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Reduced real lifetime of PV panels – Economic consequences

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ABSTRACT

The maintenance and analyzing failures of PV systems and plants are becoming more and more important issues. Our data from the long-term operation of 85 photovoltaic power plants in central Europe show that their actual lifetime is about half that of the originally planned lifetime. After about 10 years, serious failures of 1st tier (bankable) PV panels occur at an increasing rate. This article presents selected typical data and describes the most serious failures. Furthermore, economic calculations of returns on investment are carried out in relation to the price of electricity, which is currently changing at a rapid pace. It shows that the PV panel lifetime reduction from 20 to 30 years, declared at commercial leaflets, to real lifetime about 10–12 years can reduce PV power plant profit substantially, but the investment is still worth it. The reason is that after 10–12 years ser vice/maintenance expenses to replace damaged PV panels and inverters are growing very quickly. The new information could be helpful for owners of PV power plants to get a more realistic estimation of profits.

1. Introduction

After discovering the photovoltaic (PV) effect, understanding physical principles, developing practical technology, decreasing the price of solar cells and modules production, creating massive amounts of PV systems and huge PV plants - maintenance and analyzing failures of PV systems and plants are becoming more and more important issues.

Renewable energy sources have an important place in the energy mix today. Renewable electricity is growing rapidly, with solar electricity growing relatively faster than any other fuel source in the last ten years sources [1]. As the world accelerates its transition to clean energy, it is useful to track the rate of growth, but the data are tracked in different ways from different. The incorporation of solar energy sources into the distribution network in terms of advanced distribution management and maximizing energy efficiency and reliability is important issue. The work [2] provides a review of the photovoltaic systems, where the design, operation and maintenance are the key points of PV systems including their performance, thermography and electroluminescence, dirt, risks and failure modes.

Some papers give the data on long-term reliability of PV generation systems at different locations [3,4] and provide the main signs of degradation on crystalline silicon photovoltaic modules caused by outdoor exposure with analysis of the most significant defects like severe browning, milky pattern and oxidation of the metallization grid.

The article [5] deals with the economics of solar energy trade in terms of market prices and the article [6] deals with the economics and cash flow of small roof integrated photovoltaic systems in Poland. This is also the similar subject of this article. Some authors, analysing specific geographic conditions, for example, [7] explore the extent of damage as well as degradation pathway for the PV backsheets after erosion by sand particles sourced from desert A and desert B.

The energy balance of a photovoltaic system is affected by many factors. For example, the cited work [8] analyses the influence of changes in tilt angle and azimuth on the production of electricity in a PV system. The temperature of PV panels also has a significant effect on the efficiency of photovoltaic energy conversion. The increasing temperature of PV panels means a decrease in the efficiency of energy conversion and the cited works [9,10] explain this in detail from the point of view of the physical theory of semiconductors. The cited works [11,12,13] deals with innovative regression-based methodology to assess the techno-economic performance of photovoltaic installations in urban areas. Households present in cities a significant contribution in the energy consumption, and photovoltaics (PV) has become an economically feasible technology that can play an important role to lower this

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consumption and the associated emissions. The usage of tracking stands of PV panels can increase the produced electricity amount, the cited work [14] deals with performance and economic comparison of fixed and tracking photovoltaic systems. Roof photovoltaic chargers for electric cars are important in terms of reducing the carbon footprint [15]. Horizontal roofs are good places to install PV systems [16].

The cited work [17] examines the mechanisms of interaction of economic development and the subsidy strategies of distributed PV systems in China. The results of the simulation analysis and empirical analysis show that the response effect of distributed PV systems is limited by regional economic development. Based on local economic development, the government chooses a high subsidy strategy or a low subsidy strategy that will reasonably manage the development of distributed PV systems. The decreasing prices of PV panels may increase the demand for investments in distributed PV systems even in the case of smaller subsidies. That is why governments have reduced subsidies. However, the subsidy strategy remains an important tool that co-ordinates local economies with the construction of distributed PV systems.

The cited work [18] evaluates the impact of subsidies and political uncertainty on the installation of PV systems in residential buildings. The study suggests that keeping perceived political uncertainty low is more important for residential solar investors than full hedging in the electricity market.

