Feasibility Assessment of Grid-Connected Residential Solar Photovoltaic Systems in Seven Zones, Vietnam

Thanh Ba Nguyen[1,*]

ARTICLE INFO

Article history:
Received: 24 June 2021
Revised: 3 September 2021
Accepted: 10 January 2022

Keywords:
Solar photovoltaic (PV) system
Rooftop solar photovoltaic (PV)
Energy analysis
Economic analysis

ABSTRACT

The electricity produced by a solar power system highly depends on the intensity of solar radiation at the site where it is built. Thus, solar energy projects in different areas obtain different economic and environmental efficiency. The installation of rooftop solar power systems has had a quick move in Vietnam in the past years; however, the assessment of the economic efficiency of these systems within the country is still limited. This research aims at conducting a comparative assessment of the economic and energy efficiency and CO_2 emissions of 10kWp household rooftop solar power projects in the seven different regions of Vietnam, including Hanoi, Quang Binh, Dak Lak, Khanh Hoa, Binh Thuan, Binh Duong and Dong Thap. This study designs a 10kWp rooftop solar power system and uses these models as a reference to simulate, evaluate and compare economic and energy efficiency and CO_2 emissions among the selected projects. The software used to simulate energy efficiency is PVsyst. The economic indicators of the project calculated include the payback period (PB), internal rate of return (IRR), net present value (NPV) and benefit cost ratio (BCR). The results show that the two projects in Khanh Hoa and Binh Thuan Province have higher power outputs than the rest. In economic terms, the projects are not really effective due to the long payback period and low NPV, IRR and BCR. In addition, if households use more electricity during the daytime, it is more beneficial than using electricity at night. This study provides useful information to the people planning to invest in residential rooftop solar power projects as well as renewable energy policymakers in Vietnam once taking into account the economic potential, energy potential and CO_2 emissions.

1. INTRODUCTION

Vietnam is currently one of the fastest developing nations in East Asia. Along with the process of industrialization and economic modernization, it is forecast that the energy demand of the country will rise by over 10% per year in the period of 2021-2030 [1-3]. This is a tough challenge for the Government of Vietnam to meet such an increasing energy demand.

Vietnam has great potential to develop renewable energy, including solar energy. However, the development of solar power in Vietnam has been slow, and solar power had not been considered a viable option for power generation until 2015 when the Vietnamese Government issued the strategy for renewable energy development [3]. In 2017, the Prime Minister issued Decision No. 11/2017/QD-TTg on the mechanism for encouraging the solar power development throughout the country [4]. According to this decision, solar farm and rooftop projects that started operating before June 30, 2019 are eligible to sell their electricity to the state-owned company - Electricity of Vietnam (EVN). In particular, in April 2020, Decision No. 13/2020/QD-TTg was issued to replace Decision No. 11/2017/QD-TTg which created a strong impetus for solar power development, including rooftop solar power. As stated in the Decision, the selling price of rooftop solar power, 8.38 UScent/kWh, is applied only for the projects installed in 2020 and the later projects have to wait for a new policy issuance [5].

Thanks to the Government's incentive policy, there has been an impressive boom in the installed solar capacity in Vietnam. In 2018, there was only 86 MW of capacity. However, as of June 2019, the capacity soared to 4,450 MW. Vietnam is one of the most attractive solar energy markets in the world, which installed nearly 5GW of electricity in the first half of 2019 and surpassed Thailand to rank the first in Southeast Asia in terms of the largest installed solar (PV) capacity in this period of time (Figure 1) [6], [7].

As of 2020, the capacity of the installed solar PV was roughly 16,500 MW, equivalent to one fourth of the country's installed power capacity [8]. This far surpasses its 2020 target of 850 MW [9]. As of 2020, rooftop solar

[1]*Institute of Engineering and Technology, Thu Dau Mot University, Thu Dau Mot City, 75109, Vietnam.*
**Corresponding author:* Thanh Ba Nguyen; Phone: +84934-001-305; E-mail: thanhnb@tdmu.edu.vn

capacity contributed about 48% of the total solar capacity of Vietnam [10].

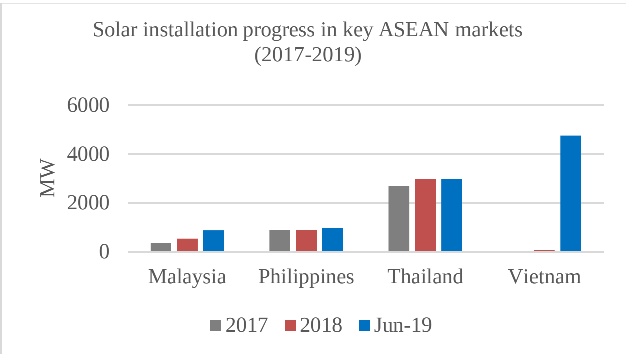

Fig. 1. Installed solar capacity in key ASEAN markets, 2017–2019 [7].

A grid-connected rooftop power system offers many benefits such as reducing the risk of national power shortages, contributing to emission reduction, taking up no additional installation space and helping to cool down buildings [11]. There has been a great deal of research on the economic and technical feasibility of grid-connected solar power systems in different countries around the world.

Elamim, A. et al [12] evaluated a 5.94 kWp solar power system with photovoltaic panels made from three different technologies, including a-Si, pc-Si and mc-Si under Morocco's climate condition. Research results showed that polycrystalline technology panels best suited to the local weather conditions.

Cristea, C. et al. [13] carried out the economic assessment of the rooftop solar energy projects in Romania. This study was conducted by using PVSOL software. The results showed that photovoltaic systems were economically competitive in certain situations, including the recommendation on increasing subsidies, especially in the North of Romania in order to compensate for the lower level of irradiation.

V. Tomar and G. N. Tiwari [14] conducted a study among the three different households in New Delhi, India using the grid-connected rooftop/building integrated photovoltaic (BIPV) system to electrify the optimal consumption. The feed-in tariffs/net metering process along with the Tariff of day (ToD) tariff regulation were also incorporated. HOMER was adapted when evaluating technological and economic values of this grid-connected PV system.

Li, C. et al. [15] presented an economic-technical assessment of the rooftop solar power projects for five different climate zones of China. The authors used HOMER software in their study. Among the grid/PV projects located in the five different climate zones, the one in Kunming with the least NPC ($113,382) and COE ($0.073/kWh) seems to be the most suitable to generate grid/PV power systems.

Duman, A. C., & Güler, Ö. [16] carried out an economic assessment for a 5kWp grid-tied solar PV system in nine different provinces of Turkey. The evaluated economic indicators in this study include Discounted Payback Period (DPBP), Internal Rate of Return (IRR) and Profitability Index (PI). The study was implemented by using HOMER Grid software. The research results showed that only one southern province is economically attractive.

Raghoebarsing, A., & Kalpoe, A. [17] evaluated the energy and economic efficiency of the 27kWp project in Suriname. This study used PVsyst software to simulate the performance evaluation and RETScreen software to calculate the levelised cost of energy (LCOE). The results showed that the LCOE was 0.36 USD/kWh, which was three times higher than the electrical energy price in Suriname.

