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DESIGN, PERFORMANCE AND ECONOMIC EFFICIENCY ANALYSIS OF THE PHOTOVOLTAIC ROOFTOP SYSTEM

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Key words: Economic indicators, Electricity saving, Power grid, Rooftop, Solar energy.

Solar energy represents the main renewable source development trend in the world to address the problems of energy shortage and environmental pollution. The development of power electronics and semiconductor technology helps to lower the cost of installing solar projects, speeding up building many solar power plants around the world, especially in China and America. In parallel, with the large capacity solar power plant, small solar systems are also receiving much attention from small capacity consumers. Rooftop systems are seen as a cost-saving solution for loads in the need to use the grid and to increase the proactive power supply for consumption loads. Installing a rooftop system must always be considered in terms of design capacity, cost, efficiency and capital recovery. This study builds a rooftop system with the capacity of 2 kW for a household load in Vietnam, which has a high potential for solar power development. Assessing the amount of capacity obtained by simulation and experimental methods, and economic factors are also presented. The results reflect the operability of the installation system, the errors between simulation and reality and are evaluated the indicators of economic efficiency of the photovoltaic rooftop system, which are not mentioned in previous studies. The economic values show the benefits of the system when the cost of paying to the power company is low but the ability to recover the project's capital is quite long.

1. INTRODUCTION

According to The International Renewable Energy Agency (IRENA), the number of countries that established new targets for renewable energy has increased to 160, showing the interest of countries in this type of energy [1–3]. In particular, photovoltaic (PV) power continues to be one of the fastest growing industries in the world [3–5]. The photovoltaic market presents three clear trends: Rooftop resident (PV rooftop power for people) is increasing, clearly showing savings for utilities; Rooftop factory (Roof solar power for production factories) is gradually becoming necessary for businesses, maximizing production costs, with a capacity of 20 kWp to 1 MWp; solar plant (PV plant) with a large scale, capacity of 5 MWp – 1 GWp, is gradually meeting the demand for electricity worldwide. In 2016, there were 303 GW of solar power supplied to the electricity system, an increase of 75 GW over the end of 2016 (228 GW) and an increase of 44.5 times in installed capacity over the past 10 years (2005–2015). In the last 5 years, solar energy powers named in positions from 1 to 5 have been constantly changing between Germany, Spain, India, China and the United States. In 2023, the total installed capacity of the PV in the world can reach more than 1100 GW with a total expected generating capacity of up to 1700 TWh [6].

Technologies in the field of power electronics and semiconductors are increasingly developing, helping to reduce the initial investment costs of PV systems, small operating and maintenance costs, so the cost of producing electricity from the sun is gradually competing with fossil fuel sources (such as coal).

The cost of installing solar panels has dropped sharply from 3.5 ÷ 4 EUR/Wp (in 2008) to only 0.40 ÷ 0.53 EUR/Wp (in January 2017) [7].

This situation leads to strong solar power development in many developing countries like Thailand, China, including Vietnam. Thanks to these advantages, the rooftop system is increasingly being installed, gradually becoming the main power supply solution for small loads (households, offices).

Therefore, the dependence on traditional electricity sources as well as prices of electricity consumption to be paid to electricity companies was reduced.

However, lots of current studies are mostly focusing on large-capacity developed in PV plants, analyzing the impact of these plants on the connected grid [3, 8–10], with little interest in public systems with small capacity.

Moreover, only a few studies on the rooftop are at the level of theoretical simulation [11–16], not showing the actual performance as well as the investment value and ability to recover capital. On the other hand, some researches showed economic and environmental indicators, cost optimization for rooftop photovoltaic systems with a large capacity [17–19], while small capacity installed rooftop systems (usually less than 5 kW) are increasing. Therefore, this paper analyzes and evaluates the performance of a rooftop system with a small capacity of about 2 kW through simulation and experimental methods. Within the paper is analyzed the economic values for installation costs, the ability to recover capital and the saving costs in electricity bill to local electricity companies.

