Energy assessment and economic sensitivity analysis of a grid-connected photovoltaic system

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Abstract

This paper presents techno-economic assessment results of a grid-connected photovoltaic (PV) system for domestic building application. The PV system electricity output, energy conversion efficiency and cell temperature are explored based on the local weather condition, the system life cycle cost is evaluated with full account of the life of assets, volatile economic fluctuations, uncertainty influence factors, net present value (NPV) and discounted payback period (DPP) under Feed-in Tariff (FiT) scheme, the annual savings and payback time are compared for the FiT and new Smart Export Guarantee (SEG) schemes. Technical analysis results indicate that the system is capable of fulfilling the building electrical energy demand from April to October, and the extra electricity of 1530.23 kWh is exported to the grid in this period. The life cycle cost assessment results illustrate that the system achieves a NPV of £1335.32 and has a DPP of 9.34 years under the FiT scheme. Moreover, the sensitive analyses reveal that the high discount rate decreases the system NPV whereas the high initial cost leads to long payback period to realize the positive NPV. Furthermore, the FiT is the most cost-effective solution for PV system and has the shortest DPP compared with the SEG.

Keywords: Techno-economic assessment, Photovoltaic system, Economic sensitivity analysis, Feed-in Tariff, Smart Export Guarantee

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1. Introduction

Electricity plays a significant role in economic development, it is reported that approximately 20% of the global energy consumption is in form of electricity produced by fossil fuels [1], which leads to huge greenhouse gas (GHG) emission. There are various goals for reducing GHG emission in energy consumption sector, for example, the Europe 2030 program aim is to decrease nearly 40% GHG [2], the UK government has established the target to reduce 80% GHG by the year 2050 compared to the 2010 level's [3, 4]. The application of renewable energy resources can alleviate GHG and improve energy security through diversification of its supply [5-7]. Solar energy is the most abundant renewable energy resource with the potential to meet a significant proportion of building electricity demand. In order to improve energy generation from renewable energy source, solar photovoltaics (PV) modules have been wildly utilized to produce electricity for building application [8-10]. In domestic building aspect, the PV systems are supported by the UK government incentive measures like the Feed-in tariff (FiT), Export tariff (ET), financial support for installation expenses and decreased tax [11, 12]. Typically, a PV module can be connected into the grid that is referred to as grid-connected system, or it can be a stand-alone system mainly known as off-grid system. Currently, most residential buildings adopt the grid-connected system because of simple installation without a battery system, the varying domestic electricity demands can be fulfilled by either purchasing from the power grid when the system generates less energy compared to the building electricity need or selling extra electricity to the power grid when the system provides more energy in excess of the building electricity demand.

Many researches have been carried out to investigate the PV system performance and PV cell temperature influence. The nonlinear characteristics of PV cell parameters including the maximum voltage and current, short circuit current, diode saturation current, open circuit voltage, photocurrent, shunt conductance as well as series resistance are extracted to assess the PV module performance. Osma-Pinto G and Ordóñez-Plata G [13] established a green roof integrated photovoltaics system to investigate the effects of air velocity, type of roof and height of installation on PV electricity production in Colombia. It is found that concrete roof slightly increases the surrounding air temperature up to 100 cm above the surface. Meanwhile, it can produce up to 1.3 ± 0.4% more energy compared to a concrete roof with a PV panel installed at height between 50 and 75cm on a green roof. Moreover, when the air velocity is in the range of 0 to 2.1 m/s, the PV panel can generate about 2.0 ± 0.4% more energy. Mateus et al. [14] studied a PV system energy performance for a detached family house to realize nearly Zero Energy Building in Portugal, and demonstrated that the PV system is able to fulfil the building energy demands for heating, ventilation and air conditioning and domestic hot water. Nordin and Rahman [15] proposed an innovative optimization approach for sizing PV system by means of the PVSYST V6.10 software, and found that 10 units of 140Wp PV module are capable of providing 2.215 kWh heating need. Fares and Bicer [16] developed a thermodynamic modelling of the PV cell to compare the exergy efficiency between anti-soiling coated and uncoated. Their results conclude that the anti-soiling coated PV cells have higher exergy and energy efficiencies in comparison with the uncoated PV panels for different types of material. Cuce et al. [17] set up a novel mathematical model of PV module to estimate the system energy efficiency and PV cell temperature, and found that the system efficiency rises with incident solar intensity, in the meantime, the shunt resistance is highly sensitive to the PV cell temperature. Kim and Choi [18] presented an innovative extracting parameter approach for the PV module, which is used to establish a precise solar cell simulator and evaluate the ideality factor features of the diode obtained from the cell current-voltage curve. Humada et al. [19] developed single and double diode models to assess the system performance and parameter potential influences on the current–voltage (I-V) and power–voltage (P-V) curve features. Lin et al. [20] gave a revised simplified swarm optimization (MSSO) algorithm for single and double diode models to extract the cell parameters accurately and efficiently, their results demonstrate that the MSSO has the best performance among these approaches with regards to efficiency and accuracy. Simola et al. [21] analysed electricity generation of a PV system installed at a grocery store in Finland, and concluded that the system not only fulfils the store electricity consumption but also exports the additional electricity to the grid in June. However, in October, the system is not capable of producing enough electricity to cover the store power consumption owing to low solar radiation.

The financial analyses of solar PV system have been investigated extensively in the fields of industry and academia. Several studies have been performed to predict the PV system return on investment (ROI) via the life cycle cost (LCC) and levelized cost of heat (LCOH) methods in different regions. Nordin and Rahman [15, 22] carried out a LCC assessment for a stand-alone PV system to fulfil energy requirement at the lowest initial cost in Malaysia, their results reveal that the optimal system has the lowest initial investment cost of about RM 20752.28 and the levelized cost of energy (LCOE) of around 1.12/kWh. McKenna et al. [23] developed an economic approach to determine the PV self-consumption for a family house in the UK, and concluded that 45% electricity requirement can be met by the installed system, resulting in an electricity expense saving of about £138/household per annum. Muhammad-Sukki et al. [24] conducted an economic study of the PV system for residential building in Japan, where it is denoted less time is required in Japan for ROI (7.70 years) compared to the UK (9.80 years) and Germany (12.32 years). Korsavi et al. [25] studied economic performance of 14 rooftop PV systems with the power of 5 kW in Iran, and concluded that the mean PBP is 11.6 years when the actual price of electricity is $ 0.21 whereas it is in the range from 46.9 to 50.5 years when the subsidized average tariffs are considered. Ozcan et al. [26] carried out a techno-economic assessment of PV system under 30 years lifetime, and obtained that the electricity output is in the range of 3913.84 kWh to 4323.94 kWh, and the discounted payback period is less than 7 years.

The main novelty of this paper is applying the techno-economic assessment methodology for the PV system with full consideration of the life of assets, volatile economic changes, uncertainty impact factors with regard to discount and interest rates, prospective maintenance cost, net present value (NPV) and discounted payback period (DPP) under the FiT scheme. Meanwhile, this paper also investigates the system 25 years' cumulative NPV for the domestic building application in the UK by employing the @Risk software. Several vital parameters like the initial expense (IE), system electrical energy expense (SEEE), mortgage payment (MP), maintenance and insurance expense (M&I), periodic expense (PE), income tax rate (ITR), present worth of money as well as cumulative PV system savings, are taken into account in the process of economic study under the FiT scheme. The DPP is attained by the SEEE and cumulative cash flows, the sensitivity analysis of economic model is achieved as well. Furthermore, the annual saving and payback time are compared for the FiT and new Smart Export Guarantee (SEG) schemes.

2. Techno-economic model of PV system

To evaluate the system technical and financial performance, the designing of the grid-connected PV system for a domestic building contains two parts. The first part is to establish PV model for the maximum power production, the second part is to perform the financial evaluation, including the calculations of NPV and DPP.

2.1 Mathematical model

2.1.1 PV model

The PV electricity output is utilized to meet the building's electrical energy requirement, the additional electricity is transferred into the power grid. After considering the influence of temperature, the monthly PV power output with an active area and a solar radiation incident on tilted PV module surface is written as follows:

$$P_{PV} = \eta_{PV} \cdot \eta_{inverter} \cdot A_{PV} \cdot \psi \cdot \frac{G}{G_{ref}}[1 + \psi_T (T_{cell} - T_{cell,ref})] \quad (1)$$

where P_{PV} is the PV power output (W); η_{PV} is the efficiency of PV module (%); $\eta_{inverter}$ is the efficiency of inverter (%); A_{PV} is the PV panel active area (m^2); ψ is the factor to consider the losses in the PV system; G is the total radiation incident on the plane of the PV array (W/m^2); G_{ref} is the incident radiation at standard reference condition (G_{ref} =1000W/m^2); ψ_T is the maximum power temperature coefficient (%/°C) which ranges between 0.3 and 0.5 %/°C [27]; T_{cell} and $T_{cell,ref}$ are the PV cell operating temperature (°C) and the reference temperature at standard test condition (STC) (25 °C), respectively.

$$\psi = \psi_{service,age} \cdot \psi_{external} \cdot \psi_{AC} \cdot \psi_{DC} \quad (2)$$

where $\psi_{service, age}$ is the derate factor to consider energy loss in the PV system due to age; $\psi_{external}$ is the derate factor to consider losses owing to exterior reasons such as snow cover, shading or anything else that would render the PV electricity production to deviate from the expected under ideal condition; ψ_{AC} is the AC interconnection derate factor with a value of 0.99 ; ψ_{DC} is the DC power derate factor (normal value of 0.955) including connection, diodes, module mismatch, DC wiring losses. In this study, the derate factor is treated as 0.9.

The PV cell operating temperature (T) is determined based on linear approximation as:

$$T = T_a + \frac{G}{0.8}(T_{cell,ref} - 20) \tag{3}$$

where T_a is the ambient temperature (°C);

The solar radiation incident on a tilted plane at an angle θ can be calculated as:

$$G = G_d[\cos(\theta) \cdot B \cdot \cos^2(\frac{\varphi}{2}) + \Gamma(\cos(\sigma) + B) \cdot \sin^2(\frac{\varphi}{2})] \tag{4}$$

where G_d is the radiation incident onto the plane of the PV array (W/m^2); B is the diffuse portion constant; Γ is the reflection index; σ is the zenith angle.