Ali, H., & Khan, H. A. [18] technically evaluated a 42kWp rooftop solar project with photovoltaic panels made from two technologies, polycrystalline-Si and CIS thin-film. The simulation was performed by using PVSOL software. The research results showed that polycrystalline-Si panels were economically beneficial, but their energy generated was less than CIS thin-film.

Mondal, MAH, & Islam, A.S. [19] conducted a pre-feasibility assessment of a 500kW project in Bangladesh by using HOMER and RETScreen software. The research results showed that the amount of electricity produced from the PV system was competitive compared to diesel power generation.

Tarigana, E., & Kartikasari, F. D. [20] used PVsyst and RETScreen software to evaluate a 1kW solar PV system in Surabaya, Indonesia. The research showed that without financial support from the government, the project will not be economically viable. The payback period of the project is 17.6 years. If there were a government policy to buy solar energy with the price of USD 0.25/kWh, the payback period would be shortened to 6.5 years.

Bakhshi, R., & Sadeh, J. [21] evaluated the feasibility of a 5 kW grid-connected PV system in 15 Iranian cities. The article showed that building solar PV systems was feasible, especially in the central cities of the country.

Coria, G. et al [22] demonstrated that with the current Argentine policy, investing in residential solar power projects is not economically viable.

Rodrigues, S. et al [23] studied the feasibility of 1kW, 3kW, 5kW PV systems in Chinese cities and showed that the higher the capacity of the PV system is, the more beneficial it is.

Duong, M. Q. [24] evaluated a 2kWp residential solar power system in Quang Binh Province, Vietnam. PVsyst software was used for simulation. Research results showed the feasibility of energy, but the payback time was long.

In general, the evaluation of these above-mentioned projects' economic and energy feasibility was conducted with the help of simulation software.

In Vietnam, although the market for rooftop solar power is booming, there have been no studies examining the economic viability of residential rooftop solar systems in different regions. The country is located in the tropical climate, extends from north to south and is divided into seven economic zones [25]. With the geographical stretching, the intensity of solar radiation varies from one to another region (Figure 3); hence, the amounts of power obtained from the PV systems in such regions are also different. Therefore, this study provides useful information for Vietnamese stakeholders in the field of residential rooftop solar power.

The main aims of this study:

- Design and select equipment for seven 10kWp residential rooftop solar PV systems in the seven different regions of Vietnam;
- Simulate the PV systems by using PVsyst software;
- Evaluate the economic and energy efficiency and environmental impact of the seven solar PV systems in the seven different regions in Vietnam.

The household rooftop solar power sector is a new field in Vietnam; however, only the energy or economic efficiency of few individual projects has been evaluated. Furthermore, there is no comparison among the projects in the different regions of Vietnam. This paper aims to provide useful information for stakeholders in residential rooftop solar PV investments and energy policymakers in Vietnam as well.

2. MATERIALS AND METHODS

The methodology adopted to evaluate the technical and economic feasibility study of the rooftop solar PV system is a four-phase approach as illustrated in Figure 2.

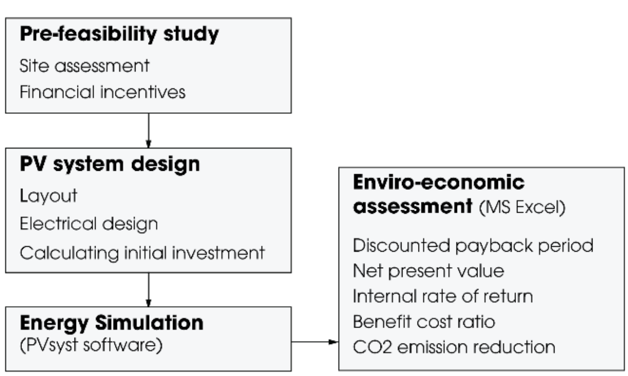

Fig. 2. General scheme of the proposed methodology used in the study.

Step 1: Carry out an overall assessment of the projects, including geographical location, weather conditions and government support policies on solar energy development.

Step 2: Design a 10kWp rooftop solar PV system for a household in Binh Duong province and calculate the initial investment cost of this PV system.

Step 3: Evaluate energy efficiency for seven 10 kWp solar PV systems in the seven different regions based on simulation by using PVsyst 7.1 software [26]. The technical parameters of PV systems in the seven regions are obtained from the designed PV system in the second step and the solar radiation data is obtained from meteonorm database [27-28] integrated in Pvsyst software.

Step 4: Calculate the economic indicators and CO_2 reductions of the different PV systems.

2.1 Pre-feasibility study

2.1.1 Site assessment

The purpose of this step is to collect the information about the solar PV systems to be installed, including geographical location, orientation of the house, weather conditions, solar radiation intensity and financial support policies from the government.

The solar energy output obtained from PV panels is directly influenced by the following parameters: radiation intensity, number of sunshine hours, orientation and inclination of the PV panels [29]. Seven locations of the PV projects are randomly selected from the seven different regions of Vietnam, including Hanoi City (HN) representing the Red River Delta region, Quang Binh (QB) Province representing the North Central region, Dak Lak (DL) province representing the Central Highlands region, Khanh Hoa province (KH) representing the central region, Binh Thuan Province (BT) representing the South Central region, Binh Duong Province (BD) representing the Southeast region and Dong Thap Province representing the Southern region. The parameters of geographical location, radiation intensity, sunshine hours in each PV project are described in detail in Table 1 below.

Figure 3 shows the solar radiation data of the proposed sites obtained from the Meteonorm V.7.3 software [27].

Figure 4 depicts the annual solar radiation intensity of Vietnam. The average daily solar radiation is roughly 5 kW/h/m2 in the Central and Southern regions and about 4 kW/h/m2 in the Northern part. The annual sunshine duration in Northern region is 1,500-1,700 hours while it is about 2,000-2,600 hours in both the Central and Southern parts of the country [30], [31].

Table 1. Locations and yearly irradiation in the different regions [31]

Parameter	HN	QB	DL	KH	BT	BD	DT
Longitude	21°08'25.3"	10°48'26"	12°35'41"	12°13'51.9"	10°43'27"	10°58'36"N	17°48'31"
Latitude	105°24'00.9"	105°25'52"	108°26'42"	109°10'15.0"	107°57'32"	106°40'40"E "	106°24'20"
Height	26 m	2 m	508 m	75 m	9 m	29 m	9 m
Hours of sunshine	4.8	5.0	5.2	5.5	5.1	4.9	4.8
Radiation intensity (kWh/day/m2)	1.730	3.595	3.702	4.129	4.338	3.444	2.544