Considering the aforementioned, this work aims to analysing data from the long-term operation of 85 photovoltaic power plants in central Europe (Czech Republic) and their actual lifetime with economic calculations of returns on investments.

2. PV power plants in the Czech Republic

Most photovoltaic (PV) power plants currently operating in the Czech Republic were installed during the solar boom in 2009–2010. At that time, the solar boom was supported by a subsidy policy, and at the end of 2010, the total installed nominal output of all PV power plants in the Czech Republic was approximately 2000 MWp. However, the subsidy policy has changed since 2011, and since then, this installed capacity has increased only slightly to about 2,200 MWp. The cited work [19] speaks of similar consequences of a subsidy policy in Spain on the installation of PV power plants. However, the installation of PV power plants is seeing exponential growth worldwide and it comes with the need to recycle old PV panels. This issue is discussed in detail, for example, in the cited works [20,21].

In the years 2009–2010, the expected lifetime of PV power plants in the Czech Republic was 20–25 years. Today, after about 12 years, it turns out that this estimate was too optimistic and the real lifetime is about half. Power plants built in 2009–2010 have reached the end of their lifetime today.

The cited work [22] talks about the monitoring system Solarmon-2.0 for PV power plants. Some authors of this article participated in the development of this system. Today, our monitoring system is installed at 85 PV power plants with the bankable (1st tier) PV panels in the Czech Republic and abroad, and we have detailed data from these power plants. It turns out that the real lifetime of PV power plants is about 12 years. Data from all PV power plants show very similar results, which we will discuss in this article.

Crystalline silicon-based PV panels are the most commonly used panels. PV cells are encapsulated in EVA (ethyl vinyl acetate). PV panels have a Glass/EVA/TPT laminate design. The natural decline in performance is around 1% per year [23,24], but after about 10 years, the probability of serious failures increases rapidly. The biggest problem is the delamination of the encapsulation of PV cells in the PV panel and the subsequent penetration of moisture [25,26]. The contacts corrode and conductive channels are formed to the grounded frame. Interrupted contacts and short-circuit currents to the grounded frame cause serious failures of PV power plants, which we have already referred to in the cited work [27,28].

The market price of electricity is currently increasing at a fast but steady pace. On 1st January 2021, it was EUR 0.04 per kWh, on 1st September 2021 it was EUR 0.07 per kWh, and on 1st October 2021, it was EUR 0.11 per kWh. The highest subsidized purchase price was EUR 0.52 per kWh.

At Fig. 1 it is shown a map with the location of the selected PV power plants, and it includes geographical coordinates.

3. Materials and methods

Thanks to the mentioned monitoring system [22], we have detailed data from 85 PV power plants located in central Europe, mostly in Czech Republic. For this article, we evaluated typical data from five selected PV power plants. These power plants were installed during the solar boom in the Czech Republic in 2010, i.e. they have been operating for more than 10 years. All the selected power plants are equipped with PV panels based on crystalline silicon. PV panels are installed on fixed stands facing south with an inclination of 35°.

During the operation of the power plants, we monitored the gradual degradation of 1st tier (bankable) PV panels and some results were already in the mentioned work [27]. Fig. 2 shows an example of delamination of PV panels and channels for moisture penetration from the front and back view. Fig. 3 shows the formation of a conductive channel between the electrode and the grounded frame of the PV panel, where there is a high probability of short-circuit currents that can destroy not only the PV panel but also other power plant equipment such as the inverter. Fig. 4 shows how the number of damaged inverters rises sharply after about 10 years of operation. For better comparison, the number of inverters is given as a percentage of the total number of inverters in the power plant. The Fig. 5 shows expenses for replacement of damaged inverters which rise sharply as well after about 10 years of operation.

During last 10 years prices of photovoltaic panels were reduced about 10 times [29] and the economic consequences were discussed in the work [30]. Today, the prices of PV panels are around EUR 0.3 per 1 Wp of installed capacity, while the price of the entire PV power plant is around EUR 0.8 per 1 Wp of installed capacity. The market purchase price of electricity on 1st October 2021 was around Eur 0.07 per kWh and it is gradually increasing. The highest subsidized price is EUR 0.52 per kWh. These values are used below for an economic evaluation of the return on investment in a PV power plant.

