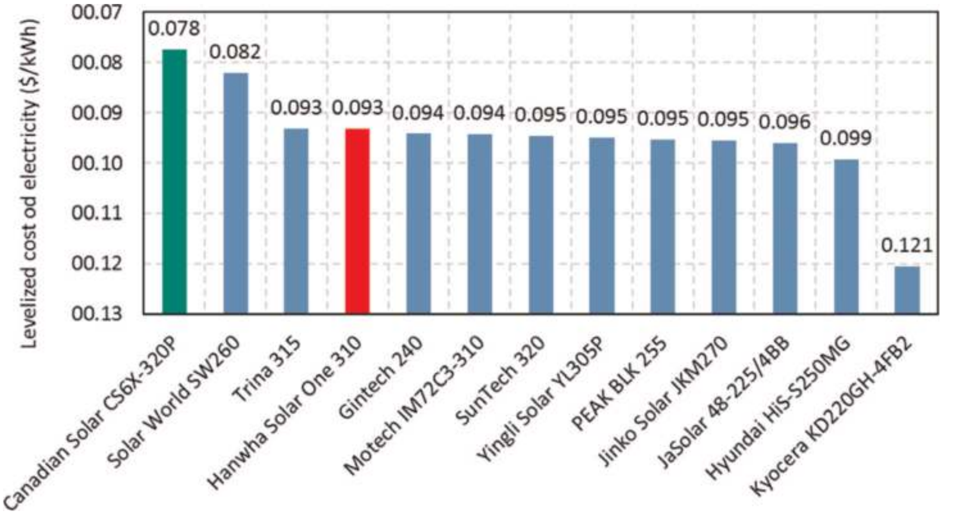

Figure 8.
The levelized cost of electricity of different brands of the polycrystalline module at working conditions of Padiham, UK.

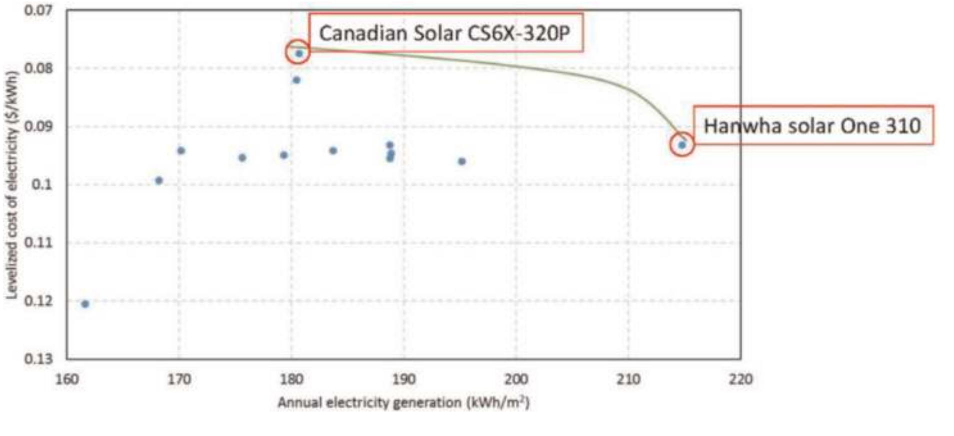

Figure 9.
The levelized cost of electricity versus annual electricity generation per square meter of different brands of the polycrystalline module at working conditions of Padiham, UK.

CS6X-320P (see **Table 6**). Hence, the preference of the decision-maker should be considered in order to select a suitable PV brand.

In order to investigate the potential of installing polycrystalline PV modules on the south-facing façade, the analyses were repeated for the modules installed on south-facing façade. The simulations show that a similar conclusion can be drawn with regard to modules installed on the roof. Namely, in the case of installing PV cell on the south-facing façade, among the considered brand (see **Table 1**), the best polycrystalline brand from energy viewpoint is Hanwha Solar One 310, while Canadian Solar CS6X-320P seems to be the best brand from the economic viewpoint. **Table 7** shows the comparison between the two different polycrystalline PV module brands installed on the roof of the building and installed on the south-facing façade. As shown, modules which are installed on the roof can generate 29–30% more electricity per year. This is due to the fact that the roof module receives more solar energy compared to the façade. Still, the temperature of modules installed on