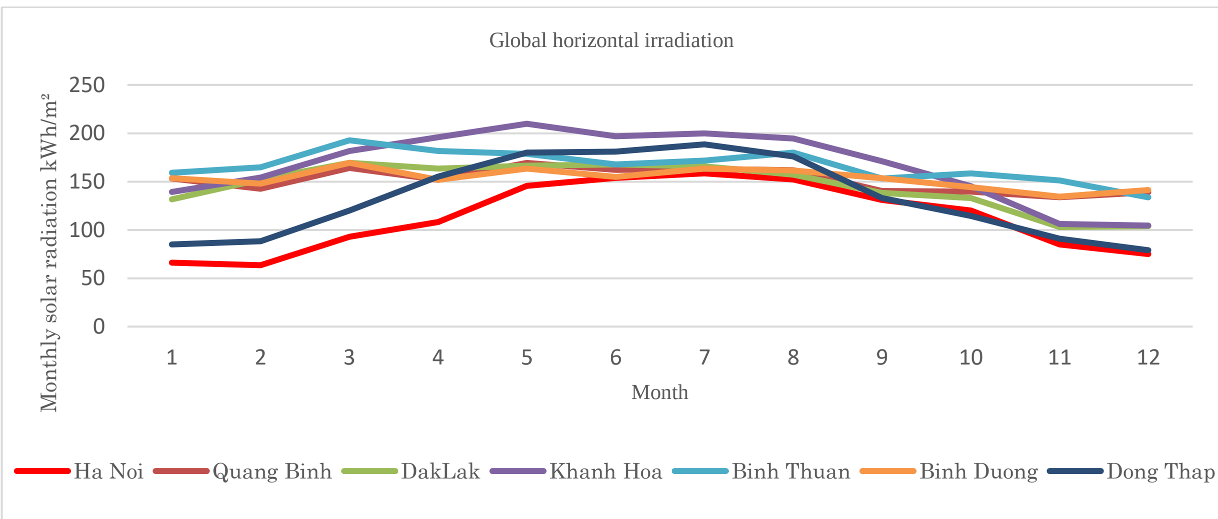

Fig.3. Monthly average global solar radiation at the proposed sites [27].

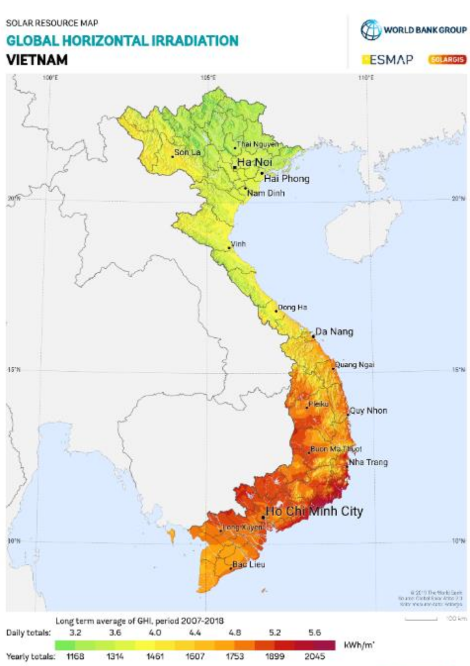

Fig. 4. Global horizontal irradiation in Vietnam [31].

2.1.2 Financial incentives

Currently in Vietnam, EVN sells electricity to households according to the tiered electricity tariff described in Table 2. The selling price of electricity from solar energy projects to EVN is described in Table 3. Accordingly, the solar power generated by the rooftop PV projects installed before December 31, 2020 are purchased by EVN at the price of 8.38 USc/1kWh which will be applied for 20 years from the date of commercial operation [5].

Table 2. Electricity tariffs of urban areas in Vietnam [32]

Segment Tariff	Price per unit (VND/kWh)
From 0 to 50 kWh	1,678
From 51 to 100 kWh	1,734
From 101 to 200 kWh	2,014
From 201 to 300 kWh	2,536
From 301 to 400 kWh	2,834
Above 401 kWh	2,927

Table 3. Feed-in tariff for solar power [5]

Description	Feed-in Tariff	
	VND/kWh	Equivalent to UScent/kWh
Ground-mounted project	1,620	7.09
Floating project	1,758	7.69
Rooftop solar project	1,934	8.38

(Note: The applicable exchange rate between VND and USD is the central exchange rate published by the State Bank of Vietnam on March 10, 2020)

2.2 Photovoltaic system design

The rooftop solar PV systems must be optimally designed, ensure both investment cost and technical requirements. Among the components that make up a PV system, inverters and solar panels play an main role in the quality and cost of the project.

2.2.1 Layout of PV systems

The structure of the rooftop PV system is designed based on the current state of the house. In Vietnam, the optimal direction to place the solar panels is west – south and the tilt angle of the battery is 12-15 degrees [31-30]. In this design, the house surveyed has a flat roof and is surrounded by no tall trees or tall buildings; therefore, there is no shade.

Depending on their components and grid connection, solar PV systems are divided into on-grid (grid-tied) systems, off-grid systems and hybrid systems [33]. In Vietnam, grid-tied PV systems are commonly used for households because of their low initial investment costs. The components of this system include PV modules, inverters, conductors, mounting systems, electrical cabinets, protection devices and bidirectional meters [34]. If more solar energy is generated than the household needs, the excess energy is discharged into the grid. In contrast, if the generated solar energy is not enough to meet the household needs, the remaining demand is met by importing electricity from the grid. The energy flows in on-grid connected PV system is illustrated in Figure 5.

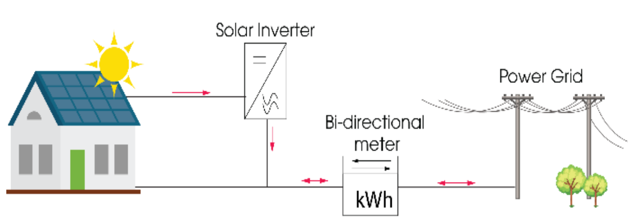

Fig. 5. A typical household grid-tied system in Vietnam

2.2.2 Electrical design

Electrical design includes choosing solar panels, inverters, switchgear, wiring, protective devices, protective grounding, etc. In this study, the selection of panels and inverters is carried out as below:

The sizing of the PV array is based on the inverter specifications and the house structure. The number of panels to be used is:

$$N_{SolarPV} = \frac{P_{SolarPV,req}}{P_{Array}} \quad (1)$$

where, $N_{SolarPV}$: solar panels are needed; $P_{SolarPV,\,req}$: required installed power (Wp); P_{Array}: rated power of solar PV panel (Wp).

The power of the inverter is selected according to the rule [35-36]:

$$P_{Inverter} = \frac{P_{SolarPV,req}}{1.2} \quad (2)$$

where, $P_{Inverter}$: the rated power of the inverter; 1.2 is a compatibility coefficient selected based on the previous domestic simulations.