2. BUILDING THE ACTUAL ROOFTOP SYSTEM

2.1. INSTALLATION LOCATION OF THE SYSTEM

Vietnam is located in the equatorial area with an average number of sunshine hours and solar radiation in the year, and along with many policies that encourage the development of solar energy [2], there is a huge advantage that helps PV projects to develop [3, 21]. In addition, the rooftop system has been installed more and more for small consumers, creating an attractive market for investment in distribution units. In this study, the installation location, Quang Binh Province, was selected as the rooftop system installation area to facilitate the research and evaluation process. The installation location of the photovoltaic rooftop system is a household chosen by the Central Power Corporation - Vietnam Electricity to investigate the operation process of the rooftop system. This area has an

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average amount of radiation about 1700 kWh/m^2 and the total sunshine hours in the year is about 1800 hours. Figure 1 and Table 1 show more details about these parameters.

2.2. STRUCTURE OF THE ROOFTOP SYSTEM

The chosen technology solution for the rooftop system is a grid-connected system without storage.

This is the solution that is often chosen because it is cheaper. The durability of a storage system is often very low, and the investment costs are high.

The design of battery capacity is designed based on the household's electricity consumption during the sunny period, which accounts for about two-thirds of the day.

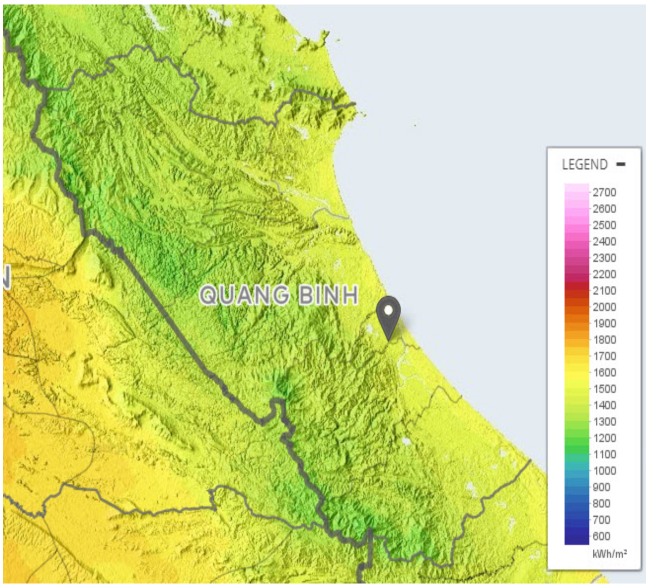

Fig. 1 – Sun radiation at Quangbinh province and at the installation area.

Table 1

Sunshine duration at the installation area (unit: hours)

Month	1	2	3	4	5	6
Sunshine duration (hours)	87.2	66.7	108.2	168.4	229.1	221.4
Month	7	8	9	10	11	12
Sunshine duration (hours)	239.1	201.7	165.4	139.6	95.9	85.4

With the installation location selected, ignoring the effect of the solar panel tilt angle and the temperature effect, the peak power of the solar array is determined with the equation [22–24]:

$$E_{W\,p} = \frac{I_0 E_d}{I_T \eta} \quad [\mathrm{W}], \tag{1}$$

where I_0 = 1,000 W/m^2 is solar radiation at standard conditions; E_d = 10,788 W is the calculated load capacity; I_T = 4,285 Wh/m^2 is the average solar radiation in the installation area [25]; η = 0.8 is the overall performance of the system including: controller, converter, battery charging and discharging efficiency.