To calculate the economic efficiency of investments in PV power plants, the methods as payback period (PP), net present value (NPV), and internal rate of return (IRR) were used. The WACC (weighted average cost of capital) rate has often been used to discount future revenue values in so-called discounted indicators.

Net present value is the difference between the discounted cash flows (incomes – expenses) from the investment and the initial investment cost as shown in Eq. (1):

$$NPV = \sum_{i=1}^{n} \frac{CF_i}{(1+r)^i} - IC \tag{1}$$

where:

CF … cash flow from investment in individual years of lifetime,
IC … investment cost,
r … discounted rate,
i … lifetime of investment.

Internal rate of return is the calculation of r on assumption that NPV $= 0$, or $\sum_{i=1}^{n} \frac{CF_i}{(1+r)^i} = IC$.

Payback period is the ratio of the initial investment cost to the average annual cash flows from the investment. In the case of discounted PP (DPP), the sum of the total discounted cash flows is used, and the initial investment cost is multiplied by the lifetime of the PV plant (see

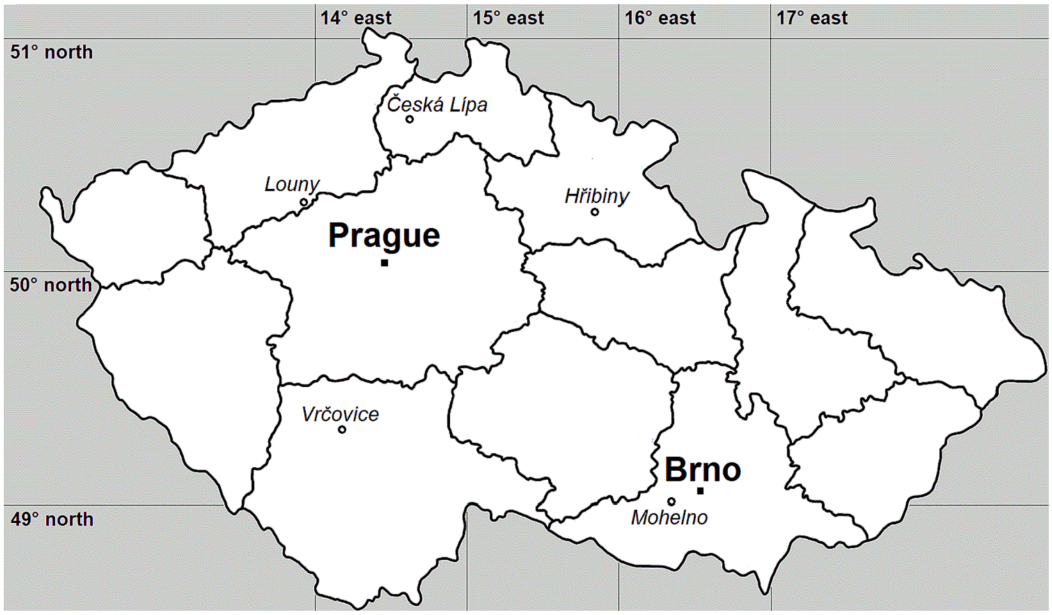

Fig. 1. Location of selected PV power plants on the map.

Fig. 2. Delamination of the PV panel and channels for moisture penetration when viewed from the front and back.

Fig. 3. Formation of a conductive channel between the electrode and the ground of the PV panel.

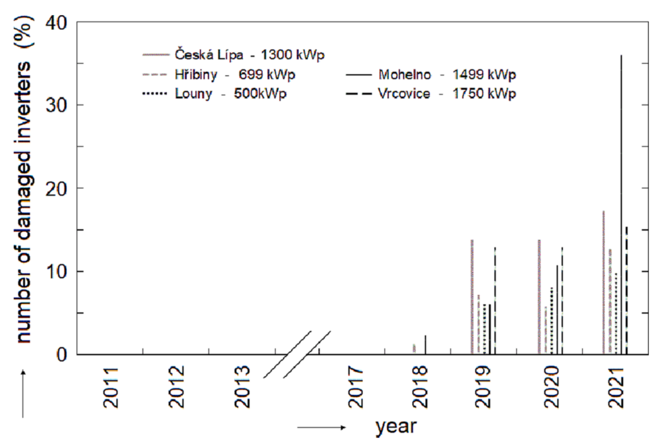

Fig. 4. Number of damaged inverters in selected PV power plants.