The angles θ, σ, φ can be expressed as follows [27]:

$$\cos(\theta) = [\cos(\varphi) \cdot \cos(\sigma) + \sin(\varphi) \cdot \sin(\sigma) \cdot \cos(\xi - \tau)] \tag{5}$$

$$\cos(\sigma) = \sin(\varsigma) \cdot \sin(\lambda) + \cos(\varsigma) \cdot \cos(\lambda) \cdot \cos(\alpha) \tag{6}$$

$$\tan(\xi) = \frac{\sin(\kappa)}{\sin(\lambda) \cdot \cos(\kappa) - \cos(\lambda) \cdot \tan(\psi)} \tag{7}$$

where ξ is the sun azimuth angle; τ is the plate azimuth angle; ς is the solar declination angle; λ is the latitude; κ is the solar angle which is determined by the following equations [27]:

$$\kappa = \frac{360}{24}(t_e - 2) \tag{8}$$

$$t_e = LST - EOT - 4L + 60t_z \tag{9}$$

where t_e is the solar time (day); LST is the local standard time; EOT is the equation of time to account for the irregularity of the earth speed around the sun; L is the longitude; t_z is the time zone.

2.1.2 One-diode mathematical model

A PV module composes of a number of solar cells connected in series, each cell is a p–n junction usually, which can directly convert solar energy into electrical energy. Fig. 1 gives the equivalent circuit including five parameters of PV module: photocurrent (I_p), diode reverse saturation current (I_D), shunt resistance (R_{sh}) and series resistance (R_s).

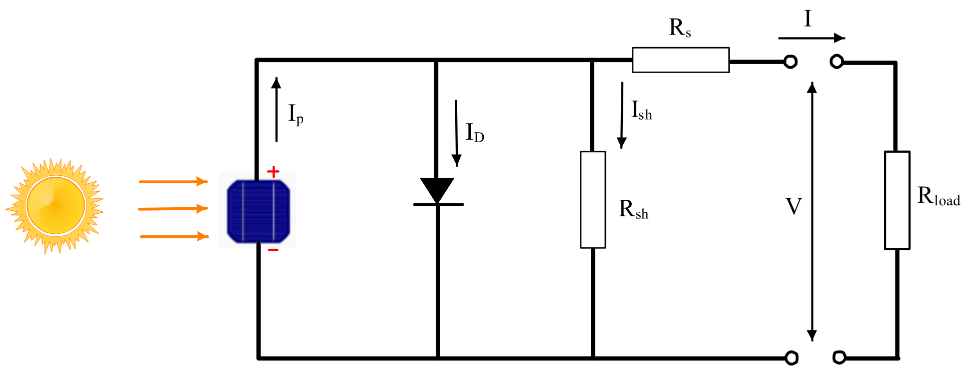

Fig. 1. Equivalent circuit for a PV cell

Following the work of McCormick [28] and Duffie [29], the PV current (I) is given as:

$$I = I_p - I_D - I_{sh} = I_L - I_o[\exp(\frac{V + I \cdot R_s}{\Theta N V_{th}}) - 1] - \frac{V + I \cdot R_s}{R_{sh}} \quad (10)$$

where I_p is the photocurrent in the standard test condition (STC) (A); I_D is the diode reverse saturation current (A); I_o is the diode reverse saturation current (A); V is the PV module voltage (V); I is the current generated by PV module (A); R_{sh} is the shunt resistance (Ω); R_s is the series resistance (Ω); Θ is the diode ideality factor (equal to 1.5); N is the number of PV cells in a PV module; V_{th} is the thermal equivalent voltage of a PV module (V) and given as:

$$V_{th} = \frac{kT_{cell}}{q} \quad (11)$$

where k is the Boltzmann's constant (1.381×10^{-23} J/K); q is the electron charge (1.602×10^{-19} coulomb); T_{cell} is the cell temperature (°C).

2.1.3 Parameter extraction model

The five unknown parameters (I_L, I_D, R_S, R_{SH}, Θ) are obtained based on the algebraic equations as follows:

At the open circuit (OC) point:

$$I_p = I_o[\exp(\frac{V_{oc}}{\Theta N V_{th}}) - 1] - \frac{V_{oc}}{R_{sh}} \quad (12)$$

where V_{oc} is the open circuit voltage (V).

At the short circuit (SC) point:

$$I_{sc} = I_p - I_o[\exp(\frac{q I_{sc} R_s}{\Theta N V_{th}}) - 1] - \frac{I_{sc} R_s}{R_{sh}} \quad (13)$$

I_{sc} is the short circuit current (A);

PV module current (I_{mpp}) at the maximum power point (MPP):

$$I_{mpp} = I_p - I_o[\exp(\frac{V_{mpp} + I_{mpp} R_s}{\Theta N V_{th}}) - 1] - \frac{I_{sc} R_s}{R_{sh}} \quad (14)$$

where V_{mpp} is voltage at MPP (V).

Besides Eqs. (12) - (14), the differential equation is established:

$$\frac{dV}{dI} = -R_s - \frac{\Theta N V_{th} R_{sh}}{\Theta N V_{th} + I_o R_{sh} \exp(\frac{V + IR_s}{\Theta N V_{th}})} \tag{15}$$

By substituting the value at the open circuit (V_{oc}, 0) point into Eq. (15), the following two equations are obtained [30-32]:

$$\left.\frac{dV}{dI}\right|_{I=0} = -R_s - \frac{\Theta N V_{th} R_{sh}}{\Theta N V_{th} + I_o R_{sh} \exp(\frac{V_{oc}}{\Theta N V_{th}})} \tag{16}$$

$$\left.\frac{dV}{dI}\right|_{V=0} = -R_s - \frac{\Theta N V_{th} R_{sh}}{\Theta N V_{th} + I_o R_{sh} \exp(\frac{I_{sc} R_s}{\Theta N V_{th}})} \tag{17}$$

By combining Eqs. (16) and (17), the parameter extraction equation at the short-circuit point is given as [30-32]:

$$\left.\frac{dI}{dV}\right|_{I=I_{sc}} = -\frac{1}{R_{sh}} = \frac{-\frac{1}{R_{sh}} - \frac{I_o}{\Theta N V_{th}} \exp(\frac{I_{sc} R_s}{\Theta N V_{th}})}{1 + \frac{R_s}{R_{sh}} + \frac{I_o R_s}{\Theta N V_{th}} \exp(\frac{I_{sc} R_s}{\Theta N V_{th}})} \tag{18}$$

Owing to the single peak feature of a PV module electricity production at STC condition, the value of the electricity output at the MPP is regarded as zero:

$$\left.\frac{dP}{dV}\right|_{P=P_{mpp}} = I_m + V_m \left.\frac{dI}{dV}\right|_{P=P_{mpp}} = 0 \tag{19}$$

By substituting the value at short circuit (0, I_{sc}) points into Eq. (18), it is given as [30-32]:

$$\left.\frac{dP}{dV}\right|_{P=P_{MPP}} = -\frac{I_m}{V_m} = \frac{-\frac{1}{R_{sh}} - \frac{I_o}{\Theta N V_{th}} \exp(\frac{V_{mpp} + I_{mpp} R_s}{\Theta N V_{th}})}{1 + \frac{R_s}{R_{sh}} + \frac{I_o R_s}{\Theta N V_{th}} \exp(\frac{V_{mpp} + I_{mpp} R_s}{\Theta N V_{th}})} \tag{20}$$

2.2 Economic assessment

The main novelty of this study is applying the techno-economic assessment methodology for the PV system with full account of the volatile economic changes, life of assets, uncertainty impact factors regarding discount and interest rates, as well as prospective maintenance cost and PP. In addition, the annual saving and income are studied and compared between the FiT and Smart Export Guarantee (SEG) schemes. To obtain an accurate analysis data, all system costs are kept up to date, as any variation could cause significant changes in the results. The total installed PV system cost involves the modules, inverter, support structure, electrical circuits and protections, the cables and structure anchor, as well as the mechanical and electrical installation costs, and value-added tax (VAT). According to the studies [15, 29, 33, 34], all of PV system components considered would have 25 years of lifespan except the inverter. To guarantee a positive rate of return (ROR) from the PV system, the inverter 5-year replacement is assumed based on the product specification [35]. Specifically, if the inverter is used over 5 years, there would be some failures, such as electro-mechanical wear on capacitors, over-current, over-voltage and ultrasonic vibrations, etc. These not only have direct influences on the system performance and the inverter thermal load, but also lead to the additional cost for maintenance during the operation period. Meanwhile, the same assumption condition is also applied in other researches [15, 29, 33, 34]. Furthermore, in order to attain the most optimal arrangement along with the lowest initial cost, it is necessary to implement life cycle cost (LCC) evaluation for assessing the feasibility of investment. Based on the International Standard of Environmental Management ISO 15686-5 [36, 37], the LCC refers to the systematic financial analysis of combined initial expense (IE), system electrical energy expense (SEEE), mortgage payment (MP), maintenance and insurance expenses (M&I), income tax saving (ITS), remaining debt principal (RDP) as well as periodic expense (PE) during the entire LCC period.

Therefore, the LCC is the summation of IE, SEEE, MP, M&I, ITS and PE in present value by using the following equation:

$$LCC = E_{IE} + E_{SEEE} + E_{MP} + E_{M\&I} + E_{ITS} + E_{PC} \tag{21}$$

where E_{IE} includes the expenses of PV array, installation, inverter, electrical meter and isolation switch (£); E_{SEEE} is the PV system electrical energy expense (£); E_{MP} is the yearly mortgage expense in present worth (£); $E_{M\&I}$ is the PV system maintenance and insurance expenses (£); E_{ITS} is the PV system income tax savings expense (£); E_{PE} is the PV system periodic expense (£).