From equation (1), the peak power of the rooftop system is:

$$E_{W\,p} = \frac{1{,}000 \times 10{,}788}{4{,}285 \times 0.8} = 3{,}147 \quad [\mathrm{W}] \tag{2}$$

The amount of power system needs to achieve:

$$E'_{W\,p} = \frac{2}{3} \times E_{W\,p} = \frac{2}{3} \times 3{,}147 = 2{,}098 \quad [\mathrm{W}]. \tag{3}$$

From the above data, the installation system has a capacity of 2,160 Wp with the configuration of 8 panels and a capacity of 270 Wp/panel, the installation area is of about 13 m^2. The installation position, deflection angle and installation direction of the rooftop system are shown in Figs. 2 and 3. The rooftop system is installed along the slope of the roof (Fig. 2) with 30^0 of plane tilt and 0^0 of azimuth (as shown in Fig. 3) based on the installation geographic location, which is 17.48^0 North latitude and 106.6^0 East longitude. The solar radiation loss of the system with this type of installation is only 3.8 %, this parameter was calculated automatically after entering the geographic location data.

Fig. 2 – Location and form of the installed rooftop system.

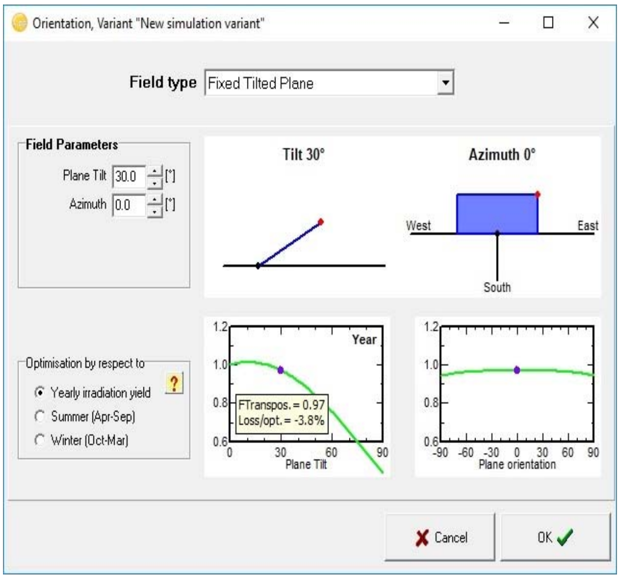

Fig. 3 – Angle and direction for installing the rooftop system.

2.3. SIMULATION OF SYSTEM OPERATION

From the configuration parameters of the system, the operability of the Rooftop system is simulated via PVSyst software with loss factors (as presented in Fig. 4) including:

- thermal loss factor: U = 15 W/m^{2}K, in rooftop form;
- ohmic losses $\Delta U/U$ = 1 % (according to reference values from some European countries);
- module quality is –0.5% (from PV panel manufacturer);
- light induced degradation is from about 1 % to 3 %,

and is chosen a default value of 2 %;

- soiling loss is 1% in months from 4 to 8, these are the hot and sunny months and the environment is full of dust and smoke at the survey area. The remaining months' values are 0 %;
- aging is 0.72 % (according to the manufacturer's specifications and panel warranty for 25 years).

Simulation parameters in Fig. 4 will depend on the type of the selected PV panel, losses in the PV panel and in devices (conductors, inverters, ...) provided by the manufacturer or from the standards of the power company.

Elements in the installation system: PV panel and inverter are installed with the same specifications to ensure accuracy. Specifically, the simulation system parameters are shown in Fig. 5. Users can use data of the PV panel or inverter available in the software library based on information about the manufacturer, year of manufacture, category name or import external data to serve the process of building the system.