Table 4. PV module specifications

Specifications	Descriptions
Model	AE 360M6 -72 (1500)
Manufacturer	AE Solar
Maximum power (Pmax)	390 Wp
Cell-type	Mono-crystalline
Maximum power voltage (Vmp)	40.79 V
Maximum power current	9.56 A
Open circuit voltage (Voc)	49.06 V
Short circuit current (Isc)	10.10 A
Module efficiency STC	19.29%
Operating temperature	-40°C~+85°C
Maximum system voltage DC	1500VDC (IEC)
Number of panels	26
Module area	52.2m2
Cell area	47.2m2
Space requirement for system installation	55.5m2
Number of strings	2 string x 13 in series
Tilt angle	12^{o}

The specifications of the selected panels and inverter are described in Table 4 and Table 5. The monocrystalline silicon solar panels are adapted since their efficiency is higher than that of the polycrystalline silicon [37]. Figure 6 depicts a single-line diagram of the solar PV system. This system consists of 26 panels with a rated power of 390Wp divided into 2 strings, connected to a 10kW inverter. The solar PV system specifications selected in this section are used to simulate all the seven PV systems at the seven different locations in Vietnam. Section 2.3 below describes these simulations.

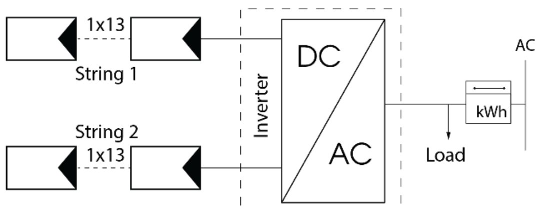

Fig. 6. One-line diagram of the proposed PV system.

Table 5. Inverter specifications

Specifications	Descriptions
Model	PVI - 10.0 -TL-OUTD
Manufacturer	ABB
Max input power (Pdc,max)	10kW
DC voltage range (Vmpp)	300V to 750V
Number of Maximum 1 Power Point (MPP) Trackers	2
Maximum DC voltage (Vmax-input-inv)	1000V
Maximum DC current (Imax-input-inv)	34 A
Input Voltage (Uin)	200V to 850V
Maximum Input Power DC	13750 W
Number of Phases	3-phase
Ambient temperature range (°C)	-25 °C to +60 °C
Rated Efficiency (EURO/CEC)	97.8%
Number of inverters	1

Table 6. Initial investment cost of the proposed PV system

Items	Quantity	Prices (VND)	Costs (VND)
Solar Panel	26	3.560.000	92.560.000
Inverter	1	81.121.000	81.121.000
Cabling, installation cost, and others			27.820.335
Total initial cost			201.501.335

2.2.3 Initial investment cost

The initial investment cost of the system including solar panels, inverter, wires, related equipment and installation costs are described in Table 6.

2.3 Simulation by PVSYST software

Currently, there are various types of simulation software supporting solar energy research such as RETScreen, HYBRID2, TRNSYS, HOMER, PVSYST, etc. RETScreen is the software used in pre-feasibility study to compare cost and benefit of the projects on generating electricity from both renewable energy and conventional energy [38]. HYBRID2 is used for the performance assessment of hybrid renewable energy projects [39]. TRNSYS is widely used for transient simulation of thermal and electrical systems [40]. HOMER simulation tool focuses on the optimization numbers of equipment with different renewable resources, cost-effective and reliable microgrids that combine traditionally generated and renewable power, storage, and load management [15]. PVsyst is a simulation tool which does not evaluate the PV system's economic efficiency, but the system's energy efficiency only [41]. In this study, the PVsyst software is selected because of its reliability [42-44]. In PVsyst software, energy assessment is implemented based on IEC 61724 Standard [34], [45].

The simulation procedure for energy assessment is shown in Figure 7. The simulations are performed for seven solar PV systems in the different provinces with the same specifications, but only different in weather parameters.

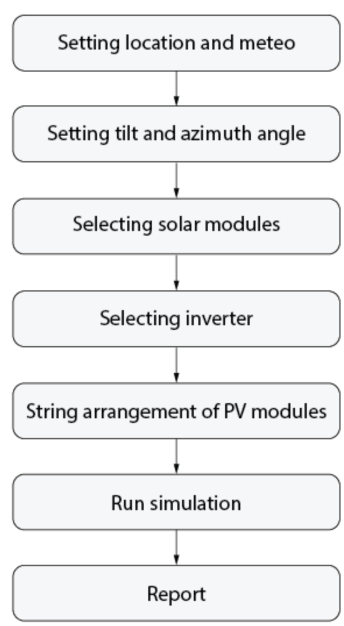

Fig. 7. Simulation process of the solar PV system by PVsyst software [36].

2.4 Enviro-economic assessment

The rooftop solar PV project is proved to offer energy benefits as well as reduce CO_2 emissions to the environment. The amount of CO_2 emission reduction of the project is calculated based on the formula below (3).

$$t_{CO_2} = \sum_{n=1}^{N} E_{Grid_n} * EF_{Grid} \quad (3)$$

where, E_{Gridn}: the energy generated by the system in n^{th} year; EF_{Grid} (the CO_2 emission factor of the Vietnamese grid) = 0.8649 t_{CO2}/MWh [34].

The economic efficiency of solar PV projects is assessed by basic economic indicators such as payback time, NPV, IRR, B/C. The profit of the power systems depends on the initial investment cost, annual maintenance cost, equipment replacement cost, the price of electricity purchased by EVN based on the 6-tiered prices applied for households, the amount of electricity produced by the PV system, and the selling price of solar power to EVN according to Decision No. 13/2020/QD-TTg [5].

The following section presents the main economic criteria of the solar power project investment evaluation:

Net Present Value (NPV) is the sum of the present values of the cash inflows and outflows. The project is effective if NVP > 0 [46]. The formula for calculating the NPV is:

$$NPV = \sum_{m=0}^{M} \frac{EB_m}{(1+r)^m} - \sum_{m=0}^{M} \frac{EC_m}{(1+r)^m} \quad (4)$$

where, EB_m: expected benefit as of the year m; EC_m: expected cost as of year m; r: discount rate; M: the system's total lifetime; m: the m th year.

Internal Rate of Return (IRR) is a rate that makes the net present value of any project equal to zero. The project is considered feasible when the IRR is higher than the expected interest rate [46]. IRR is the solution of the equation NPV = 0 where r = IRR.

$$\sum_{m=0}^{M} \frac{EB_m}{(1+r)^m} - \sum_{m=0}^{M} \frac{EC_m}{(1+r)^m} = 0 \quad (5)$$

Payback period (PB) refers to the amount of time it takes to recover the cost of an investment. The payback period is the length of time an investment reaching a break-even point. Shorter paybacks mean more attractive investments [47].

$$\sum_{m=0}^{M} (EB_m - EC_m) = 0 \quad (6)$$

Benefit cost ratio (BCR) is defined as the ratio of project benefits to project costs (7). If the BCR is higher than one, the PV project is profitable.

$$BCR = \frac{\sum_{m=0}^{EM} \frac{EB_m}{(1+r)^m}}{\sum_{m=0}^{M} \frac{EC_m}{(1+r)^m}} \quad (7)$$

3. RESULTS AND DISCUSSION

3.1. Enegy results

This section presents the simulation results of the seven PV systems located in the seven different provinces of Vietnam, including Hanoi, Quang Binh, Khanh Hoa, Binh Thuan, Dak Lak, Binh Duong and Dong Thap.

Table 7 presents the monthly weather and solar power outputs of the PV system located in Khanh Hoa Province. The total energy produced by the system is 16,549 MWh/year. The largest amount of electrical energy is obtained in May with 1,716 MWh and the lowest in December with 0.88 MWh.