The SEEE is regarded as the fuel expense saving which is calculated by the PV power production and electricity price. The annual SEEE is written as:

$$E_{SEEC} = e_{SEEC} \times \frac{1}{(1+d_{SEEE})^N} \tag{22}$$

$$e_{SEEE} = M_{used} \cdot \beta \tag{23}$$

where E_{SEEE} is the PV system energy expense (£); e_{SEEE} is the PV electricity expense per annum (£); d_{SEEE} is the inflation rate of electricity price (%); N is the lifetime of financial analysis; M_{used} is the PV electrical energy used for the household (kWh/year); β is the electricity price (£/kWh).

The mortgage payment (MP) consists of interest payment (IP) and payment of principal (POP), which can be expressed as:

$$E_{MP} = \Theta \times \frac{d_{MP} \cdot (1+d_{MP})^N}{(1+d_{MP})^N - 1} \tag{24}$$

where Θ is the POP (£); d_{MP} is the annual interest rate (%).

The yearly M&I involves expected, unexpected costs concerning repair and system corrective maintenance, can be given as:

$$E_{M\&I} = e_{M\&I} \times \frac{1}{(1+d_{M\&I})^N} \tag{25}$$

where $E_{M\&I}$ is the maintenance and insurance expense for each year (£); $e_{M\&I}$ is the maintenance and insurance expenses for the first year (£); $d_{M\&I}$ is the inflation rate of maintenance and insurance expenses (%).

The periodic expense (PE) means the replacement expense of the key components. In terms of the PV system, only the inverter is needed to be changed every 5 years [15, 29, 33, 34]. So the PE is written as:

$$E_{PE} = e_{PE} \times \frac{1}{(1+d_{PE})^{N}} \tag{26}$$

where E_{PE} is the inverter expense for each five years (£); e_{PE} is the inverter system PE for the first year (£); d_{PE} is the inflation rate of PE (%).

The $E_{PV\ system\ savings}$ is treated as the annualized net cash flow given as:

$$E_{PV\ system\ savings} = E_{SEEE} - E_{MP} - E_{M\&I} - E_{PE} - E_{EPT} + E_{ITS} \tag{27}$$

where E_{EPT} is the extra property tax (£); E_{ITS} is the income tax savings (£).

The E_{EPT} in present value is given as [29, 32]:

$$E_{EPT} = e_{EPT} \times \frac{1}{(1+d_{EPT})^{N}} \tag{28}$$

where e_{EPT} is the yearly system extra property tax expense (£); d_{EPT} is the inflation rate of extra property tax (%).

The E_{ITS} in present value is given by [29, 32]:

$$E_{ITS} = E_{ETR} \times (E_{IP} + E_{EPT} + E_{Subs}) \tag{29}$$

where E_{ETR} is the effective tax rate (%); E_{IP} is the interest payment (£); $E_{subsides}$ is the renewable electricity incentive for power production in the UK (£).

The NPV denotes the whole cash flow of the project in which a positive value means that the project is going to be profitable whereas a negative value will result in a net loss. The NPV is given as:

$$NPV = -E_{IE} + \sum_{N=1}^{N'} \frac{E_N}{(1+\gamma)^{N}} \tag{30}$$

where E_N is the net cash inflow during the period N (£); γ is the discount rate (%).

The discounted payback (DPP) period, shown in Eq. (31), is utilized to calculate the time required to recoup the fund expended in an investment.

$$DPP = X + \frac{Y}{Z} \tag{31}$$

where X is the last period with a negative discounted cumulative cash flow (£); Y is the absolute value of the discounted cumulative cash flow at the end of the period X (£); Z is the discounted cash flow during the period after X (£).

3. The PV system design

3.1 Building description

A semi-detached house is located in Nottingham, UK, which is situated 52.92° north latitude and 1.22° east longitude. It has three bedrooms with a total floor area of 117.18 m^2, the southern side of roof area is approximately 32.3 m^2 as shown in Fig. 2. The electricity usage is mainly for light bulbs, washing machine, fridge, TV set, computer and boiler.

Fig. 2. Photo of the semi-detached house in Nottingham, UK

According to Fig. 3, the monthly electricity consumption of the household for the period from 05/2017 to 04/2018 is based on the data from the electricity supplier. The largest electricity demand is about 531.57 kWh in December, however the lowest is approximately 70.42 kWh in June. The annual electricity energy consumption is 3743.02 kWh. Furthermore, it can be observed from Fig. 4 that in December there is only one high hourly electricity consumption period (from 17:00 to 24:00), while in June, there are two high hourly electricity consumption periods (one is from 7:00 to 10:00 and the other one is from 18:00 to 21:00).

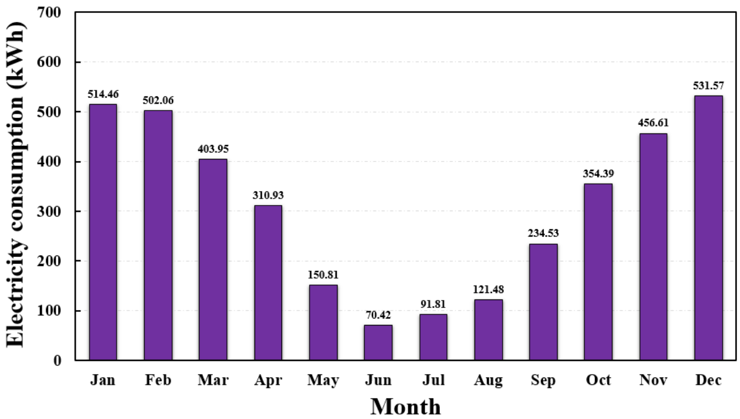

Fig. 3. Monthly building electrical energy consumption

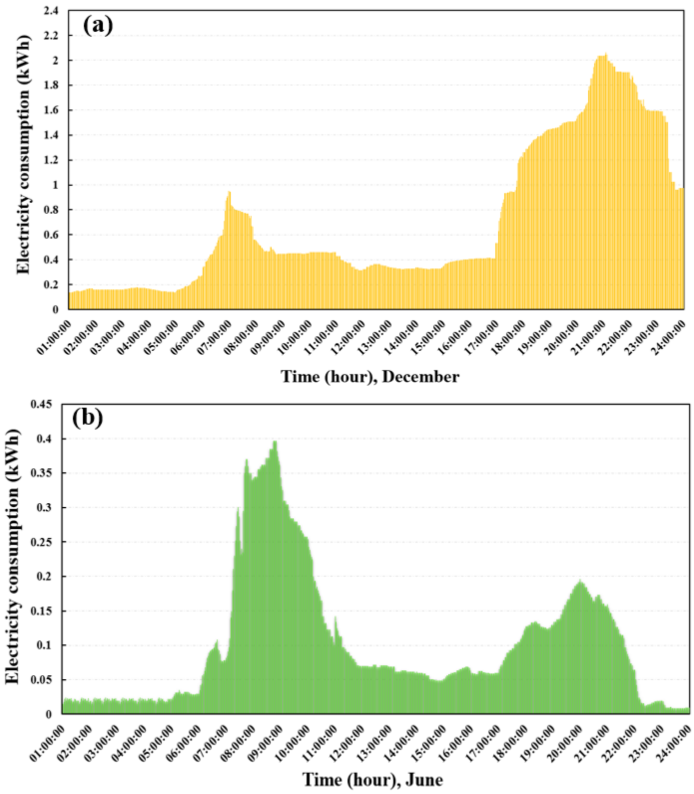

Fig. 4. Hourly building electrical energy consumption: (a) December; (b) June

3.2 Meteorological data

Meteorological data are essential for the accurate modelling of the PV system, the solar irradiation and ambient temperature are the main parameters to influence the PV system electrical energy production. The solar radiation data in this study is obtained by using the PVSYST 6.0.1 software that is primarily utilized for design, planning, sizing and analysis [38]. Table 1 presents the monthly mean global solar irradiation at the horizontal plane, ambient temperature and wind velocity in Nottingham, UK. To be more specific, the monthly average solar radiation is in the range from 14.79 kWh/m^2/ in December to 144.62 kWh/m^2/ in June [38, 39]. The highest ambient temperature is 18.41 °C in August whereas the lowest temperature is 5.28 °C in December. Furthermore, the wind velocity ranges from about 3.07 m/s to 4.49 m/s [40].

Table 1 Meteorological data in Nottingham, UK [39, 40]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Solar radiation (kWh/m^2/month)	19.30	32.81	69.16	100.01	133.74	144.62	139.84	120.39	85.58	51.31	25.19	14.79
Ambient air temperature (°C)	5.49	5.87	7.68	9.63	13.02	16.30	17.81	18.41	15.44	11.72	7.85	5.28
Wind speed (m/s)	4.30	4.49	3.92	3.77	3.89	3.71	3.47	3.07	3.37	3.88	3.52	3.89

3.3 PV system

12 (250Wp) ND-R250A5 photovoltaic solar panels from Sharp Company are utilized in the study based on the building electricity consumption, and are installed at a 25° tilt angle oriented to the south of the roof. The operational temperature of the PV modules ranges from -40 °C to 85 °C, the PV panels are coated with anti-reflex film to increase the light absorption. An inverter (Afore HNS3000TL) is choose to match the PV panel electricity output and its maximum DC and AC loads are 3200W and 3000W respectively. Moreover, the inverter is fit to translate 24 V DC electricity into 230 V AC [35]. Table 2 illustrates the PV panel parameters.