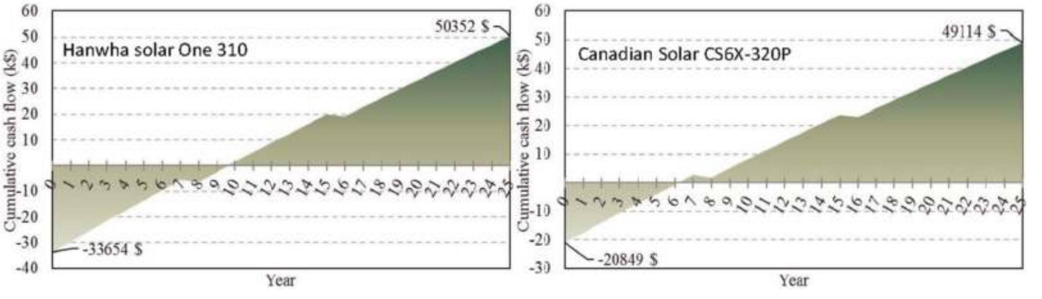

Figure 10.
Accumulative cash flow of Hanwha solar one 310 (on the left) and Canadian solar CS6X-320P (on the right) at the current conditions in the UK.

	Annual electricity (kWh/m^2)	Avg. annual efficiency (%)	LCOE (₵/kWh)	Initial cost ($/100 m^2)	Payback time (year)
Hanwha Solar One 310	215	16.7	9.3	33,654	9.8
Canadian Solar CS6X-320P	181	14.0	7.8	20,849	6.2
difference	19%	19%	19%	61%	58%

Table 6.
Comparing two polycrystalline modules of best energy and economic performance.

	Annual elect. (kWh/m^2)			Avg. annual efficiency (%)			LCOE (₵/kWh)		
	Roof	Facade	Difference (%)	Roof	Facade	Difference (%)	Roof	Facade	Difference (%)
Hanwha Solar One 310	215	166	30	16.7	17	−2	9.3	12.1	−23
Canadian Solar CS6X-320P	181	140	29	14.0	14.3	−2	7.8	10.0	−22

Table 7.
Comparison between installing modules on the roof and on the south-facing façade.

the roof will be slightly higher; the average annual efficiency of the system installed on façade will be slightly higher (**Table 7**). However, the improvement in efficiency due to the temperature effect on the façade system can be neglected as compared to the increased electricity output of the rooftop system.

6.3 Monocrystalline module type

In this section a comparison between 13 different brands of monocrystalline mentioned in the report prepared by Fraunhofer Institute for Solar Energy Systems, ISE, is shown [5].

Figure 11 illustrates the annual electrical output per square meter of different brands of monocrystalline installed on the roof. As shown, the annual electrical output per square meter of the selected modules varies from a minimum of 175 to a maximum of 226 kWh/m^2 y. The optimal slope angle of the module was found to be 48^o facing the south. Thus, from the energy viewpoint, Motech XS72D3-320 module seems to be the best among the considered monocrystalline module brands.

As expected, simulations show that the efficiency of the monocrystalline PV modules during colder months is higher than those during the warmer months. The PV module voltage reduction causes efficiency reduction due to increasing the operating temperature of the module. **Figure 12** shows that the efficiency of monocrystalline PV module ranged from 12.9% (Mitsubishi PV-MLE265HD2 in August) to 18.6% (Motech XS72D3-320 in February).

In order to compare the different brands from the economic point of view, the levelized cost of electricity was calculated for each brand. The economic analyses were carried out taking into account the assumptions shown in **Table 3**. Results illustrations in **Figure 13** shows that the levelized cost of electricity varies from a minimum of 7.5 (Solar World SW325 XL) to a maximum of 12.2 ₵/kWh (Panasonic N330).

Figure 14 shows the levelized cost of electricity versus the annual electricity generation per square meter of different monocrystalline brands. As shown, the annual electricity generation and levelized cost of electricity are somehow contradicting. Apparently, among the considered monocrystalline brands, Motech