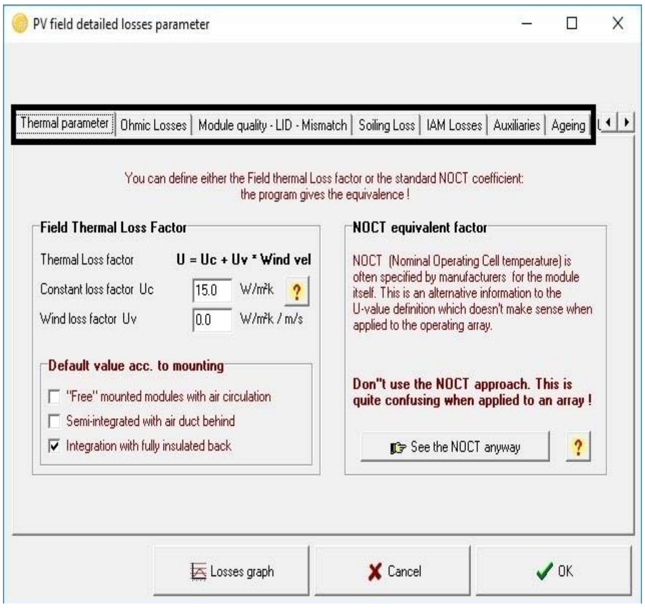

Fig. 4 – Software interface to enter the loss factors in the simulation.

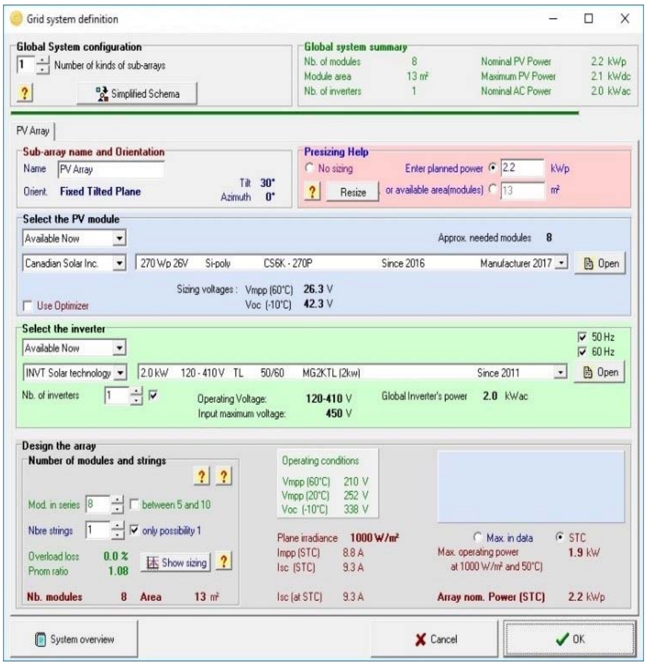

Fig. 5 – Parameters of PV panel and inverter of the rooftop system.

The rooftop system uses a 270 Wp PV panel, code CS6K-270P produced by Canadian Solar Inc. and a MG2KTL inverter produced by INVT Solar Technology Co.,Ltd with a capacity of 2.0 kW.

From the configurations established for the rooftop system, the simulation results will be evaluated. After that, the actual system was installed based on simulated data and collected data for a long time.

3. RESULTS

3.1. SIMULATION RESULTS

Based on the established conditions presented in the previous sections, the power output of the rooftop system is shown in Fig. 6.

From the end of April to the beginning of September, the amount of obtained power is quite stable, less fluctuating compared to the remaining months, but these months have not achieved the maximum power.

Because the rooftop system is affected by two factors of radiation and temperature, high radiation will increase the generating power of the PV system, but the increase in temperature gives the opposite result.

The months of May to August often fall into the peak of hot weather in the installation area, leading to the rise of working temperature of the rooftop system, so that the amount of power cannot be peaked.