Table 2 PV module parameters [41]

Description	Value
PV Module	
Module dimensions (single)	1.652 × 0.994 × 0.046 m
Number of PV panels	12
Cell type	Poly-crystalline
Packing factor	0.92
Conversion efficiency	15.5%
Nominal maximum power	250 W
Maximum voltage	30.90 V
Maximum current	8.10 A
Open circuit voltage	37.60 V
Short circuit current	8.68 A
Exposed roof area and title angle	
Active total area	30 m^2
Title angle	25°

The IE of the PV system is around £3943 with 10% deposit. The remaining of the IE is paid at an interest rate of 8.2% in a period of 25 years. The M&I is regarded as being paid annually for the components of the system with an inflation rate of 4.5% [42]. Due to the operation time from 05/2017 to 04/2018, the FiT for renewable electricity generation is used to calculate the economic assessment [43]. Specifically, in terms of the FiT, the UK government subsidies include the generation tariff and export tariff. The generation tariff paid for all the electricity that a household generated. Rates are set by the government and depended on the size of solar PV system and when you signed up to the scheme. The export tariff paid homeowners for the surplus energy they exported to the grid. Rates are fixed by government for the entire contract term and are around the market rate for electricity. On the basis of the energy prices regulated by Ofgem [44] in the UK, the FiT price for domestic buildings is £0.1097/kWh whereas the export tariff price for feeding electricity into the power grid is £0.052/kWh [42]. The property tax is 2% of the IE whereas the M&I for the PV system is expected to be £80/year. The mean effective ITR is defined as 20% throughout the life cycle period. Table 3 descripts the M&I and main PV system expenses including for the PV array and inverter units. Details of the expenses, component prices and financial parameters are exhibited in Table 4.

Table 3 PV system expense breakdown

Item	Value
PV modules	£2273
Inverter	£370
Pipes and ducts	£300
Electrical meter and isolation switch	£200
Labour costs	£800
Total capital investment	**£3943**
Estimated M & I costs	£80

Table 4 Parameters utilized for financial analysis

Item	Value
Electrical price	Feed-in-tariff (building usage): £0.1097/kWh Export tariff (to the grid): £0.052/kWh
Deposit	10%
Inflation rate of electricity price	6%
Interest rate of POP	8.2%
Inflation rate of M&I	4.5%
Inflation rate of inverter price	3%
Council tax for property tax	2%
Inflation rate of EPT	4%
UK discount rate	8.75%
ITR	20%

4. Results and discussion

4.1 Validation of the model

Before analysing the PV system energy performance, the precision of the proposed numerical model within the scope of this research is validated via the experimental data, and the error is determined by Eq. (32).

$$\text{Error} = \left| \frac{PV_{numerical} - PV_{experimental}}{PV_{numerical}} \right| \tag{32}$$

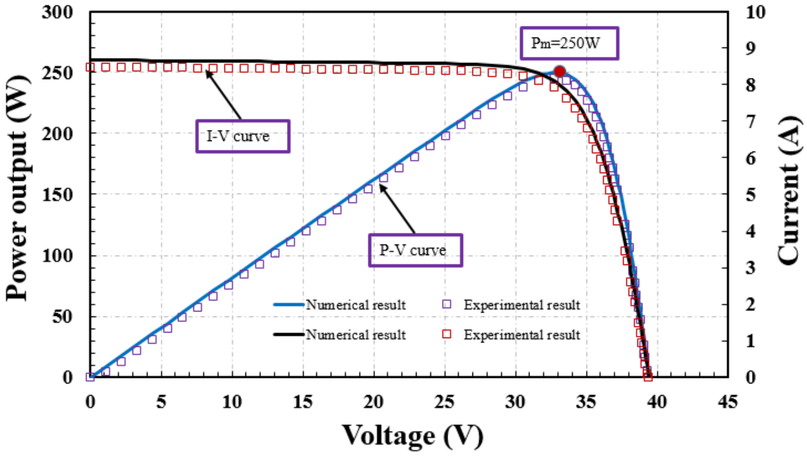

Fig. 5. The validation of numerical model through experimental result

Fig.5 illustrates a good correlation between the experimental data and numerical results. The maximum errors for the power-voltage and current-voltage curves are 2.35% and 7.09%, respectively. This indicates that the numerical results are effectively supported by the test results, hence the numerical model is able to be used for assessing the performance of the grid-connected PV system.

4.2 PV system performance

The PV system yearly running time is categorised into two periods based on the indigenous weather condition. One is heating period from November to March with 6 hours daily operation time. Another one is cooling period from April to October with 8 hours daily operation time. The simulation results for the PV system daily electricity output are presented in Fig. 6. It is observed that the minimum electricity output of approximately 0.30 kWh occurs on 29/12/2017 whereas the maximum value of 29.83 kWh appears on 24/05/2017.

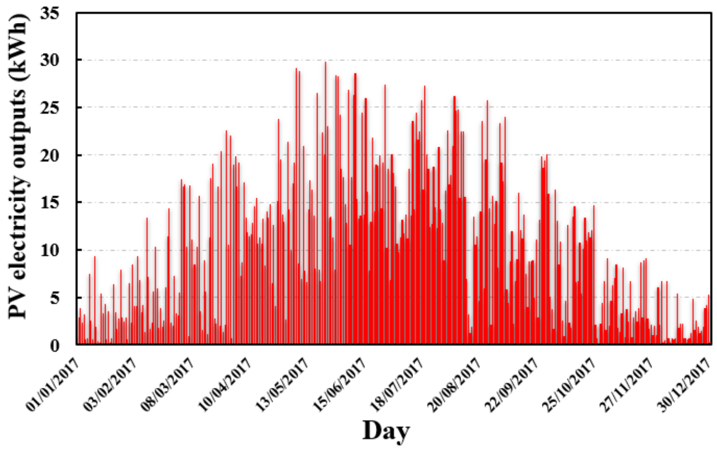

Fig. 6. PV system electrical energy generation over a year

Fig. 7 illustrates the monthly building electricity demand, PV system electricity output, electricity surplus or shortage. According to Fig. 7 (a), the system electrical energy output of 2864.60 kWh exceeds the actual energy demand of 1334.36 kWh for the building from April to October, particularly in the summer period from June to August. The additional electricity of approximately 1530.23 kWh can be fed into the power grid. By contrast, from November to March, the PV system electricity output of 1072.77 kWh cannot fulfil the building electricity requirement of 2408.64 kWh as presented in Fig. 7 (b). This denotes that approximately 1335.87 kWh of electricity has to be purchased from the power grid during the heating period. The total electricity production from the PV system is approximately 3937.37 kWh per annum. The highest monthly electricity generation of 494.45 kWh is achieved in June whereas the lowest is about 151.33 kWh in December.

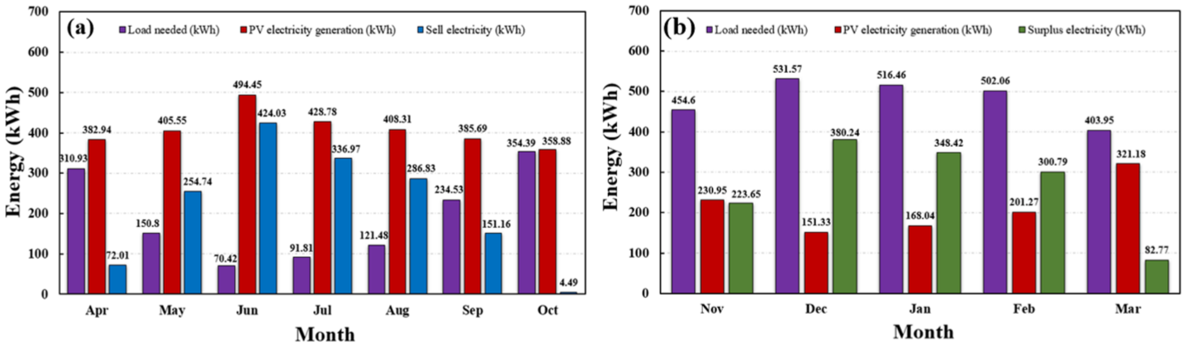

Fig. 7. Monthly electricity demands, PV electricity generation, selling or surplus electricity: (a) from April to October; (b) from November to March

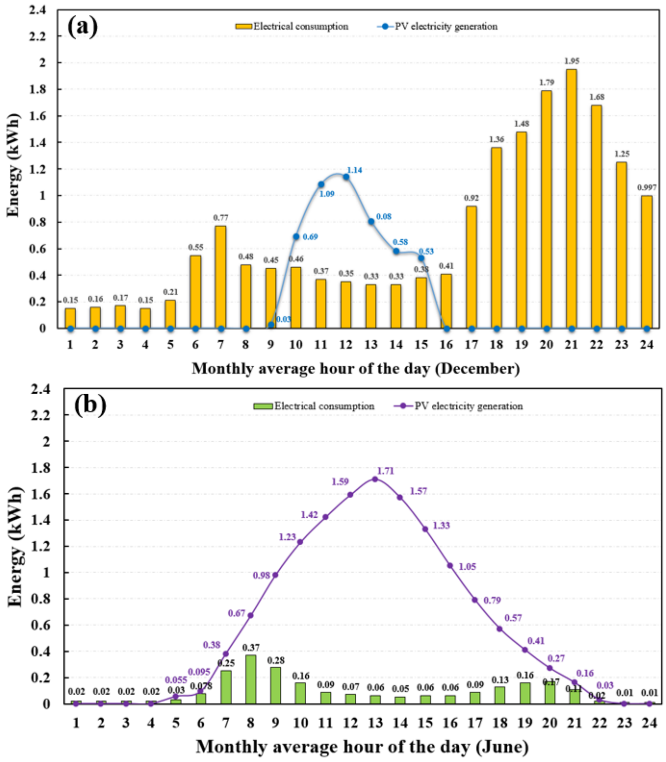

Fig. 8. Building electricity consumption and PV power generation: (a) December; (b) June

Fig.8 illustrates the system electricity generation and building electricity consumption based on monthly average hour of the day in December and June. The building hourly electricity consumption data are provided by British Gas. It is found from Fig. 8 (a) that the major electricity consumption period is from 17:00 to 24:00 in December, whereas the PV system electricity output period is from 9:00 to 15:00. This leads to the mismatch between the system electricity generation and the building electricity consumption. It is also found that the total electricity generation is less the overall electricity consumption, so the system does not meet the building electricity requirement. By comparison, in June, the major electrical energy consumption periods are from 7:00 to 10:00 and from 18:00 to 21:00 as shown in Fig. 8 (b), the PV system is able to produce sufficient electricity from 5:00

to 22:00. It is indicated that the building electricity consumption can be met by the system, and the extra power can be exported to the grid.