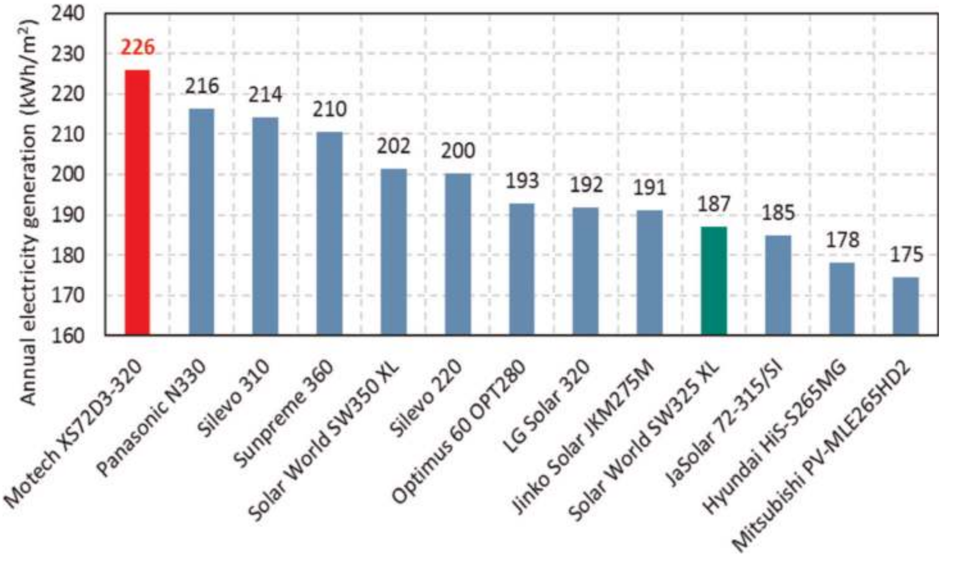

Figure 11.
Electrical output per square meter of monocrystalline PV module installed on the roof. The optimal slope angle of the module was found to be 48° facing the south.

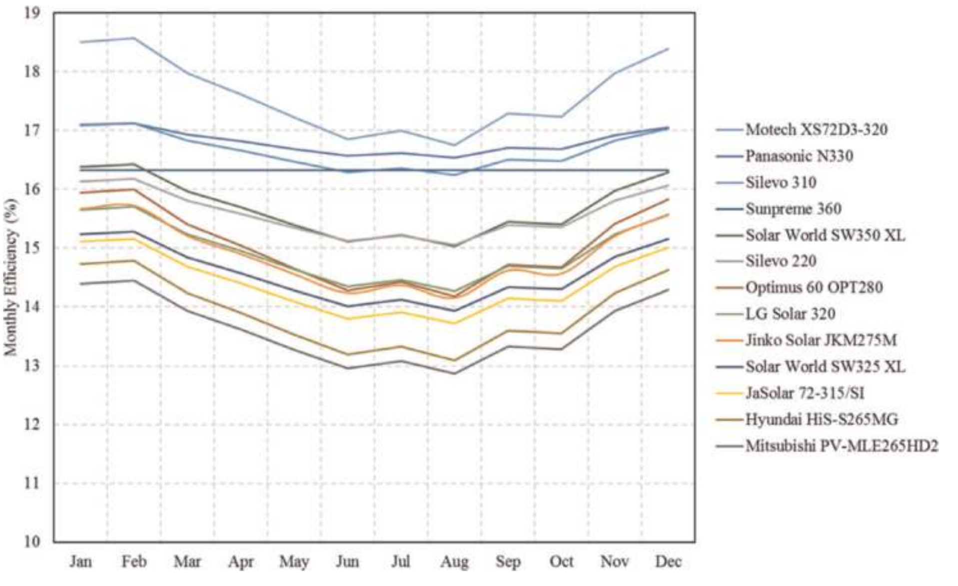

Figure 12.
Monthly average efficiency of different brands of the monocrystalline module at working conditions of Padiham, UK.