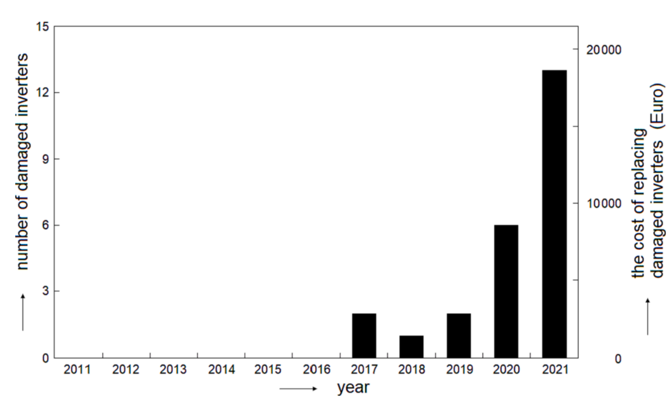

Fig. 5. Shows the annual values of service maintenance expenses in selected PV power plant for 12 years of operation.

Eq. (2) and Eq. (3).

$$PP = \frac{IC}{averageCF} \tag{2}$$

$$DPP = \frac{i^*IC}{\sum_{i=1}^{n} \frac{CF_i}{(1+r)^i}} \tag{3}$$

4. Results

In the case of the use of a repair gel (or other repair means), the cost of replacing the inverters is eliminated. These costs start to appear from the 7th year of the PV panel's lifetime and extend the payback period of the investment by up to one year (in the case of a simple payback period) or 1.6 years in the case of a discounted payback period. The increase in the payback period can of course be minimized by the rising purchase price of 1 kWh of energy, as shown by the example of the Louny power plant (500 kWp capacity - see Table 1).

Unfortunately, in the 11th year of the panels' lifetime, the cost of replacing the inverters is already enormous, and after the 11th year, the performance of the panel without the use of siloxane renovation (or another repair means) decreases so much that it needs to be replaced completely.

Photovoltaic power plant revenues were calculated according to data on electricity production in kWh per year for individual years of the monitored period. This production was then further converted into monetary income according to the price of electricity. The price range from EUR 0.04 to EUR 0.2 per kWh was used to calculate the individual variants.

Three discount rates were used to calculate dynamic methods - the lowest 2%, then the WACC rate, and the last rate was 10%. The WACC rate for the energy industry (CZ NACE D - Electricity, gas, steam and air conditioning supply) in 2019 was 6.78%. It is a rate that covers the costs of both equity and debt and it is the threshold value that should be used to assess the effectiveness of an investment project.

After the dynamic indicators for all five photovoltaic power plants have been calculated and the average value has been calculated, it is possible to achieve this interest rate at the price of one kWh at the level of EUR 0.106 (see Fig. 6).

At this price, the payback period calculated from discounted income is around 10 years. At this price and using the WACC discount rate, the net present value is zero (see Fig. 7). If we only wanted to cover the investment costs (i.e. not to make any profit or loss), we would have to set the internal rate of return to zero, in which case a price of around EUR 0.075 per kWh is needed to reach this turning point (Fig. 6). At this price, however, the investment would not be efficient and would not create additional resources beyond the wear and tear of the power plant.

As can be seen from Figs. 8 and 9, the payback period of photovoltaic power plants decreases as the price of electricity increases. If we take only the simple payback period without taking into account the effect of time, then the price of EUR 0.075 per kWh is the price that will allow the payback period of photovoltaic power plants to be around 10 years. Even at prices of EUR 0.15 per kWh and higher, the payback period of photovoltaic power plants is less than five years.

As for the payback period calculated from the discounted incomes, it is clear that the higher the rate used for the discount, the longer the payback period. If we wanted a ten-year payback period for discounted revenues, at a 2% discount rate, an energy price of around EUR 0.085

Table 1
Increased payback period (example of the Louny power plant).