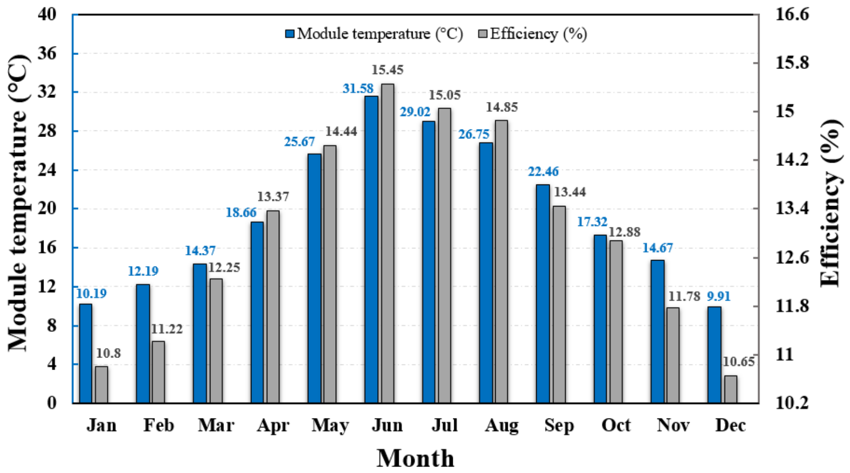

Fig. 9. PV efficiency and cell temperature

Fig. 9 shows the PV monthly average efficiency and cell temperature over one year, the annual average PV system efficiency is about 13.02%. To be more specific, the maximum monthly cell temperature is 31.58 °C in June, while the minimum is 9.91 °C in December, with the corresponding PV electrical efficiencies of about 15.45% and 10.65%, respectively. Moreover, it is noticeable, the system average electrical efficiency can achieve approximately 14.21% from April to October, however, from November to March, the system mean efficiency is about 11.34%.

4.3 PV module sensitivity analysis

Fig. 10 displays the current-voltage (I-V) and power-voltage (P-V) curves for five diverse solar radiation levels from 200 W/m^2 to 1000 W/m^2. It can be found that the PV module performance largely relies on the solar radiation level. The diode reverse saturation current (I_o) is equivalent to short circuit current (I_{sc}), which is nearly proportional to the solar radiation intensity.

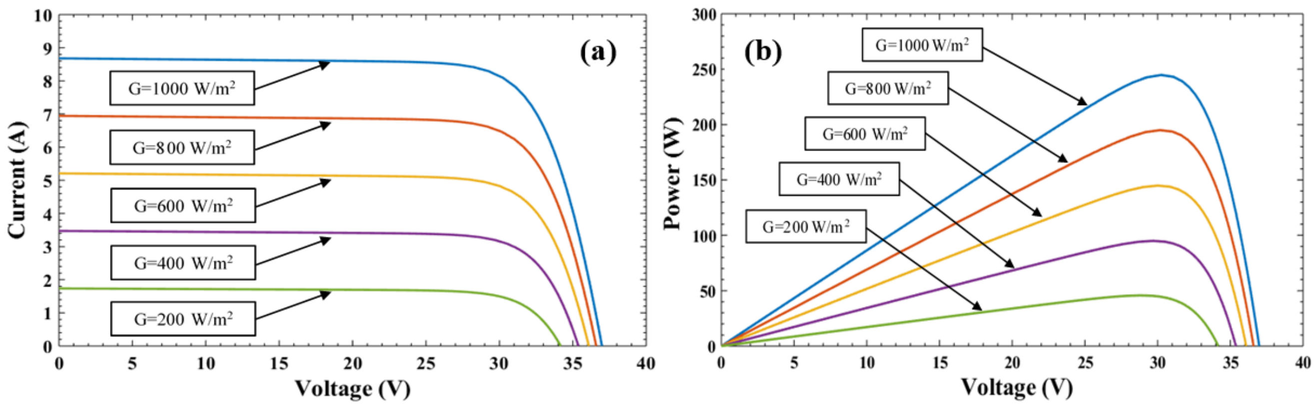

Fig. 10. The curves of Sharp ND-R250A5 polycrystalline silicon PV module at several radiation levels: (a) I-V; (b) P-V

As indicated in Fig. 10 (a), the I_o values of the PV module are 1.74 A, 3.47 A, 5.21 A, 6.94 A and 8.68 A at different solar radiation levels of 200 W/m^2, 400 W/m^2, 600 W/m^2, 800 W/m^2 and 1000 W/m^2, respectively. By comparison, the voltage values are less impacted, while the open circuit voltage (V_{oc}) logarithmically rises with the solar radiation. The maximum power (P_m) output of the PV module prominently increases with the solar radiation intensity due to the growths in both voltage and current. The simulation results in Fig. 10 (b) reveal that the maximum power (P_m) values of the system are 44.6 W, 92.7W, 141.6W, 190.5W and 239.2 W for the above solar radiation levels, respectively.

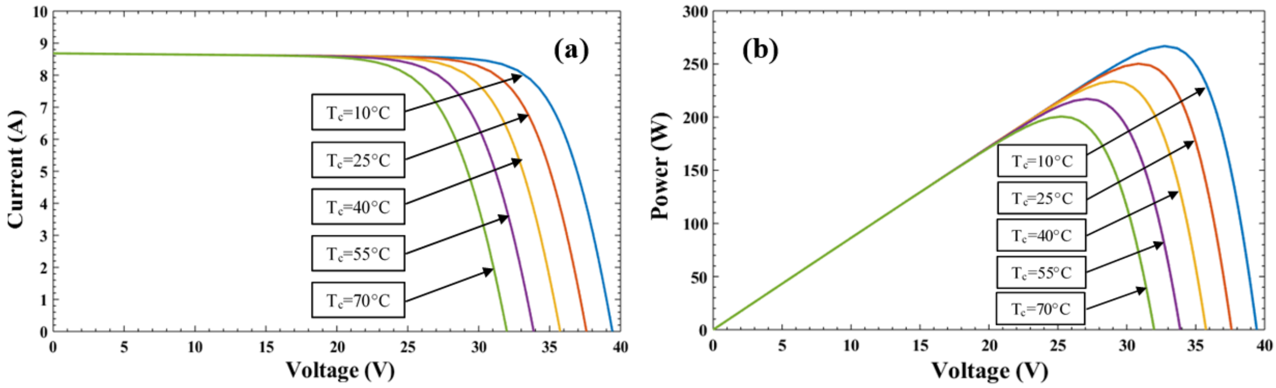

Fig. 11. The curves of Sharp ND-R250A5 PV module at several temperature levels: (a) I-V; (b) P-V

Fig. 11 reflects the effects of PV cell temperature on the I-V and P-V characteristic curves. It can be found in Fig. 11 (a) that the PV module temperature has significant influence on the module performance, the maximum power (P_{max}) values are 266.8W, 250.3W, 233.7W, 217.1W and 200.6W at the cell temperatures of 10 °C, 25 °C, 40 °C, 55 °C and 75 °C, respectively. It is also demonstrated in Fig. 11 (b) that P_{max} significantly reduces with the PV cell temperature (T_{cell}) because of huge reduction in the voltage value. Alternatively, the current increases with the cell temperature T_{cell}.

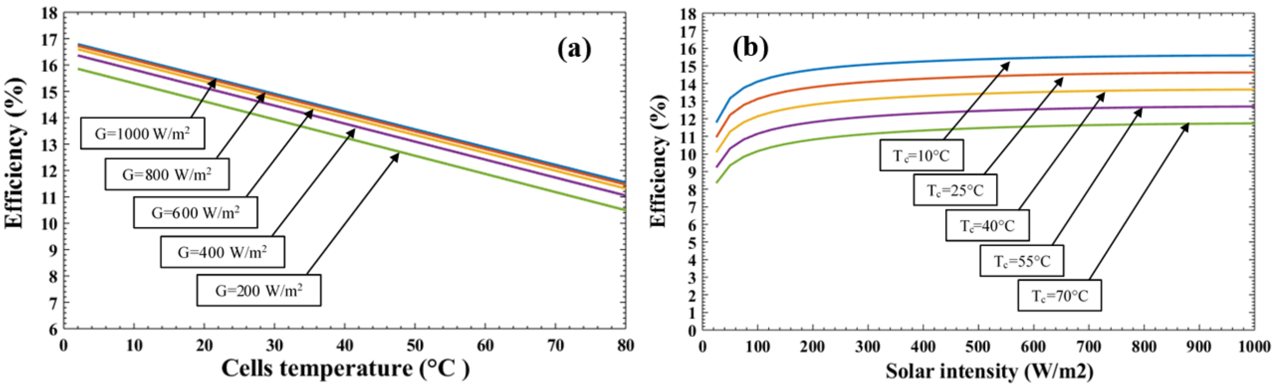

Fig. 12. Performance of Sharp ND-R250A5 PV module: (a) cell temperature; (b) solar intensity

The PV module operates over a wide-range of climate conditions. The influences of the ambient air temperature and solar radiation intensity on PV output power are indicated in Fig. 12. It can be found that the PV system performance drops linearly with the PV cell temperature whereas it rises with the solar radiation intensity. Specifically, as indicated in Fig. 12 (a), the system efficiencies are 13.25%, 13.78%, 14.03%, 14.17% and 14.23% at the solar radiation levels of 200 W/m^2, 400 W/m^2, 600 W/m^2, 800 W/m^2 and 1000 W/m^2, respectively. Furthermore, according to Fig. 12 (b), the system efficiencies are 16.25%, 15.24%, 14.23%, 13.22% and 12.22% at the module temperatures of 10 °C, 25 °C, 40 °C, 55 °C and 75 °C, respectively.

4.4 Economic assessment

The NPV of the PV system is found to be nearly £1335.32 at the market discount rate of 8.75% over a 25-year operational period. The simulation results including the system electrical energy expense (SEEE), mortgage payment (MP), payment of principal (POP), remaining debt principal (RDP), maintenance and insurance expenses (M&I) and present worth of the PV system savings are listed in Table 5.