Table 8 and Figure 9 show the first year PV systems' power outputs in the selected locations which are listed from the highest to the lowest as follows: 16.55 MWh in Khanh Hoa, 16.49 MWh in Binh Thuan, 15.09 MWh in Quang Binh, 14.71 MWh in Binh Duong, 14.68 MWh in Dak Lak, 13.28 MWh in Dong Thap and 11.36 MWh in Hanoi. The corresponding power output values in kWh/kWp are 1632 kWh/kWp in Khanh Hoa, 1627 kWh/kWp in Binh Thuan, 15.09 kWh/kWp in Quang Binh, 1451kWh/kWp in Binh Duong, 1448 kWh/kWp in Dak Lak, 1310 kWh/kWp in Dong Thap and 1121 kWh/kWp in Hanoi.

Table 8 also shows the amount of CO_2 emissions saved by each solar power system. The amount of CO_2 emitted by each system is calculated based on their annual electricity outputs.

The electricity outputs obtained in Binh Thuan and Khanh Hoa Provinces are higher than those in the other regions due to their higher radiation intensity while Hanoi has the lowest output because of its lowest radiation level (Figure 8).

Table 9 and Figure 9 describe the monthly power output of solar power systems. The graph shows that the highest amounts of electricity produced are in the summer months, from April to July, when the radiation intensity is higher than the rest of the year.

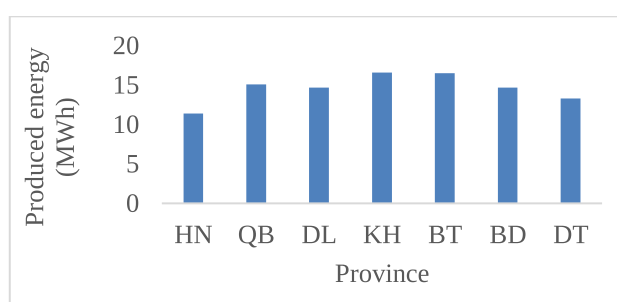

Fig. 8. Produced energy of the proposed PV systems in the different regions.

Table 7. The monthly weather and energy production of the PV system in Khanh Hoa Province

Month	GlobHor kWh/m2	DiffHor kWh/m2	T_Amp oC	GlobInc kWh/m2	GloEff kWh/m2	EArray MWh	E_Grid MWh	PR ratio
Jan	139.2	63.58	24.16	139.1	134.4	1.210	1.174	0.832
Feb	154.3	67.03	24.65	154.3	150.0	1.334	1.296	0.828
Mar	181.7	75.71	26.03	181.6	177.1	1.552	1.507	0.818
Apr	195.9	76.97	27.24	195.8	191.4	1.662	1.615	0.813
May	209.8	70.35	28.30	209.7	204.9	1.766	1.716	0.807
Jun	196.8	75.78	28.41	196.7	191.7	1.665	1.618	0.811
Jul	199.9	74.00	28.83	199.8	194.8	1.684	1.636	0.808
Aug	194.4	77.13	28.73	194.4	189.8	1.640	1.593	0.808
Sep	171.1	79.54	27.60	171.0	166.6	1.455	1.414	0.815
Oct	145.1	78.02	26.87	145.0	140.5	1.246	1.209	0.822
Nov	106.2	64.47	25.49	106.1	102.2	0.921	0.890	0.827
Dec	104.5	61.65	24.90	104.5	100.5	0.910	0.880	0.830
Year	1999.0	864.23	26.78	1998.2	1943.9	17.045	16.549	0.817

Legends

GlobHor Global horizontal irradiation
DiffHor Horizontal diffuse irradianton
DiffHor Ambient Temperature
GlobInc Global incident in coll. plane
GloEff Effective Global, corr. for IAM and shadings
EArray Effective energy at the output of the array
E_Grid Energy injected into grid
PR Performance Ratio

Table 8. The CO2 emissions and energy of the proposed PV system in the different regions

System production	HN	QB	DL	KH	BT	BD	DT
Produced energy [MWh/year]	11.36	15.09	14.68	16.55	16.49	14.71	13.28
Specific production [kWh/kWp/year]	1121	1489	1448	1632	1627	1451	1310
Avoided CO2 emissions [ton/year]	9.83	13.05	12.70	14.31	14.26	12.72	11.49

Table 9. Monthly produced energy of the PV systems in the seven regions (kWh)

Month	HN	QB	DL	KH	BT	BD	DT
Jan	575	1278	1115	1,174	1332	1498	733
Feb	547	1185	1282	1,296	1368	1341	762
Mar	795	1347	1416	1,507	1580	1376	1024
Apr	917	1249	1366	1,615	1485	1113	1299
May	1214	1393	1382	1,716	1460	1116	1485
Jun	1272	1344	1397	1,618	1391	1017	1483
Jul	1305	1352	1376	1,636	1420	1095	1534
Aug	1259	1335	1313	1,593	1492	1157	1441
Sep	1093	1163	1157	1,414	1266	1071	1102
Oct	1012	1168	1120	1,209	1319	1250	966
Nov	725	1119	869	890	1258	1275	771
Dec	652	1160	887	880	1122	1405	679

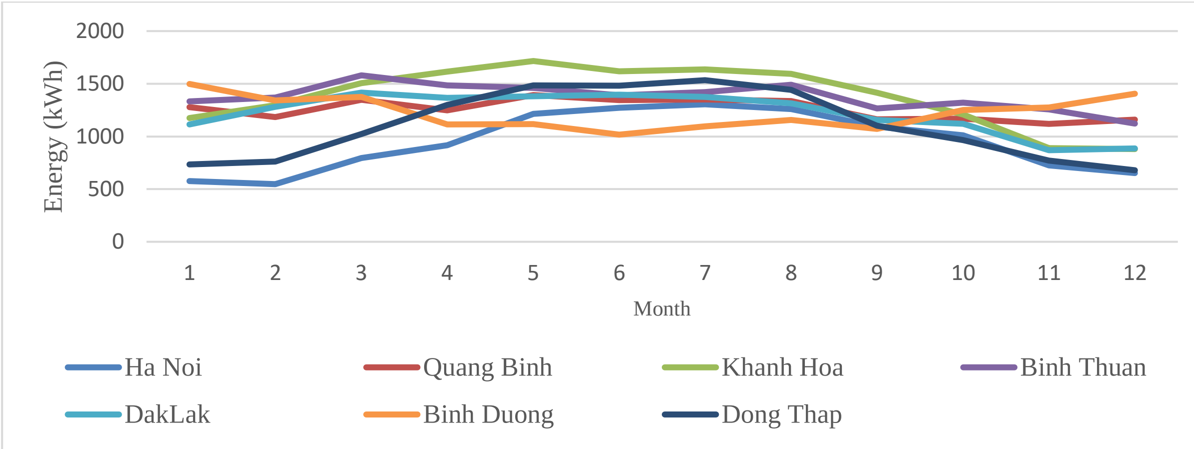

Fig. 9. Monthly energy production of the PV systems in the different regions.