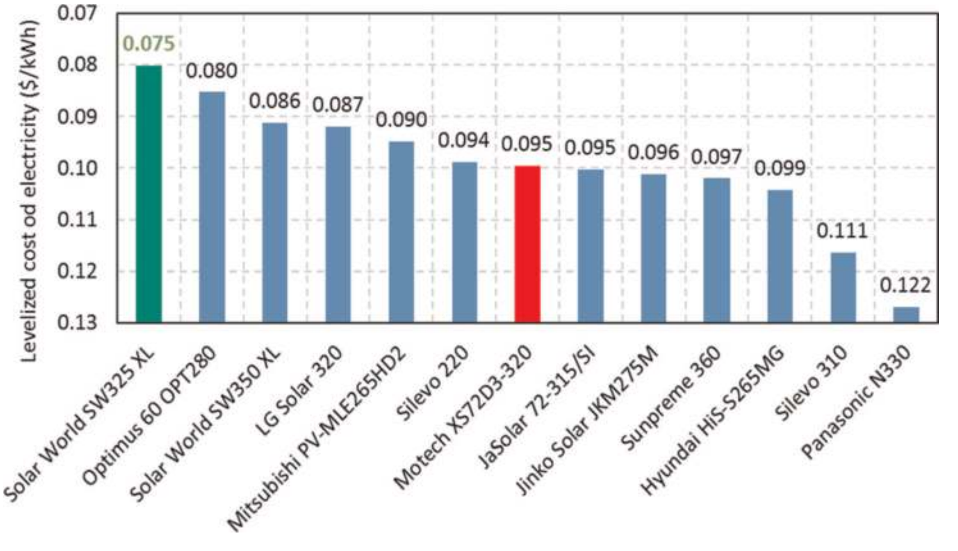

Figure 13.
The levelized cost of electricity of different brands of the monocrystalline module at working conditions of Padiham, UK.

XS72D3-320 and Solar World SW325 XL are the best from annual electricity generation and levelized cost of electricity, respectively.

Figure 15 shows the accumulative cash flow of Motech XS72D3-320 (of the best energy performance) and Solar World SW325 XL (of the best economic performance). Obviously, the installation cost of Motech XS72D3-320 is 71% more than the initial cost of Solar World SW325 XL for the same available area of PV cells (which is in our case assumed to be 100 m^2).

In another word, as shown in **Table 8**, comparing to Solar World SW325 XL, using Motech XS72D3-320 results in increasing the annual electricity by 21% (positive), while the initial cost of such system is 71% higher (negative). Hence, the preference of the decision-maker should be considered in order to choose the most suitable PV brand.

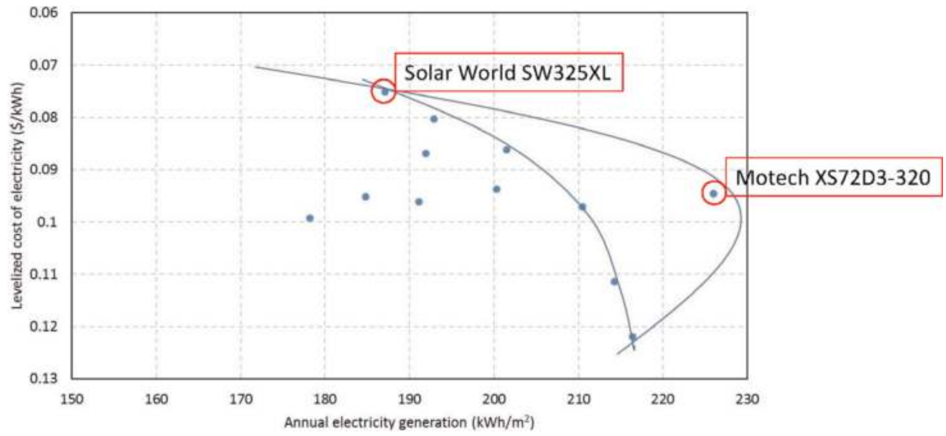

Figure 14.
The levelized cost of electricity versus annual electricity generation per square meter of different brands of the monocrystalline module at working conditions of Padiham.

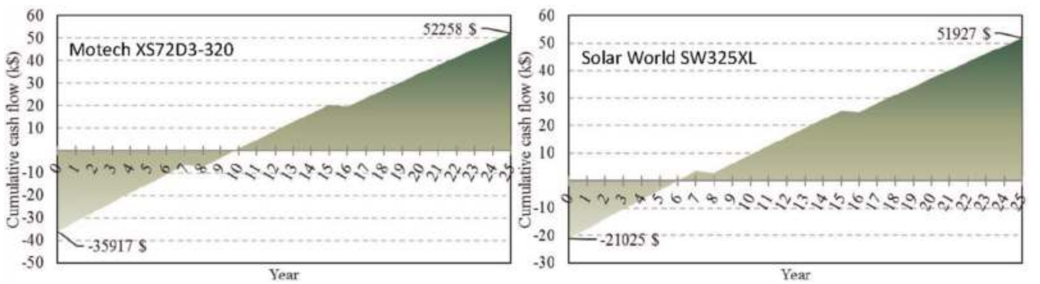

Figure 15.
Accumulative cash flow of Motech XS72D3-320 (on the left) and solar world SW325 XL (on the right) at the current conditions in the UK.