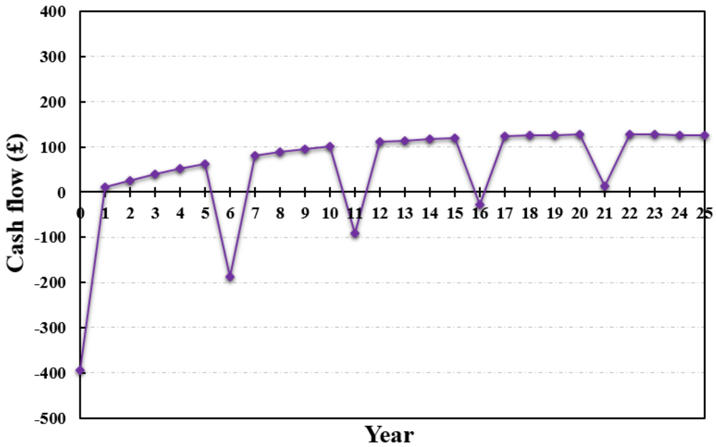

Fig. 13. Annual PV system savings during the 25-year LCC period

As shown in Fig. 13, the cash flow becomes positive from the first year. However, it turns negative due to the cost induced by inverter replacement in the sixth, eleventh and sixteenth years. After the sixteenth year, the cash flow becomes consistently positive by the end of the service lifetime cycle of the PV system. As indicated in Fig. 14, the cumulative SEEE savings are £4275.69, which exceed the IE of £3943 in the eighth year. Afterwards the cumulative PV system savings turn into positive because of the relatively low IE and M&I. The cumulative PVS of £2495.26 surpasses the RDP balance of £1748.48 by the end of the eighteenth year.

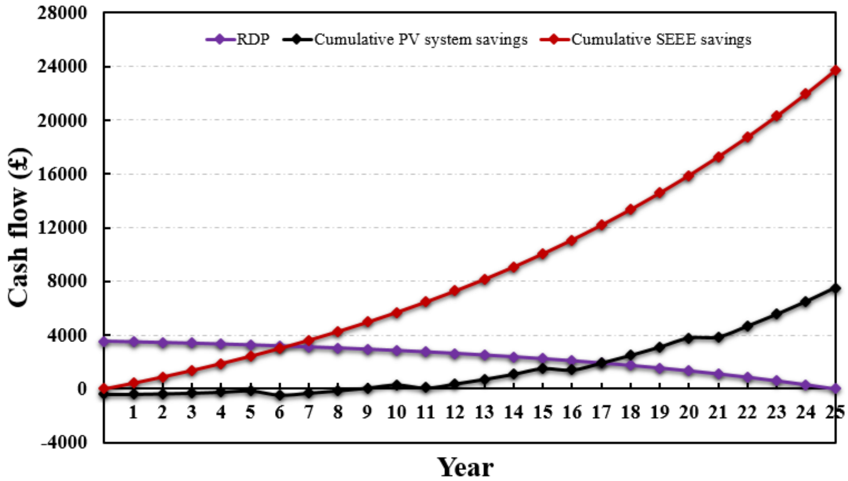

Fig. 14. Variation of RDP, cumulative PV system savings and cumulative SEEE savings

4.4.1 Discounted payback period

As indicated in Table 5, the operation of the PV system results in a negative cumulative cash flow (£128.10) until the end of the eighth year, but the absolute value and cash flow at the end of the ninth year are £128.10 and £95.06, respectively. A DPP is approximately 9.34 years (8 + £128.10 /£95.06) based on Eq. (31), this is deemed an acceptable payback time which is less than ten years for an engineering project, as well as the DPP is more reliable since it considers the time value of money.

Table 5 The financial analysis of the PV system for the domestic house, UK (25-year life cycle)

Year	Electricity production (kWh/year)	SEEE (£)	MP (£)	IP (£)	POP (£)	RDP (£)	Inverter replacement	M&I (£)	EPT (£)	ITS (£)	PV system savings (£)	Present worth of PV system savings(£)	Cumulative PV system savings (£)	Cumulative SEEE savings (£)
0						3548.70					(394.3)	(394.3)	(394.3)	
1	3938	431.99	(338.14)	290.99	47.14	3501.56	-	(80)	(78.86)	75.99	11.00	10.12	(383.29)	431.99
2	3938	457.92	(338.14)	287.13	51.01	3450.55	-	(83.6)	(82.01)	75.86	30.03	25.39	(353.27)	889.92
3	3938	485.39	(338.14)	282.95	55.19	3395.36	-	(87.36)	(85.29)	75.68	50.28	39.09	(302.99)	1375.31
4	3938	514.52	(338.14)	278.42	59.72	3335.64	-	(91.29)	(88.71)	75.45	71.83	51.36	(231.16)	1889.83
5	3938	545.39	(338.14)	273.52	64.61	3271.03	-	(95.40)	(92.26)	75.18	94.78	62.31	(136.38)	2435.22
6	3938	578.11	(338.14)	268.22	69.91	3201.12	(428.93)	(99.69)	(95.95)	74.86	(309.73)	(187.25)	(446.11)	3013.33
7	3938	612.80	(338.14)	262.49	75.64	3125.48	-	(104.18)	(99.78)	74.48	145.18	80.71	(300.93)	3626.13
8	3938	649.57	(338.14)	256.29	81.85	3043.63	-	(108.87)	(103.77)	74.04	172.83	88.34	(128.10)	4275.69
9	3938	688.54	(338.14)	249.58	88.56	2955.07	-	(113.77)	(107.93)	73.53	202.24	95.06	74.1367	4964.23
10	3938	729.85	(338.14)	242.32	95.82	2859.25	-	(118.89)	(112.24)	72.94	233.53	100.94	307.66	5694.09
11	3938	773.64	(338.14)	234.46	103.68	2755.58	(497.25)	(124.24)	(116.73)	72.27	(230.44)	(91.59)	77.22	6467.73
12	3938	820.06	(338.14)	225.96	112.18	2643.39	-	(129.83)	(121.40)	71.50	302.19	110.44	379.42	7287.79
13	3938	869.27	(338.14)	216.76	121.38	2522.02	-	(135.67)	(126.26)	70.63	339.83	114.21	719.25	8157.06
14	3938	921.42	(338.14)	206.81	131.33	2390.69	-	(141.78)	(131.31)	69.65	379.85	117.38	1099.10	9078.48
15	3938	976.71	(338.14)	196.04	142.09	2248.59	-	(148.16)	(136.56)	68.55	422.40	120.03	1521.51	10055.19
16	3938	1035.31	(338.14)	184.38	153.75	2094.84	(576.45)	(154.83)	(142.02)	67.31	(108.81)	(28.43)	1412.69	11090.50
17	3938	1097.43	(338.14)	171.78	166.36	1928.48	-	(161.79)	(147.70)	65.92	515.72	123.91	1928.42	12187.92
18	3938	1163.27	(338.14)	158.14	179.99	1748.48	-	(169.07)	(153.61)	64.38	566.83	125.24	2495.26	13351.20
19	3938	1233.07	(338.14)	143.38	194.76	1553.72	-	(176.68)	(159.76)	62.65	621.16	126.19	3116.41	14584.27
20	3938	1307.05	(338.14)	127.41	210.73	1342.99	-	(184.63)	(166.15)	60.74	678.88	126.83	3795.29	15891.32
21	3938	1385.48	(338.14)	110.13	228.01	1114.98	(668.26)	(192.94)	(172.79)	58.61	71.96	12.36	3867.26	17276.80
22	3938	1468.61	(338.14)	91.43	246.71	868.28	-	(201.62)	(179.70)	56.25	805.40	127.22	4672.66	18745.41
23	3938	1556.72	(338.14)	71.20	266.94	601.34	-	(210.69)	(186.89)	53.65	874.65	127.05	5547.31	20302.13
24	3938	1650.13	(338.14)	49.31	288.83	312.51	-	(220.17)	(194.37)	50.76	948.21	126.65	6495.52	21952.26
25	3938	1749.13	(338.14)	25.63	312.51	0	-	(230.08)	(202.14)	47.58	1026.36	126.06	7521.88	23701.39
Total												**1335.32**		

4.4.2 Sensitivity analyses

The sensitivity analyses are carried out in relation to the net present value (NPV) and payback period (PP) by using the @Risk software. Figs. 15 and 16 present the distribution bar charts of the cumulative probability versus NPV and PP for the PV system during the entire LCC assessment period.