3.2 Economic analysis

The profits generated by the rooftop PV systems have several sources of uncertainty. Each of these calculation parameters, if changed, will affect the economic profit. Several assumptions are made for the economic calculation as follows:

- The PV system's lifetime is 20 years according to [5];
- The inverter replacement is10 years [48], [49];
- The discount rates of this study are 0% and 10%.
- The load and electricity price are constant throughout the project lifetime and the PV degradation is 1% per year [50], [51];
- Residential energy consumption between daytime and nighttime are 70% - 30%, 50% - 50% and 30% - 70%. Such assumptions are based on the actual survey shown in Table 10.

The household has to purchase electricity from EVN based on the tiered electricity tariff (shown in Table 2). As a result, when operating a solar power system, they do not have to pay a certain amount of electricity at a high rate and they can sell the unused solar energy to EVN at the same time. Therefore, the solar PV system's profit consists of the money saved from purchasing electricity at the lower rate and the money from selling the unused solar energy to EVN:

$$Y = (Be - Af) + (3-1) * 1,934 \text{ (VND)} \tag{8}$$

where, Y: Profit of the solar PVsystem (VND); Be: Amount to pay without the solar PV system (VND); Af: Amount to pay with the solar PV system (VND); (3-1): the unused solar energy (kWHh); 1,934: the selling price of residential rooftop solar energy to EVN (VND/kWh).

In this study, economic indicators PB, NPV, IRR, BCR are evaluated at the discount rates of 0% and 10% for 3 scenarios of the energy usage between daytime and nighttime: 70% - 30%, 50% - 50% and 30% -70%. In case of the discount rate of 0%, the discount rate is not considered. In the case of 10% discount, the rate is selected based on the bank interest rate in Vietnam, but the interest rate may change over time [52]. However, in this study, the author takes the average discount rate of 10% to evaluate the systems.

3.2.1 In the case of energy consumption between daytime and nighttime is 70% - 30%

Table 10 describes the electricity consumption of the household in Khanh Hoa, the system's produced electricity amount and its profit at the first year while Table 11 describes the cumulative cash flows of the PV system in Khanh Hoa at the discount rates of 0% and 10%. The figures in these two tables are calculated by using Excel software. The other cases are also done similarly by Excel software. The energy obtained from the systems will reduce over time. Hence, the projects' net profit will gradually decrease over years.

Table 12 below presents economic indicators for the case where the household's consumption between day and night is 70% - 30% with the discount rate of 0%. The payback period of the projects in Khanh Hoa, Binh Thuan, Quang Binh, Binh Duong, Dak Lak, Dong Thap, Hanoi is 6.55 years, 6.57 years, 10.29 years, 10.57 years, 11.81 years, 14.00 years, respectively, which means that the project's payback time in Khanh Hoa and Binh Thuan is shortest and nearly equal to each other while the payback time of the project in Hanoi is longest; the payback period of the projects in Quang Binh, Binh Duong, and Dak Lak is in the middle group and has approximately the same values. Furthermore, the BCR coefficient of the project in Hanoi is 0.962 (< 1), indicating that the project is not economically viable.

Table 10. Electrical consumption and profitability of the PV system in Khanh Hoa Provice in the case of 70% - 30%

	Energy Consumption (kWh)			Simulated Energy (kWh) (3)	Unused Energy (kWh) (3-1)	Profit from reducing (VND)	Profit from selling (VND)	Profit (*) (Y) (VND)
	Day (1)	Night (2)	Total					
Jan	212.03	90.87	302.9	1174	961.97	526,955	1,869,108	2,396,063
Feb	211.19	90.51	301.7	1296	1084.81	523,901	2,107,786	2,631,687
Mar	220.78	94.62	315.4	1507	1286.22	558,770	2,499,125	3,057,895
Apr	214.55	91.95	306.5	1615	1400.45	536,118	2,721,074	3,257,192
May	220.99	94.71	315.7	1716	1495.01	559,533	2,904,804	3,464,338
Jun	212.03	90.87	302.9	1618	1405.97	526,955	2,731,800	3,258,755
Jul	218.75	93.75	312.5	1636	1417.25	551,389	2,753,717	3,305,106
Aug	248.15	106.35	354.5	1593	1344.85	656,331	2,613,044	3,269,374
Sep	219.59	94.11	313.7	1414	1194.41	554,443	2,320,739	2,875,182
Oct	212.59	91.11	303.7	1209	996.41	528,991	1,936,025	2,465,016
Nov	210.91	90.39	301.3	890	679.09	522,883	1,319,472	1,842,355
Dec	217.28	93.12	310.4	880	662.72	546,044	1,287,665	1,833,709
Year	2618.84	1122.36	3741.2	16548	13929.16	6,592,312	27,064,358	33,656,669

(*): The profit = the profit from reducing electricity consumption and selling unused PV energy.

Table 11. Cumulative cash flow in Khanh Hoa Provice in the case of 70% - 30%

End of year	Total cost (VND)	Net profit of PV System (VND)	Net cash flow (VND)	Net cumulative cash flow (VND)	Discouted CF at 10% (VND)	Cumulative CF at 10% (VND)
0	201,501,335		-201,501,335	-201501335	-201,501,335	-201,501,335
1	2,015,013	33,656,669	31,641,656	-169859679	28,765,142	-172,736,193
2	2,015,013	33,335,142	31,320,129	-138539550	25,884,404	-146,851,789
3	2,015,013	33,016,829	31,001,816	-107537734	23,292,123	-123,559,666
4	2,015,013	32,701,700	30,686,687	-76851047	20,959,420	-102,600,246
5	2,015,013	32,389,722	30,374,709	-46476338	18,860,304	-83,739,941
6	2,015,013	32,080,864	30,065,851	-16410488	16,971,389	-66,768,553
7	2,015,013	31,775,095	29,760,081	13349594	15,271,627	-51,496,925
8	2,015,013	31,472,383	29,457,369	42806963	13,742,080	-37,754,845
9	2,015,013	31,172,698	29,157,685	71964647	12,365,705	-25,389,141
10(*)	83,136,013	30,713,084	-52,422,930	19541718	-20,211,309	-45,600,449
11	2,015,013	30,582,289	28,567,276	48108993	10,012,656	-35,587,794
12	2,015,013	30,291,505	28,276,492	76385485	9,009,762	-26,578,032
13	2,015,013	30,003,629	27,988,616	104374101	8,107,305	-18,470,727
14	2,015,013	29,718,632	27,703,619	132077719	7,295,229	-11,175,498
15	2,015,013	29,436,485	27,421,471	159499190	6,564,482	-4,611,016
16	2,015,013	29,157,159	27,142,145	186641336	5,906,922	1,295,906
17	2,015,013	28,880,626	26,865,613	213506949	5,315,218	6,611,124
18	2,015,013	28,606,859	26,591,846	240098795	4,782,777	11,393,901
19	2,015,013	28,335,830	26,320,816	266419611	4,303,664	15,697,565
20	2,015,013	28,067,510	26,052,497	292472108	3,872,538	19,570,103