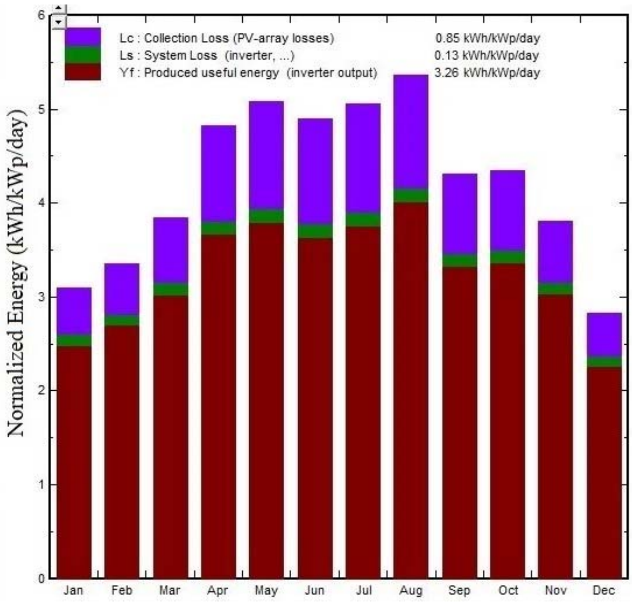

Fig. 6 – Average power output (above installed 1kWp) in the months of 2018 (normal power: 2.16 kWp).

Meanwhile, the period from February to April and around August to September, the time of late spring and early autumn, high radiation and softer temperature help the PV panel system achieve higher power, about 12 kWh/day at peak.

Figure 6 shows that the power output in April to August is quite even and at the highest level (about 4 kWh/kWp/day).

Nevertheless, this is also the reason why the converter system must operate more, resulting in an increase of losses (about 1 kWh/kWp/day).

More specifically, losses in the system and details of power output are shown in Fig. 7 and Table 2.

The highest power outputs are shown in Table 2, and are obtained in August (268.5 kWh), within the system cycle of high power generation (from April to September).

In the winter period from November to March of the following year, the panel power is very low, averaging only about 78 % of the summer.

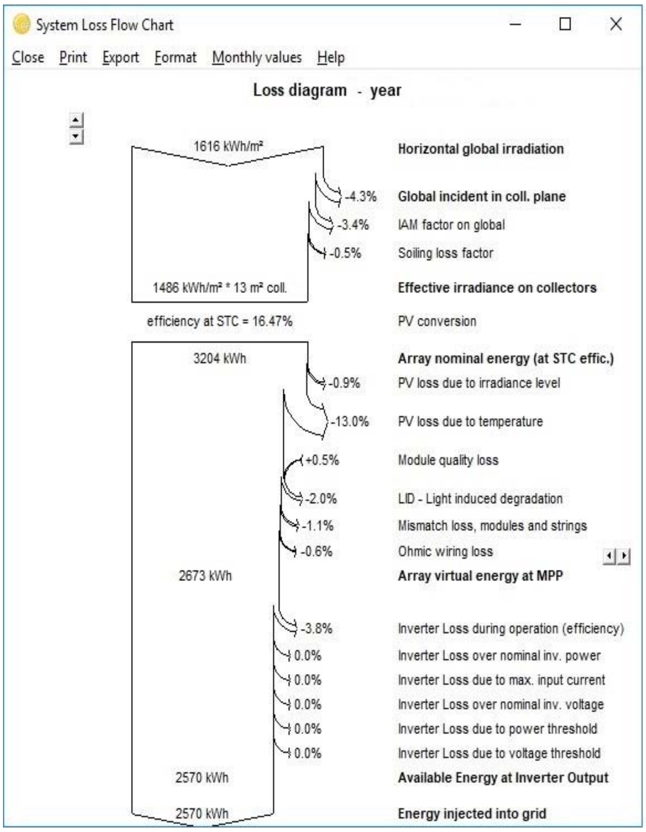

Fig. 7 – Loss flow chart of the rooftop system.

Table 2

Details of the power output of the system

Month	GlobHor kWh/m^2	DiffHor kWh/m^2	T_{Amb} ^{0}C	E_{Array} kWh	E_{load} kWh	PR
1	83.5	53.00	17.8	174.1	166.7	0.803
2	86.5	58.28	19.29	170.4	163.4	0.805
3	118.6	77.50	21.98	211.0	202.4	0.787
4	155.2	81.62	25.82	247.0	237.8	0.761
5	184.9	78.00	28.57	263.9	254.2	0.748
6	180.8	73.61	30.50	245,0	235.9	0.743
7	189.3	79.02	30.45	261.5	251.9	0.744
8	186.2	80.81	29.20	278.3	268.5	0.746
9	131.4	83.21	26.41	224.5	215.9	0.773
10	124.1	73.19	24.81	234.0	225.3	0.775
11	99.8	65.23	21.79	204.3	196.2	0.795
12	76.0	52.33	19.11	158.9	151.8	0.802
Year	1616.2	855.81	24.67	2672.8	2569.9	0.769