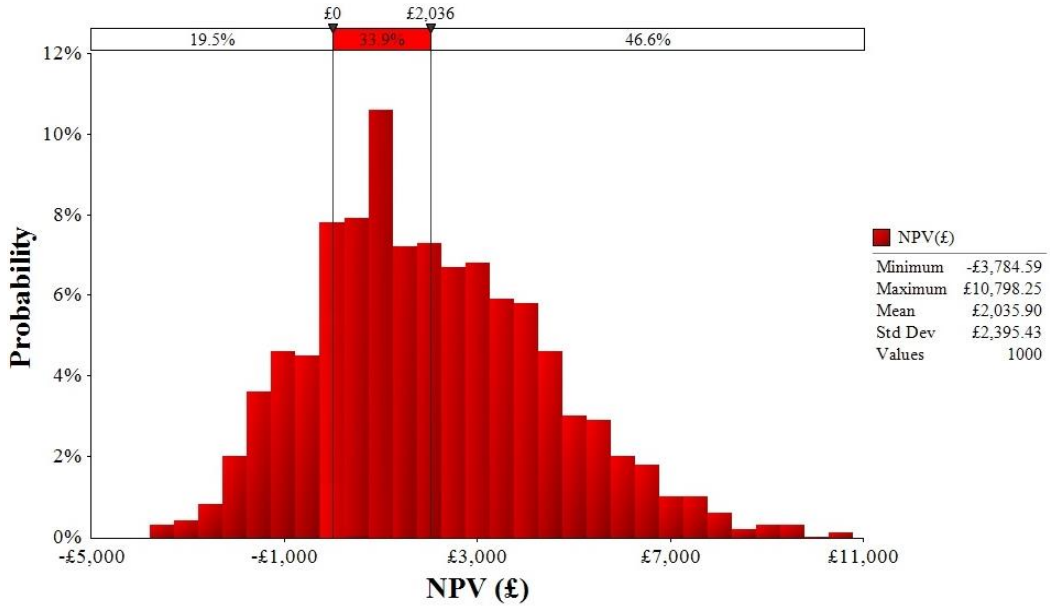

Fig. 15. Frequency forecast diagram of NPV

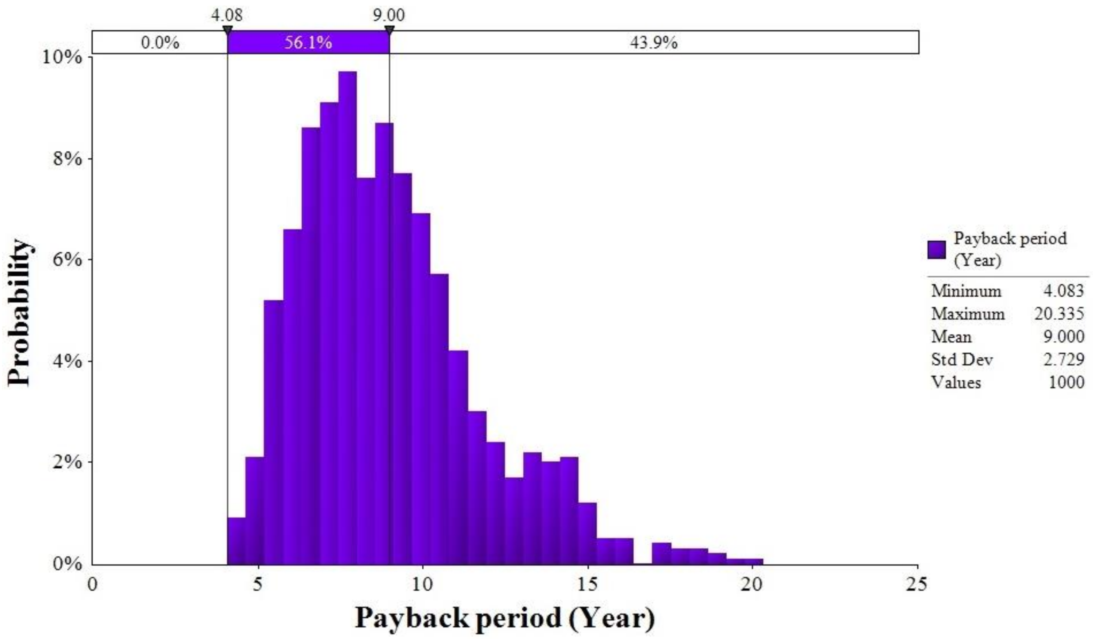

Fig. 16. Frequency forecast diagram of PP

The average, maximum, minimum, standard deviations, and number of iterations of the NPV and PP are indicated in Fig. 15. It can be observed from this figure that the PV system has the average NPV value of approximately £2036 after 25-year running period. The NPV is in a range of -£3784.59 to -£10798.25 with a certainty of 80.5% probability. The vertical lines in Fig. 15

mean the minimum and mean values of the PP, where the average PP is noted to be about 9 years when the cash flow turns positive. There is approximately 56.1% probability for this PV system to have the PP range from 4.08 to 9 years whereas about 43.9% likelihood is in the range of 9 to 20.34 years. Since there is about 56.1% likelihood to recover the invested fund within 9 years, this kind of certainty is likely to attract the investment in the residential sector in the UK.

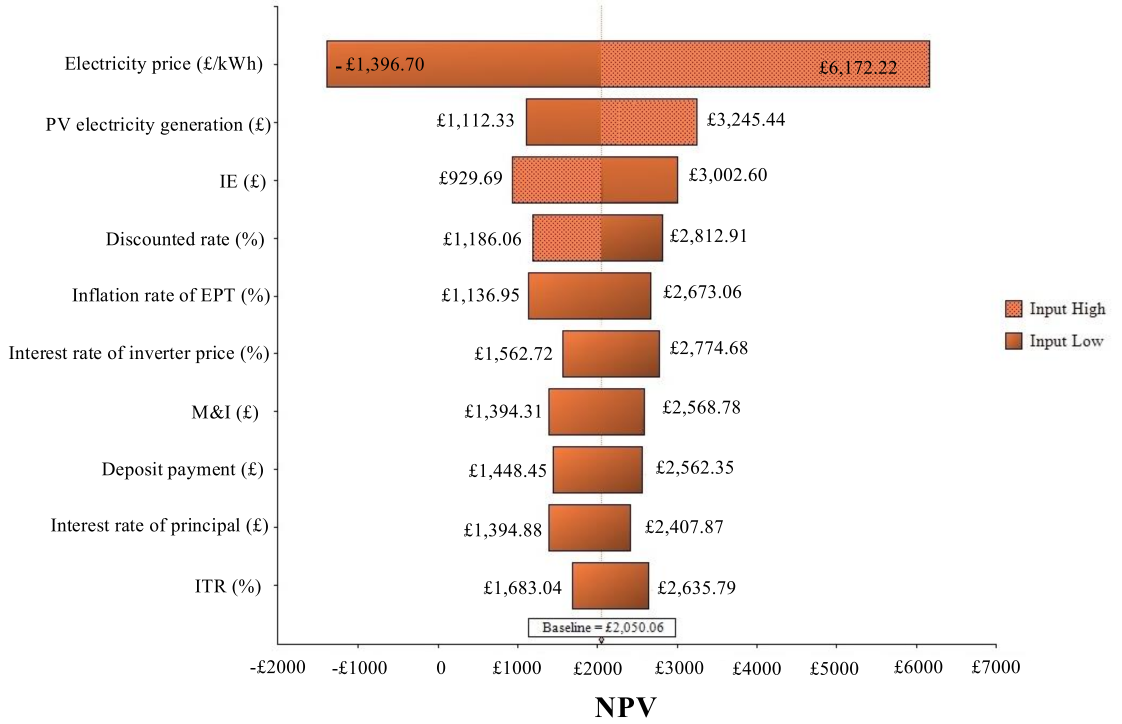

Fig. 17. Sensitivity of NPV to the selected economic parameters.

Fig. 17 shows the sensitivity analysis results of the NPV to the selected economic input parameters. The bars show deviations from the base case values, the longer of the bar, the higher of its sensitivity. Electricity price has the greatest influence on the NPV, when the electricity price increases to the high end, the NPV can reach £6172 compared to £2050 based on the current price. It means that the PV system cost is very sensitive to the uncertain electricity market. This also reflects that the more of generated electricity, the higher of the NPV. All the remaining parameters have less sensitivities.

The electricity price, IE and PV electricity production are identified as having a significant impact on the NPV, and selected for the sensitivity analysis of the payback period. The uncertainty associated with electricity price largely impacts the running expense and power output as well as the NPV, the low electricity price decreases the running cost of the building and credit payment. Therefore, it makes the payback period to increase to 14.49 years relative to the original 9 years as shown in Fig. 18. Moreover, the high electricity price makes the payback period to be 5.55 years (or 38% below the base case). Low end of capital investment can help the investors to start making net profit in the 7.73th year.

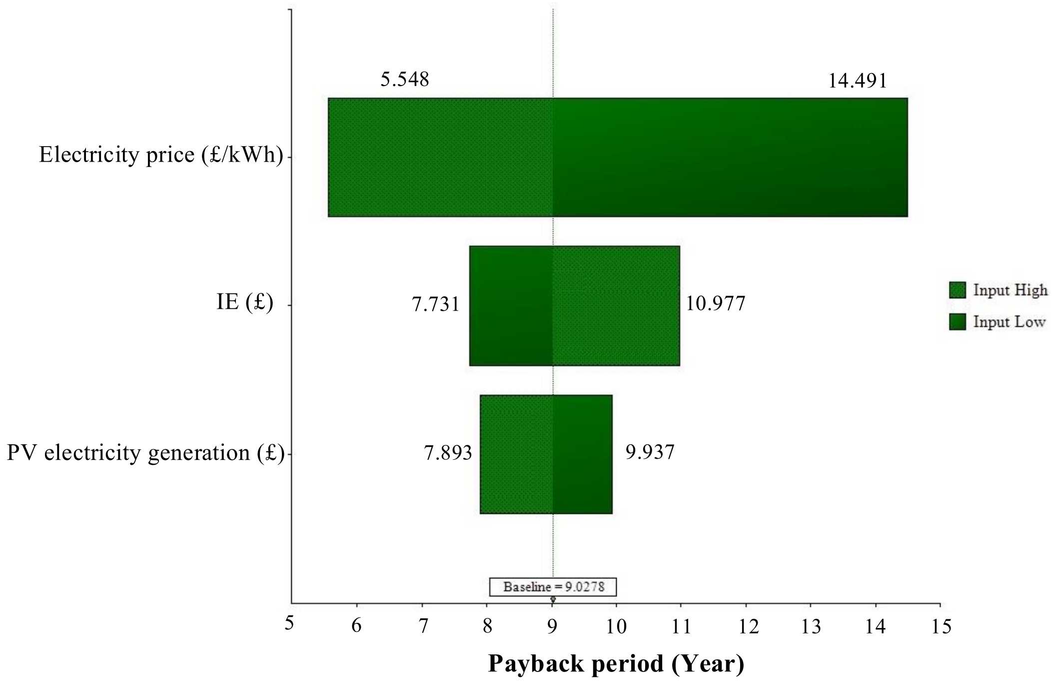

Fig. 18. Sensitivity of PP to variations of selected economic parameters

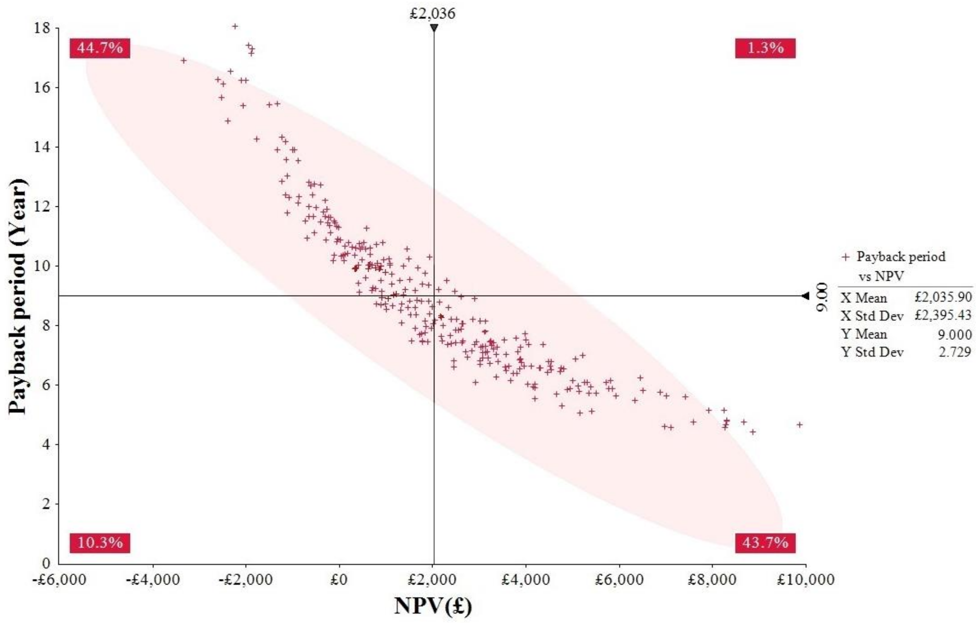

Fig. 19. The relative distribution of probability between PP and NPV.