(*): Inverter replacement

Table 12. Economic indicators at the discount rate of 0% in the case of 70%-30%

Economic criteria	Ha Noi	Quang Binh	Dak Lak	Khanh Hoa	Binh Thuan	Binh Duong	Dong Thap
Payback period (years)	14.00	10.29	10.60	6.55	6.57	10.57	11.81
NPV (VND)	109,188,026	241,013,154	226,404,129	292,472,108	290,528,894	227,611,536	176,848,826
IRR (%)	4.80%	9.76%	9.24%	11.55%	11.48%	9.28%	7.43%
BCR	0.962	1.370	1.325	1.530	1.524	1.329	1.172

Table 13. Economic indicators at the discount rate of 10% in the case of 70%-30%

Economic criteria	Ha Noi	Quang Binh	Dak Lak	Khanh Hoa	Binh Thuan	Binh Duong	Dong Thap
Payback period (years)	>20	>20	>20	15.78	15.91	>20	>20
NPV (VND)	-0,811,992	-2,998,209	-9,405,147	19,570,103	18,717,765	- 8,875,877)	-31,138,249
IRR (%)	-4.73%	-0.22%	-0.69%	1.41%	1.35%	-0.65%	-2.34%
BCR	0.563	0.794	0.769	0.885	0.881	0.771	0.682

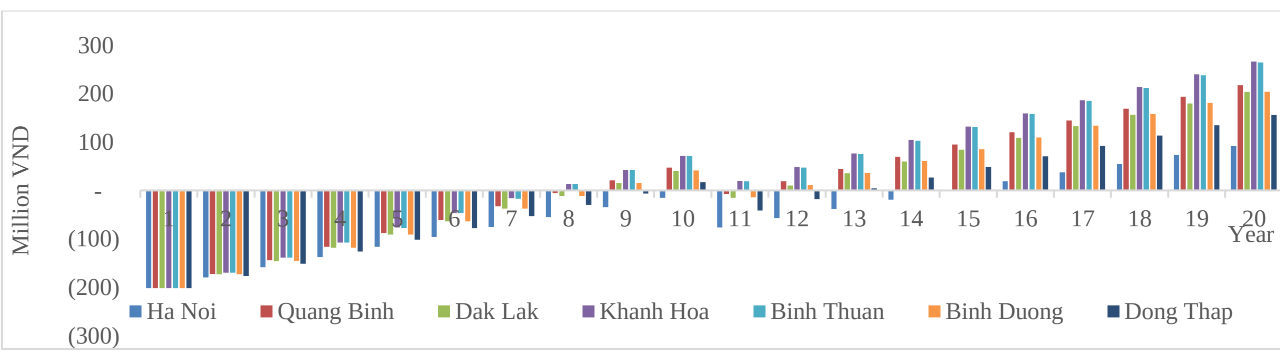

Fig. 10. Cumulative cash flow at the discount rate of 0% in the case of 70% - 30%

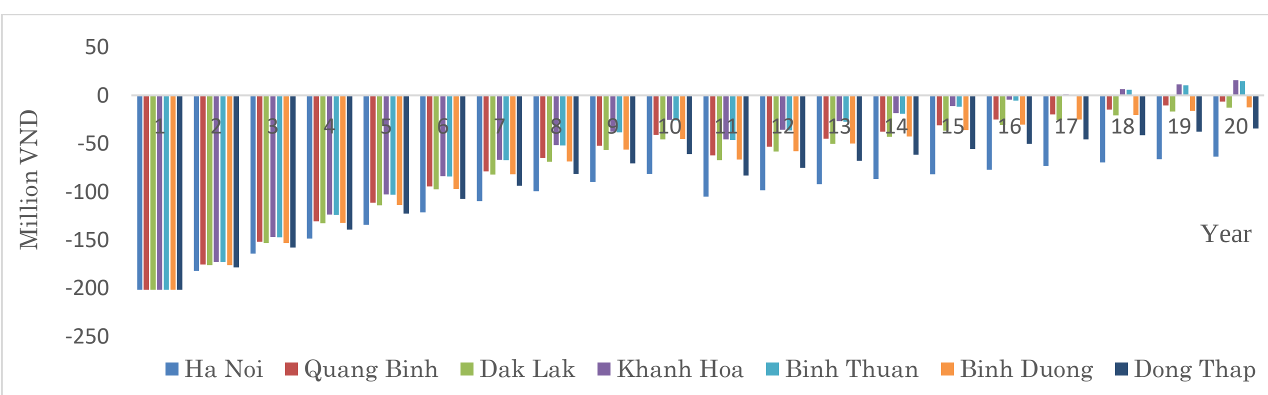

Fig. 11. Cumulative cash flow at the discount rate of 10% in the case of 70%-30%.

The IRR of the project in Khanh Hoa is highest, with an IRR of 11.55%, followed by Binh Thuan with an IRR of 11.48%. The projects in the other provinces of Quang Binh, Binh Duong, and Dak Lak have nearly equal IRR values of 9.76%, 9.28% and 9.24%, respectively. The IRR of the project in Dong Thap is 7.43%, only higher than that of the project in Hanoi.

The NPV indexes also are the same results as IRRs. The highest is the project in Khanh Hoa with NPV value of 292,472,108 VND, and the lowest is the project in Hanoi with the NPV value of 109,188,026 VND.

Table 14. Economic indicators at the discount rate of 0% in the case of 50%-50%

Economic criteria	Ha Noi	Quang Binh	Dak Lak	Khanh Hoa	Binh Thuan	Binh Duong	Dong Thap
Payback period (years)	14.14	10.36	10.67	6.59	6.61	10.65	11.91
NPV (VND)	105,619,366	237,444,493	222,835,469	288,903,447	286,960,234	224,042,876	173,280,166
IRR (%)	4.66%	9.64%	9.11%	11.43%	11.36%	9.16%	7.30%
BCR	0.951	1.359	1.314	1.519	1.516	1.318	1.161

Table 15. Economic indicators at the discount rate of 10% in the case of 50% - 50%

Economic criteria	Ha Noi	Quang Binh	Dak Lak	Khanh Hoa	Binh Thuan	Binh Duong	Dong Thap
Payback period (years)	>20	>20	>20	16.02	16.17	>20	>20
NPV (VND)	-62,330,706	-4,516,924	-10,923,861	18,051,388	17,199,050	-10,394,591	-32,656,964
IRR (%)	-4.86%	-0.33%	-0.74%	1.36%	1.24%	-0.77%	-2.46%
BCR	0.557	0.788	0.763	0.878	0.875	0.765	0.676

Table 13 presents the economic indicators of the projects at the discount rate of 10%. When considering the 10% discount factor, the projects have the payback period of over 20 years. Only in Khanh Hoa and Binh Thuan, the payback periods of these two projects are 15.78 years and 15.91 years, respectively. The BCR indexes of all projects are lower than 1, showing that the projects are economically unattractive. The IRRs of all projects are very low, in which the project in Khanh Hoa has IRR of 1.41%; the project in Binh Thuan has IRR of 1.35% and all the remaining projects have IRRs lower than 0.