	Annual elect. (kWh/m^2)	Annual efficiency (%)	LCOE (₵/kWh)	Initial cost ($\$/100\ m^2$)	Payback time (year)
Motech XS72D3-320	226	17.5	9.5	35,917	9.9
Solar World SW325 XL	187	14.5	7.5	21,025	6
Difference	21%	21%	27%	71%	65%

Table 8.
Comparing two monocrystalline modules of best energy and economic performance.

In order to investigate the potential of installing a PV system on the south-facing façade, the analyses were repeated for the module installed on the southern façade. The simulations which show the same conclusions from the modules' installation on the roof can be drawn. Namely, in the case of installing PV cell on the south-facing façade, among the considered brands (see **Table 1**), the best monocrystalline brand from energy viewpoint is Motech XS72D3-320, while Solar World SW325 XL seems to be the best brand from the economic viewpoint. **Table 9** shows the comparison between the two different monocrystalline PV module brands installed on the roof of the building or installed on the southern façade. Because the rooftop modules receive more solar radiation than those installed on the façade, the rooftop system generates 29–30% more electricity per year. More solar energy leads to higher module temperature, and consequently, the average annual efficiency of the system installed on the façade will be slightly higher. However, the difference in efficiency can be neglected as compared to the improved electricity output of the rooftop system.

6.4 Monocrystalline vs. polycrystalline vs. thin film

Figure 16 illustrates the results of the above simulations. The brands of the best energy performance and of the best economic performance for each module type have been specified. From the energy viewpoint, Motech XS72D3-320, Hanwha

	Annual elect. (kWh/m^2)			Avg. annual efficiency (%)			LCOE (₵/kWh)		
	Roof	Facade	Difference (%)	Roof	Facade	Difference (%)	Roof	Facade	Difference (%)
Motech XS72D3-320	226	175	29	17.5	17.9	−2	9.5	12.2	−22
Solar World SW325 XL	187	144	30	14.5	14.8	−2	7.5	9.7	−23

Table 9.
Comparison between installing modules on the roof and on the south-facing façade.

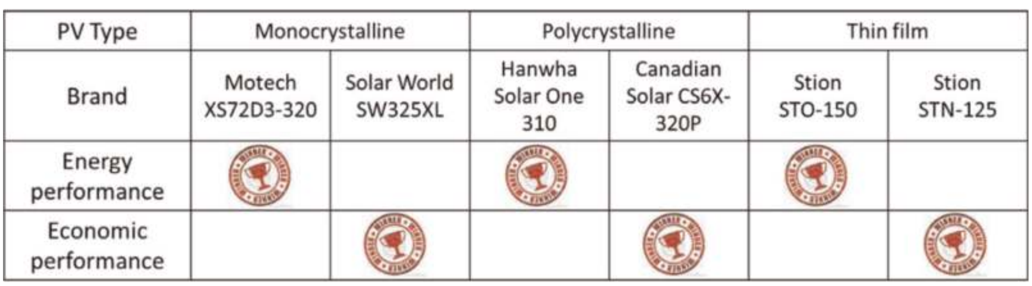

Figure 16.
The best brands of the best economic and the best energy performance for each module type.