As shown in Fig.19, the payback period has a probability of 43.7% to have less than 9 years when the NPV is above an average value of £2036. There is only 10.3% probability that the payback period can be below 9 years when the NPV is below the mean value. This means that the long PP is unfavourable to the NPV. If the PP is more than 9 years, there is a possibility of 44.7% that the NPV is lower than the average value. This demonstrates that a high NPV value and a short PP (the lower right side in Fig. 18) are favoured, though efforts are still needed to improve the likelihood in this quadrant.

4.4.3 Comparison between Feed in tariff and Smart Export Guarantee schemes

The FiT scheme was launched in April 2010 and closed for the new policy on 31st March 2019 [45]. Though the FiT has come to an end, some of the additional power generated by solar energy will inevitably go back to the grid and it would be illegal not to be paid under current legislation. Therefore, the UK government (Department for Business, Energy & Industrial Strategy) introduced a new replacement scheme, called the Smart Export Guarantee (SEG), to ensure all medium and large electricity energy supply companies such as SSE, EDF Energy, British Gas, npower, Octopus Energy and Scottish Power (those with more than 250,000 electricity customers) to offer an export tariff [46, 47]. The new scheme was set on 9th June 2019 and mainly comes into force on 1st October 2019, which commences on 1st January 2020 [48].

Under the SEG scheme, customers are only paid for the metered electricity exported to their electricity supplier. There is no longer a "generation tariff", so it is likely to take much longer before the capital investment is covered by the SEG payment and energy saving [46, 47]. In comparison to the FiT scheme, the export price is not set by the UK government, and there will be no long-term contract. Based on this policy change, one of UK electricity suppliers (Octopus Energy Ltd) has proposed two options regarding the payments. One is a flat tariff called Fixed Outgoing Octopus that is a simple fixed payment for all surplus power exported to the grid at a fair market rate of 5.5p/kWh [49]. Another one is dynamically price named as Agile Outgoing Octopus that is in the range from 4 p/kWh to 9 p/kWh at off peak time and from 10 p/kWh to 15p/kWh at peak time [49]. This means that the variation price allows house owner to consider the highly variable wholesale expense of energy throughout the day, and export at the most valuable time [49].

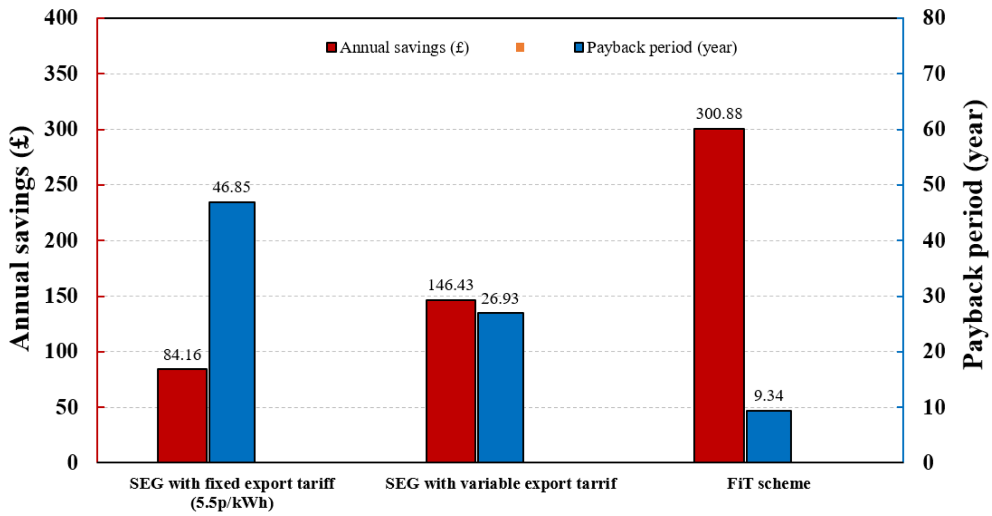

Fig. 20. Comparison of annual savings and income and PP between SEG and FiT schemes

It can be found from Fig. 20 that the annual savings under the SEG with fixed and variable export tariffs, and FiT schemes, are £84.16, £146.43 and £300.88, respectively. The FiT scheme saving is nearly four and twice times compared with the SEG with fixed export tariff and with variable export tariffs. Similarly, the payback period under the FiT scheme is 9.34 years which is far less than the SEG with fixed export tariff of 26.3 years and SEG with variable export tariff of 46.85 years. Currently, there is no minimum to the export tariff that energy companies must pay, which means that the government is envisaging a competitive market and people will likely experience very low export tariffs compared with the FiT scheme.

5. Conclusions

The techno-economic model of a grid-connected PV system is presented in terms of the energy production and economic performance. The numerical model is verified via experimental results, and the maximum differences for the I-V and P-V are both less than 8% which can be utilized to evaluate the system performance. As for the economic benefit, the system time value of money is assessed based on the life cycle cost analysis by considering the key performance parameters, including the IR, ITR, MP, SEEE, IE, M&I, EPT, ITS and PV system savings. Furthermore, the sensitivity analysis of the system is implemented for different conditions, and the comparison and contrast of NPV and payback period between the FiT and SEG schemes are illustrated. Some significant findings can be summarized as follows:

- In the period from April to October, the system electricity output with the average electrical efficiency of 14.21% could fulfil the building electricity demand, the excess electricity capacity of 1530.23 kWh can be sold to the power grid.
- In the period from November to March, the system electricity output with mean efficiency of 11.34% could not meet the building electricity requirement, thereby the additional electricity capacity of 1072.82 kWh is needed to be purchased from the power grid.
- The system DPP is 9.34 years and its 25-year' NPV is £1335.32 with 8.75% discount rate.
- The system cumulative saving is negative by the end of the eighth year, afterwards it becomes and sustains consistently positive until the end of the project lifetime.
- The cumulative SEEE saving (£4275.69) exceeds the IE (£3943) in the eighth year, while the cumulative PV system saving (£2495.26) surpasses the RDP balance (£1748.48) by the end of the eighteenth year.
- The annual savings under the SEG with fixed and variable export tariffs, and FiT schemes, are £84.16, £146.43 and £300.88, respectively.
- The FiT has the shortest payback time in comparison with the SGE.

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Nomenclature

A	Area (m^2)
B	Diffuse portion constant
b	Modified ideality factor
C	Cost (£)
D	Principal payment (£)
d	Inflation rate (%)
E	Power generated from the PV system (kWh)
G	Solar radiation (kW/m^2)
h	Period of maintenance payment (year)
I	Current (A)
i	Idenality factor
k	Stefan-Boltzmann constant (1.381×10^{-23} J/K)
L	Longitude
N	Period of economic assessment (year)
n	Number of PV cells in series
p	Year number of periodic payment
q	Electron charge (1.602×10^{-19} coulomb)
R	Resistance (Ω)

r	Interest rate (%).
T	Temperature (°C)
t	Time (s)
U	Voltage (V)
X	Last period with a negative discounted cumulative cash flow
Y	Absolute value of discounted cumulative cash flow at the end of the period
Z	Discounted cash flow during the period after X
z	Number of loan payment years
Subscripts	
a	Ambient
cell	Cell
external	External
generation	Generation
inverter	Inverter
l	Linearly function
ref	Reference condition
s	Series resistance
sh	Shunt resistance
Greek Letters	
α	Derate factor
β	Electricity price
γ	Discounted rate
θ	Angle between the tilted surface and the solar rays
Γ	Reflection index

λ	Latitude
ω	Period of extra property tax
σ	Zenith angle
τ	Plat azimuth angle
ξ	Sun azimuth angle
ψ	Solar declination angle
κ	Solar angle
μ	Short-circuit current temperature coefficient
η	Efficiency
Abbreviations	
AC	Alternating current
DC	Direct current
DPP	Discounted payback period
EOT	Equation of time
EPT	Extra property tax
ET	Export tariff
ETR	Effective tax rate
FiT	Feed-in tariff
GHG	Greenhouse gas
IE	Initial expense
IP	Interest payment
IR	Interest rate
ITR	Income tax rate
LCC	Life cycle cost

LCOE	Levelized cost of energy
LCOH	Levelized cost of heat
LST	Local standard time
M&I	Maintenance and insurance expenses
MP	Mortgage payment
MPP	Maximum power point
MSSO	Modified simplified swarm optimization
NPV	Net present value
OC	Open circuit voltage
PE	Periodic expense
POP	Payment of principal
PT	Property tax
PV	Photovoltaic
RDP	Remaining debt principal
ROI	Return on investment
ROR	Rate of return
SEEE	System electrical energy expense
SEG	Smart export guarantee