Figures 10 and 11 depict the cumulative cash flows of all the projects at the discount rates of 0% and 10%, respectively.

3.2.2 In the case of the energy consumption between daytime and nighttime is 50% - 50%

Tables 14 and 15 describe the results of calculating economic indicators in the case of the households using equal electricity during the daytime and nighttime at the discount rate of 0% and 10%, respectively. Calculation results show that the project in Khanh Hoa has the most attractive economic indicators, followed by Binh Thuan, Quang Binh, Dak Lak, Binh Duong, Dong Thap and finally Hanoi. The project in Hanoi has the worst economic indexes with a BCR of 0.951 (<1), an IRR of 4.66%, an NPV of VND 105,619,366, and payback period of 14.14 years. In contrast, the project in Khanh Hoa has the most economic attractiveness with the shortest payback period (6.59 years), the highest NPV, IRR, and BCR at VND 288,903,447, 11.43% and 1.519, respectively.

Considering the discount rate of 10%, only the projects in Khanh Hoa and Binh Thuan have a payback period of less than 20 years; the other projects have a payback period of more than 20 years. Moreover, the BCRs of the projects are all lower than 1, showing that, in general, the projects are economically unattractive.

3.2.3. In the case of the energy consumption between daytime and nighttime is 30% - 70%

Table 16 describes the results of calculating economic indicators of the projects in the case that the residential energy consumption between daytime and nighttime is 30% - 70% at the discount rate of 0%. The payback period of the projects in Khanh Hoa, Binh Thuan, Quang Binh, Binh Duong, Dak Lak, Dong Thap and Hanoi is 6.67 years, 6.69 years, 10.49 years, 10.79 years, 10.82 years, 12.08 years and 14.39 years, respectively. Similarly, the NPVs of these projects are VND 282,304,250, VND 280,361,037, VND 230,845,296, VND 217,443,678, VND 216,236,272, VND 166,680,968 and VND 9,020,169, respectively. IRR of the project in Hanoi has the lowest value while Khanh Hoa has the highest value. The BCR index of the project in Hanoi is lower than 1 (0.931); all the other projects have the value of more than 1, and the highest BCR belongs to the project in Khanh Hoa (1.498).

When considering the discount rate of 10%, the economic indicators obtained are very low. The BCR of all the projects is less than 1. The payback periods of the projects in Khanh Hoa and Binh Thuan are 16.51 and 16.67 years, respectively, which are quite a long time. The remaining projects have the payback periods of more than 20 years, beyond the project's life cycle. Similarly, the IRR and NPV of the projects in Khanh Hoa and Binh Thuan are positive while in the rest of the projects, these indexes are negative. These results prove that these projects are not economically attractive.

Table 16. Economic indicators at the discount rate of 0% in the case of 30% - 70%

Economic criteria	Ha Noi	Quang Binh	Dak Lak	Khanh Hoa	Binh Thuan	Binh Duong	Dong Thap
Payback period (years)	14.39	10.49	10.82	6.67	6.69	10.79	12.08
NPV (VND)	9,020,169	230,845,296	216,236,272	282,304,250	280,361,037	217,443,678	166,680,968
IRR (%)	4.39%	9.41%	8.88%	11.21%	11.14%	8.93%	7.05%
BCR	0.931	1.399	1.294	1.498	1.492	1.297	1.140

Table 17. Economic indicators at the discount rate of 10% in the case of 30% - 70%

Economic criteria	Ha Noi	Quang Binh	Dak Lak	Khanh Hoa	Binh Thuan	Binh Duong	Dong Thap
Payback period (years)	>20	>20	>20	16.51	16.67	>20	>20
NPV (VND)	-65,139,454	-7,325,672	-13,732,609	15,242,640	14,390,302	-13,203,339	-35,465,712
IRR (%)	-5.10%	-0.54%	-1.02%	1.10%	1.04%	-0.98%	-2.68%
BCR	0.546	0.777	0.751	0.867	0.864	0.753	0.664

Comparing with the two previous cases, we see that the more the electricity used during the daytime, the more the benefit is. For example, when the day-time and night-time load consumption rates are 70% - 30%, 50% - 50%, 30% - 70% and the discount rate is 0%, the payback periods of the project in Hanoi are 14.00 years, 14.14 years and 14.39, respectively. The other provinces have similar results.

4. CONCLUSIONS

The study is carried out to calculate the energy and economic efficiency and environmental impact of the grid-connected rooftop solar power projects in the seven different climate zones of Vietnam based on the simulation. The residential rooftop PV systems are being installed more and more; thus, the feasibility assessment of these projects is a practical need. It is expected that this study provides additional information for stakeholders to have better understanding of the possibilities of residential solar power projects in Vietnam, especially the small-scale ones.

The simulation results using PVsyst software show that the electricity output from the 10kWp solar power system in the first year in the provinces of Khanh Hoa, Binh Thuan, Quang Binh, Binh Duong, Dak Lak, Dong Thap and Hanoi are 16.55 MWh, 16.49 MWh, 15.09 MWh, 14.71 MWh, 14.68 MWh, 13.28 MWh and 11.36MWh, respectively. The corresponding CO_2 savings of these projects are 11.31 tons, 14.26 tons, 13.05 tons, 12.72 tons, 12.70 tons, 11.49 tons and 9.83 tons, respectively.

However, the economic problems, including the low economic indicators still exist, making the investment's efficiency low. The payback period of the projects in Khanh Hoa, Binh Thuan, Quang Binh, Binh Duong, Dak Lak, Dong Thap and Hanoi in the case of the daytime usage equal to the nighttime usage at the discount rate of 0% is 6.59 years, 6.61 years, 10.36 years, 10.65 years, 10.67 years, 11.91 years and 14.14 years, respectively. The cases of daytime and nighttime power usage of 70% - 30% and 30% - 70% also give nearly the same results.

If considering the 10% discount rate, the economic indicators of the projects are very low, the payback period is beyond the life of the project, except for the two projects in Khanh Hoa and Binh Thuan. However, the payback period of the projects is also nearly 20 years. The BCR of all the projects is less than 1.

The study results demonstrate that the higher the household electricity consumption during the day, the more beneficial it is.

Among all the above projects, the projects in Khanh Hoa and Binh Thuan are more economically attractive than those in the other provinces while the least attractive is Hanoi.

Currently, the Vietnamese government is offering a relatively high price for purchasing electricity generated from rooftop solar power projects; nevertheless, it is forecasted that the price will be lowered in the coming years, reducing the economic values of the projects. Therefore, from the financial aspect, these projects are not very efficient; however, the projects are feasible in terms of energy production.

Moreover, when more rooftop power systems are operated and connected to the grid, harmonics and voltage deviation are likely to occur. Phase imbalance can also happen when these systems are connected to the distribution grid randomly, based on the consumers' location. As a result, it is expected that there will be more detailed research on these impacts of the rooftop systems on the grid in the coming time.

ACKNOWLEDGEMENTS

The author would like to acknowledge Thu Dau Mot University in Vietnam for its support.

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