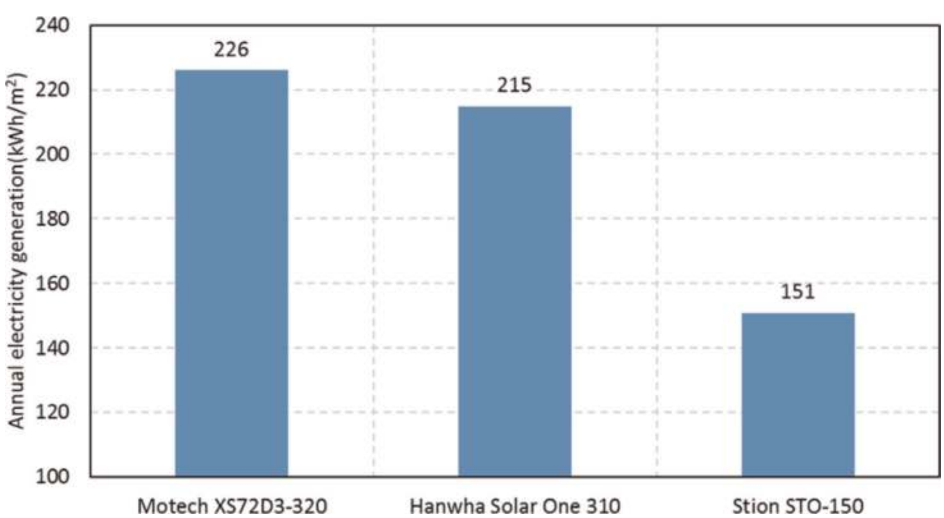

Figure 17.
Energy comparison between different modules of the best energy output.

Solar One 310, and Stion STO-150 represent the best brands for monocrystalline, polycrystalline, and thin film, respectively. While from the economic viewpoint, Solar World SW325XL, Canadian Solar CS6X-320P, and Stion STN-125 represent the best brand for monocrystalline, polycrystalline, and thin film, respectively. Hence, we do see a typical trade-off phenomenon between the environmental/ energetic and the economic performance.

Figure 17 shows the comparison between electricity generation of Motech XS72D3-320, Hanwha Solar One 310, and Stion STO-150, which represent the best brands from an energy viewpoint for monocrystalline, polycrystalline, and thin film, respectively. As shown:

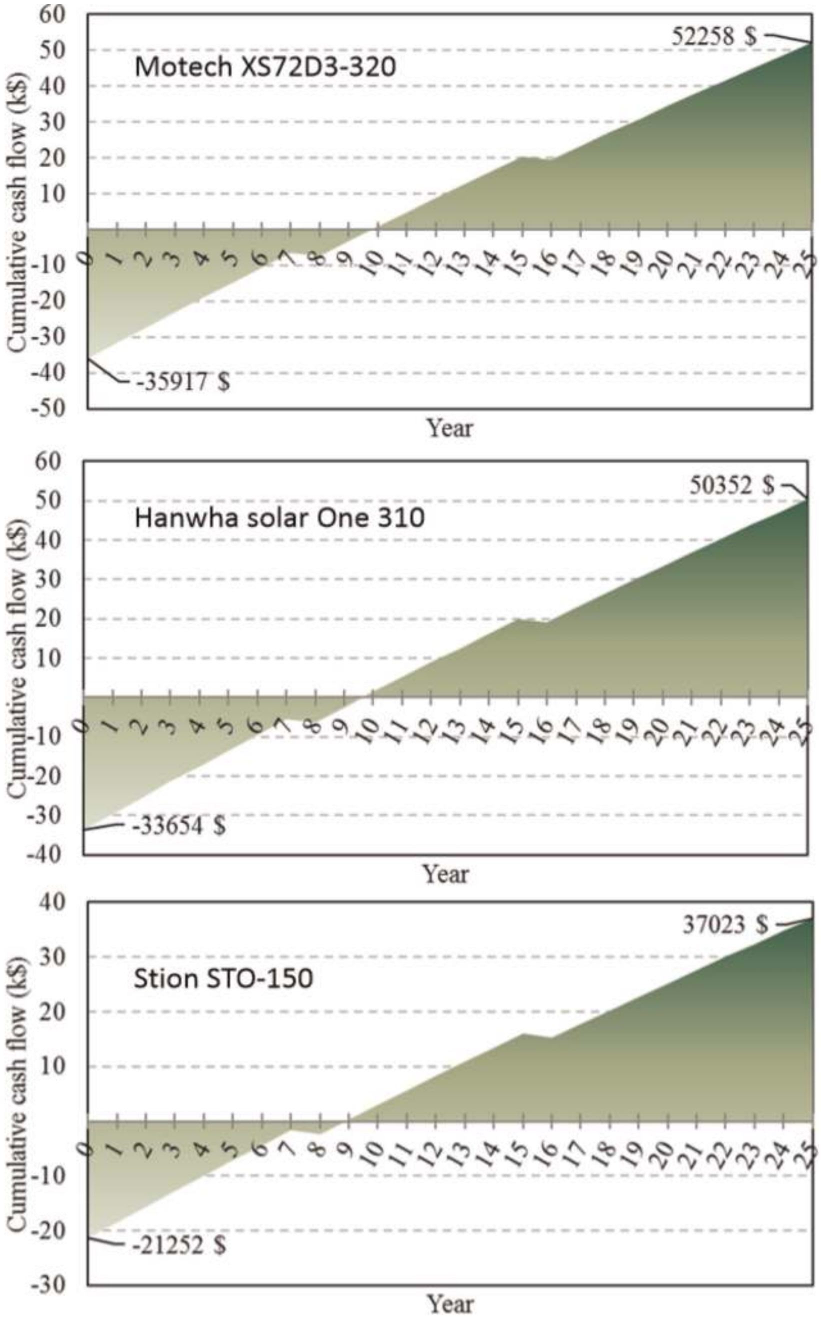

Figure 18.
Economic comparison between different modules of the best energy output.

- Monocrystalline can give 5% more annual electricity than polycrystalline.
- Monocrystalline can give 50% more annual electricity than thin-film module.
- The polycrystalline module can give 42% more annual electricity than thin-film module.

From the economic viewpoint, it seems that the thin-film module has the best economic performance (see **Figure 18**).

Figure 19 shows the comparison between the accumulative cash flow of Solar World SW325XL, Canadian Solar CS6X-320P, and Stion STN-125, which represent

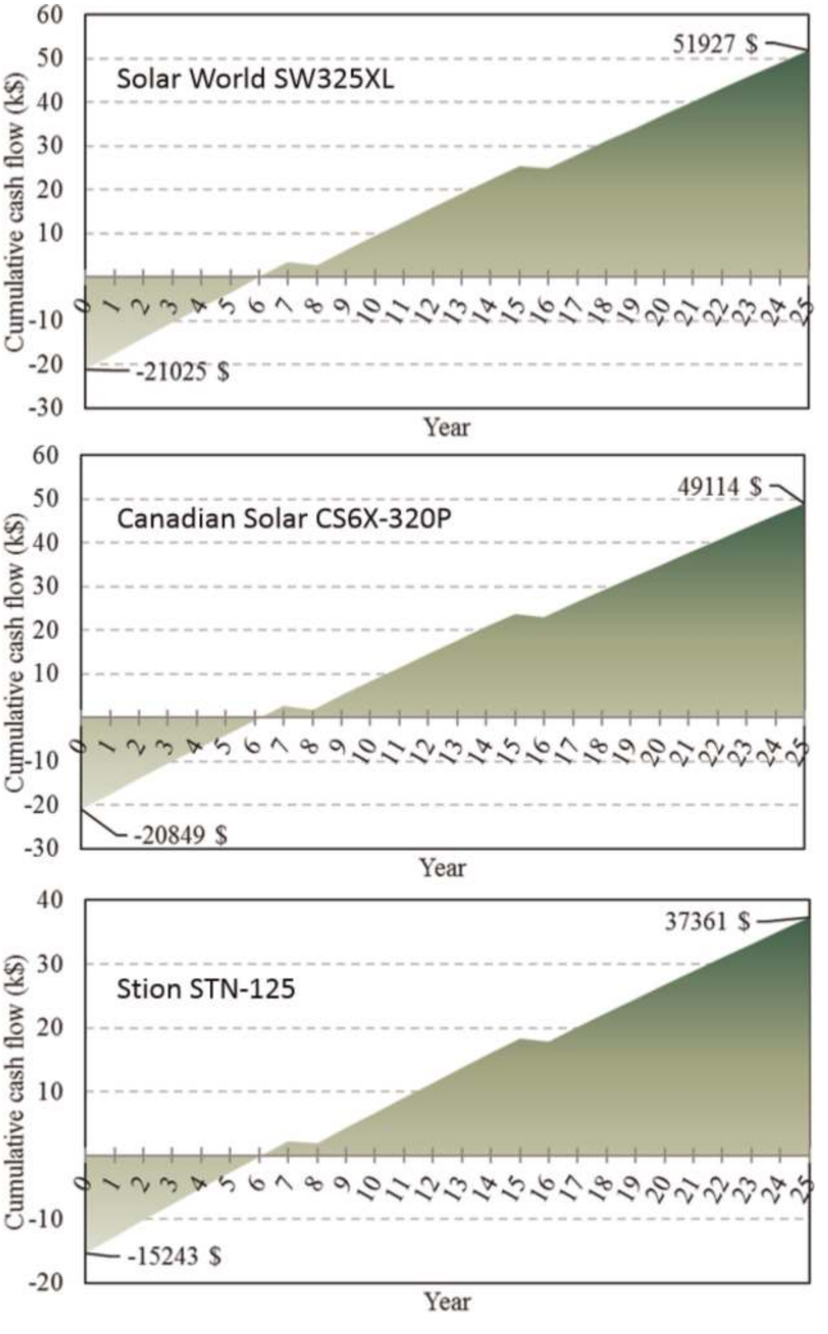

Figure 19.
Economic comparison between different modules of the best economic performance.