where: GlobHor is horizontal global irradiation; DiffHor is horizontal diffuse irradiation; T_{Amb} is ambient temperature; E_{Array} is effective energy at the output of the array; E_{Load} is energy supplied to the load; PR is performance ratio of the rooftop system.

December is the month with the lowest power output of the year due to strong wind.

This result will be verified and evaluated based on a real-time model that is monitored for a long period.

3.2. EXPERIMENTAL RESULTS

From the time simulation data and structure of the rooftop system, actual data has been monitored and collected by the authors via parameters of two-way indicators and informations from the management website of the local power company.

During the simulation, the data of radiation and temperature were sampled from Pvsyst 6.68 software through two main sources: Meteonorm 7.1 and NASA. These two sources of data are only relative, so there are still errors compared to the actual case. In addition, during the operation of the PV system, the weather can have many abnormal, unpredictable changes: sun obscuration, shading [26], making the rooftop system lose a considerable amount of power, resulting in a deviation in the results obtained.

The months of March, May and July have large deviations, especially in September, which deviates up to 90.37 Wp. In the months of March, July and August, the actual power output is lower than the simulation.

The main reason is that, during the weather survey in the installation area, rain occurs more frequently than in previous years. In sunny days, high temperature of the environment (especially July and August, the peak of the dry season) also makes the PV panel system's operating temperature actually increase, reducing the power output.

Thereby, the operation data of the PV panel system is monitored and recorded from 04/2018 to 12/2018. The data is shown in Table 3 and compared with the simulation results.

Table 3

Actual results of the rooftop system and comparison to simulation

Month	Simulation (kWh)	Actual results (kWh)	Difference (kWh)
(1)	(2)	(3)	(4) = (3)-(2)
4	237.8	252.4	14.6
5	254.2	288.88	34.68
6	235.9	234.49	-1.41
7	251.9	209.72	-42.18
8	268.5	255.3	-13.2
9	215.9	306.27	90.37
10	225.3	253.13	27.83
11	196.2	220.83	24.63
12	151.8	166.42	14.62

Particularly in May, September and October, the obtained power is higher than the simulation results.

May is the first month of summer, so the temperature is not too high, and the rainfall is low.

September and October are the transition periods for autumn, so the working temperature of the panels is not as high as in July and August.

The weather in these months is also less rainy in the installation area than in previous years, creating favorable conditions in exploiting and using installed PV systems.

During operation, the system always meets grid connection standards in Vietnam [27, 28], allowing long-term operation and investment costs recovery.

Actual parameters and standards are presented in Table 4.

From the actual results, the economic values will be calculated specifically about the benefits that this system brings as well as the payback capability of the project.

4. EVALUATION OF ECONOMIC EFFICIENCY

All investment and installation costs are presented in Table 5. The costs to be paid to the local power company during the examined period and the recovery costs from the sale of electricity from the PV system according to the price set by the Vietnamese government are detailed in Table 6.

In addition to the electricity from the solar system in the daytime, at night, consumers must receive electricity from the distribution grid to use with a capacity of 1,614 kWh.

If calculated according to the current electricity price of Vietnam Electricity, the payment from April to December is 131.609 USD.

This amount could be reduced thanks to the residual power output from PV system and brought back to the grid (or reselling electricity to the local power company).

The amount of reselling PV power has reached 128.562 USD/9 months, so that the consumers only need to pay 3.048 USD/9 months.