Price €/kWh:	0,07	0,1	0,15	0,2	0,25
Simple payback period extension (years)	0,9997	0,4768	0,2076	0,1156	0,0735
Discounted payback period extension (years)	1,5948	0,7896	0,3539	0,1999	0,1283

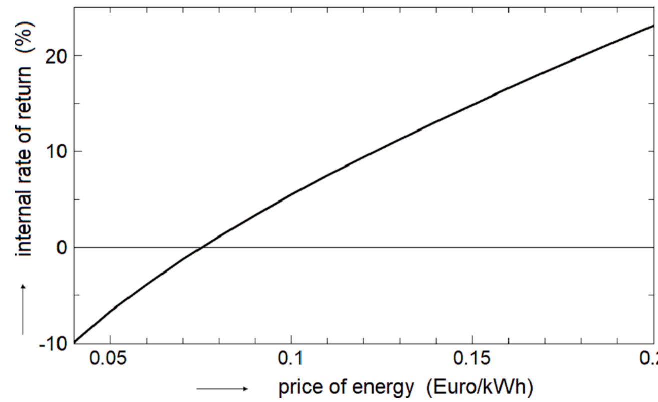

Fig. 6. Dependence of internal rate of return on the price of energy.

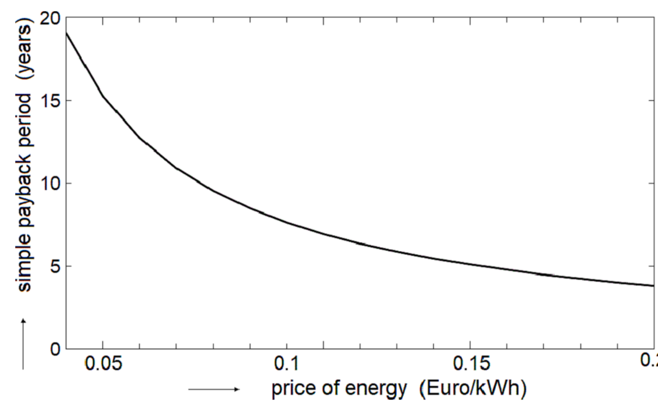

Fig. 7. Dependence of simple payback period on the price of energy.

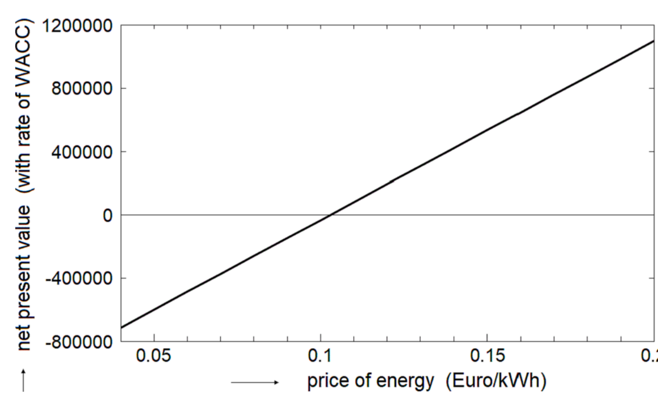

Fig. 8. Dependence of net present value on the price of energy.

per kWh would suffice, and with the WACC rate, the aforementioned price of EUR 0.106 would be required. At a rate of 10%, it would be necessary to increase this price to EUR 0.125.

Finally net present value was calculated for different PV power plant lifetimes (from 10 to 25 years) and for different price of energy (see Fig. 10). For better comparison, the values are converted per 1 kWp of installed capacity, because individual power plants have different nominal output powers. The net present value of PV power plant with real lifetime 12 years is about one half of that of PV power plant with theoretical optimistic lifetime 25 years.

5. Discussion

The lifetime of PV power plants does not reach the expected 20–25

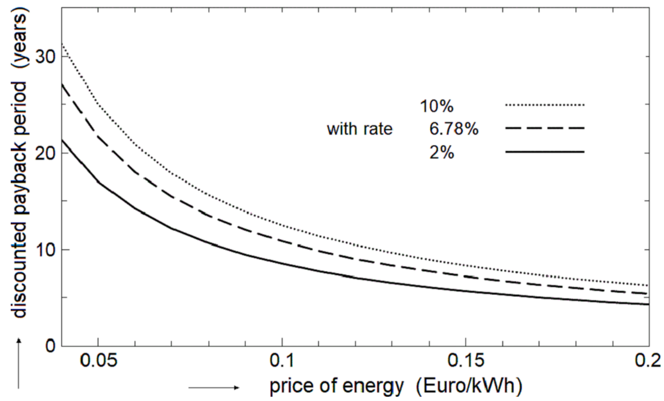

Fig. 9. Dependence of discounted payback period on the price of energy.