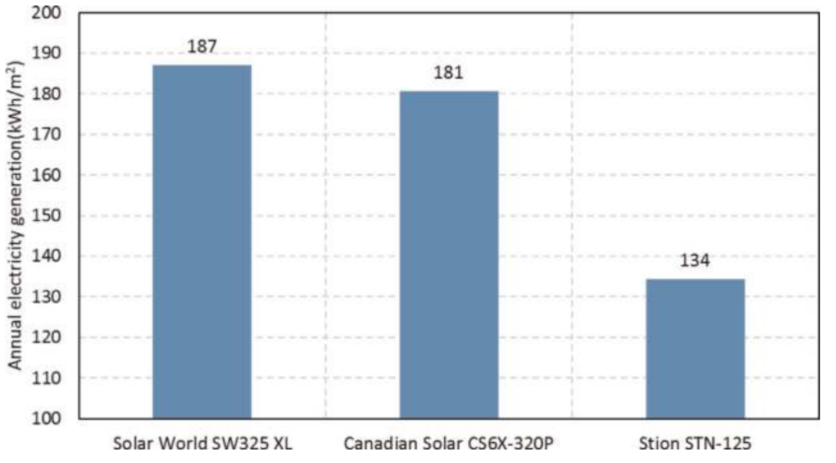

Figure 20.
Energy comparison between different modules of the best economic performance.

the best brands from the economic viewpoint for monocrystalline, polycrystalline, and thin film, respectively. As shown:

- Monocrystalline can give electricity at 3% cheaper than polycrystalline.
- A thin film can give electricity at 2% cheaper than monocrystalline module.
- A thin film can give electricity at 5% cheaper than polycrystalline module.

However, from the energy viewpoint, it seems that the monocrystalline module has the best economic performance (see **Figure 20**).

7. Conclusion

The current work investigates the potential of a grid-connected PV system under the meteorological and working conditions of Padiham (53.5 N, 2.3 W), UK. The obtained results present a comparison between different PV modules types, including thin film, polycrystalline and monocrystalline. Different brands of each type were considered in this work. The brands (**Table 1**) were chosen based on the report prepared by the Fraunhofer Institute for Solar Energy Systems, ISE [11]. An excel-based model was developed to simulate the economic and energy performance of the proposed system. The model was used to define the optimal slope angle of the module. Besides, the best module type and brand from energy and economic performance are specified.

Under the considered working conditions in the UK, simulations show that:

- There is a big potential to use a grid-connected PV system.
- Up to 226 kWh/y can be generated per square meter of such system.
- The initial cost of the system ranged from $15,000 (thin film) to $36,000 (monocrystalline).
- Initial cost per installed capacity is:

- 1.54 $/W thin-film-based system
- 1.84 $/W monocrystalline-based system
- The payback time of the systems varies from 6 to 10 years.

Another important conclusion that can be drawn from the results achieved in this work is that the energy and economic performance of a PV module are contradicting. In other words, for each module type, the brand that shows the best energy performance is not the same brand of the best economic performance. Therefore, the preference of the decision-maker should be considered as an essential factor before choosing the PV type and brand.

Comparing the results from different module types and brands show that:

- Motech XS72D3-320 which is a monocrystalline module shows the best energy performance compared to other monocrystalline brands, while Solar World SW325XL shows the best economic performance.
- Regarding polycrystalline module type, among the considered brands, Hanwha Solar One 310 and Canadian Solar CS6X-320P show the best energy and economic performance, respectively.
- Among the selected thin-film module brands, Stion STO-150 shows the best energy performance, while Stion STN-125 shows the best economic performance.

Finally, simulations indicate that monocrystalline module type shows the best energy performance, while thin-film module type shows the best economic performance at the current conditions in the UK.

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