Table 4

Actual parameters and grid connection standards

	Parameters		Measured values	Requirement	Result
1	Operating voltage		233.44 V	187 ÷ 242 V	Pass
2	Frequency		50.11 Hz	49 ÷ 51 Hz	Pass
3	Penetration of direct current		0.011 A	≤ 0.045 A	Pass
4	Voltage harmonics	THD	2 %	THD ≤ 6.5 %	Pass
		3^{nd}	0.7 %	H(3) ≤ 3 %	Pass
		5^{th}	1.6 %	H(5) ≤ 3 %	Pass
		7^{th}	0.7 %	H(7) ≤ 3 %	Pass
5	Voltage fluctuation	P_{st}	0.45	$P_{st} \leq 0.9$	Pass
		P_{lt}	0.31	$P_{lt} \leq 0.7$	Pass
6	Power factor		0.99	PF ≥ 0.9	Pass

where: THD is total harmonic distortion; P_{st} is short-term flicker severity indicators; P_{lt} is long-term flicker severity indicators.

Table 5

Installation and investment costs

	Category	Price (USD)
1	PV panels	1,189.16
2	2 kW grid-connected inverter	430.11
3	Ac electric control panel	43.01
4	Frame support panel	210.58
5	Peripherals (wires)	43.01
6	Installation costs	43.01
	Total system cost	1,958.88
	Tax (10 %)	195.89
	Total investment	2,154.77

Table 6

Power and money exchange between consumers and power company.

Month	Power consumption (from the grid) (kWh)	Additional payment due to electricity grid use (USD)	Power from rooftop systems sold to power company (kWh)	Profits from selling electricity of rooftop systems to power company (USD)
4	152.00	12.020	130.15	12.845
5	155.00	12.284	173.23	17.096
6	156.00	12.372	157.99	15.592
7	227.00	19.229	120.09	11.852
8	186.00	15.009	113.13	11.165
9	172.00	13.778	172.29	17.004
10	157.00	12.460	167.93	16.573
11	157.00	12.460	180.32	17.796
12	252.00	21.997	87.52	8.638
Sum	1,614.00	131.609	1,302.65	128.562

Table 7

Payback capability of the project

Calculated input factors	
Investment rate (USD/kWp)	906.89
Unit price of electricity (USD/kWh)	0.1
Depreciation (%/year)	0.8
Inflation coefficient (%/year)	8
Electricity price growth rate (%/year)	2
Loan rate (%/year)	0
Calculation result of payback capability	
Internal rate of return (IRR) (%/year)	12.07
Payback period (PP) (year)	8
Discounted payback period (DPP) (year)	13

As seen from Table 7, with the calculated input factors based [17–19, 23] on the installation system with the depreciation rate of 0.8 % and the entire cost of the investor (no loan so the rate is at 0 %), the period is at least 8 years for the investor to recover the capital. If discount costs are to be calculated, the payback period may last up to 13 years.

With the calculation results of the expenditures and economic values, the PV rooftop system only shows the benefits of power supply capacity for the load, reducing the dependence on the distribution grid. However, the project's payback period is quite long, and consumers need to pay a small amount of money annually to compensate for the lack of electricity due to the demand at night.

5. CONCLUSION

The rooftop PV systems are now increasingly installed. Through simulations and experiments, the obtained power output shows the efficiency of the system operation, and also points out the deviation in the simulation. However, economic problems still exist, making investment efficiency low: the purchase price of electricity from PV systems is not high, the payback period is long. The paper also shows the effectiveness as well as weaknesses of photovoltaic rooftop systems.

Currently, in Vietnam, the government has offered a high price of purchasing and selling electricity generated from renewable energy sources, especially solar energy, but it is forecasted that the price will be reduced in the coming years. This makes the payback period longer and reduces the economic values of the project.

In addition, the development of rooftop systems will create a lot of impact on the grid as harmonics and voltage deviation. Connecting these systems to the distribution grid in random order (depending on the location of consumers) will cause phase imbalance. The amount of transmission power will have a large difference if the rooftop systems that only focus on a fixed phase. Therefore, studies of the impact of rooftop systems need to be developed in the near future.

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