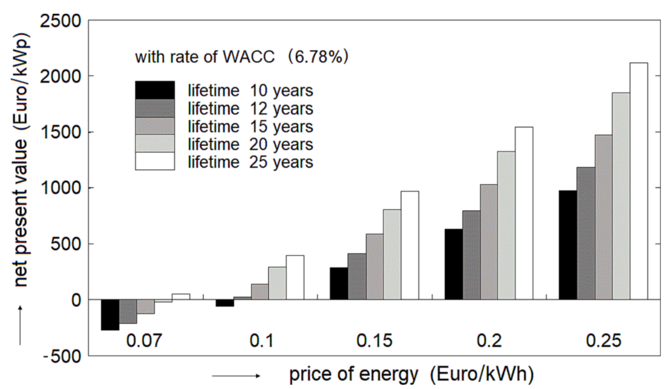

Fig. 10. Dependence of net present value on the price of energy for different PV power plant lifetimes.

years. This is no coincidence. Data from 85 PV power plants with the bankable (1st tier) PV panels installed during the solar boom give similar results. This is partly due to a poor estimation of the technical possibilities of the current PV panels and partly due to an effort to minimize the price of PV power plants. Efforts to reduce the price lead to a diminished construction of PV panels. For example, weaker frames or a smaller distance between the PV cells and the grounded frame of the PV panel are used. At the same time, the electrical voltage increases in a series-connected string of PV panels. Detailed description of the PV power plant degradation within less than 10 years is presented for example at ref. [31].

The price of PV panels has decreased by about an order of magnitude over the last 10 years. Although the main reason was the increased serial production, the depleted design also had a significant impact and this had to be reflected in the lifetime of the panels.

The market purchase price is gradually rising. At the beginning of 2021, it was EUR 0.04 per kWh, as of 1st September this price rose to EUR 0.07, and a month later (1st October 2021), it reached EUR 0.11 per kWh. If we calculated the NPV at this last price using the WACC discount rate, the average result for all power plants would be positive, the value of the IRR would be 7.51% and the average payback period would be 9.8 years. With further price increases, which seem to be more than likely at the end of 2021, the discounted payback period will, of course, decrease. With the maximum subsidized price of electricity, which is at the level of EUR 0.52 per kWh in the Czech Republic, the payback period would drop to a little over 2 years! It is clear that the longer the payback period and the shorter the lifetime of photovoltaic power plants, the less money this investment will "produce" and the financial return will decrease. Reduced lifetime and increase of service/maintenance expenses of photovoltaic power plants by about one half, will reduce substantially total money "production" after 12th year of the PV plant life in moderate climate.

6. Conclusion

The real lifetime of PV power plants is about half the planned time. After about 10 years, the above-mentioned delamination of the PV cell encapsulation, moisture penetration, contact corrosion and the formation of conductive channels to the grounded frame occur. Data from 85 PV power plants in central Europe show that, for about 10 years, the production of electricity corresponds to the expected values. Then the frequency of serious failures rises sharply. Other authors [32] have already presented similar conclusions, that the real lifetime of PV power plants is shorter than the manufacturers state. Improvement of the quality of new PV panels could help to increase final profits as well as new emerging technology of PV panel repair/renovation by polysiloxane (PDMS) film [27]. Unlike PV power plants at moderate climate of central Europe, the PV power plants at demanding tropical climate will have further reduced real field lifetime with negative economic consequences.

The market price of electricity is growing and thus the conditions for the return on investments into PV power plants are changing. The return was calculated for several models of boundary conditions. With the current relatively high electricity prices (end of 2022), the payback period of power plants falls significantly below 10 years, which in the current situation, would be enough to cover investment costs. However, any decrease in the lifetime of the panels results in a lower return on these investments. Therefore, the PV plant owners want to increase the lifetime by enhanced damaged PV panel and inverter replacement assuming additional investment costs, which would probably represent a high percentage of the total amounts invested. The PV panel lifetime reduction from 20 to 30 years, declared at commercial leaflets, to real lifetime about 10–12 years can reduce PV power plant profit substantially, but the investment is still worth it. The new information could be helpful for owners of PV power plants to get more realistic estimation of profits.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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