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The efficiency of solar water heating system with heat pump software application designed for resorts in Vietnam

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Abstract:

Solar energy is a free and nearly endless source of energy. Vietnam has the advantage of harnessing solar energy for many essential purposes because of its geographic location in the tropics. This allows electricity usage to be minimized in solar chemistry and energy conversion from solar energy into electricity; or to completely replace electricity usage in applications such as heating, cooling, ventilation, water treatment, cooking processes, and heating processes. In this paper, three solar water heating systems with a heat pump are designed for resorts located at three famous tourist destinations in Vietnam: Phu Quoc island and the towns of Bao Loc, and Sa Pa. These places represent the Southern, Central, and Northern regions of Vietnam, respectively. Ecotect and Grasshopper software applications are employed with the latest weather, heat, and radiation data and was obtained from *climate.onebuilding.org*. Data analysis is based on Ecotect software and the computational design is done in Grasshopper software. These software applications show that Phu Quoc island is the most efficient place to exploit solar energy, followed by Bao Loc, which is lower due to the fog, and Sa Pa, where solar radiation is low. In order to increase the water heating efficiency in places with very low solar radiation, a heat pump is considered along with a conventional solar water heating system and optimum azimuth angle of 180^o South for the solar collector. This method is an efficient solution that can be applied in Sa Pa as well as in other places in Vietnam where there is a lack of solar radiation. The solar energy factor (SEF) is significantly increased from 14.37 to 57.47 and the solar fraction (SF) per year is increased from 93.5 to 98.3% using this method.

Keywords: **heat pump, solar energy collector, solar water heating system.**

Classification number: **2.3**

Introduction

In recent years, increasing tourist visits to Vietnam have resulted in a significant increase in the demand for infrastructure and energy consumption. The territory of Vietnam stretches from 8.42^o to 23.39^o N, thus, Vietnam is a country of enormous sunshine with an average annual solar radiation of about 1675 kWh/m^2 and receives nearly 1854 hours/year of sunlight [1]. Solar power is a clean and valuable source of energy to be exploited for heating water. Presently, however, hot water is produced by standard types of energy such as electricity, coal, diesel, gas, and others. These methods are costly and negatively impact the environment. Therefore, solar energy is a better choice to replace these conventional energy sources [2].

Moreover, software modelling is considered to be quite an effective tool for the simulation of energy in many countries around the world. In this work, powerful software is applied to the calculation of heat radiation in Vietnam. This novel software application facilitates design, architecture, and engineering fields to realize a new view of building information modelling (BIM) in regard to the design and construction related to solar radiation, heated water, and energy analysis. Further, this software meets the BIM development roadmap of construction activities and management led by the Vietnamese Prime Minister.

Solar radiation is unevenly distributed across the regions and seasons of Vietnam. This fact is clarified by Ecotect software, which contains weather data from the Climate.

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OneBuilding website [3]. A model of a solar collector is established in Grasshopper software with variable dimensions such as the area of the solar collector, its tilt, and the actual azimuth angle. In this work, we gradually change these parameters until optimal parameters are achieved.

The results show that the coldest day at Phu Quoc island, which is located at 10.2° N, 104° E, and 4 m altitude is on the 7th of February, while the coldest day at Bao Loc, located at 11.5° N, 108° E, and 850 m altitude is on the 26th January, and finally the coldest day at Sa Pa, located at 22.4° N, 103.8° E, at 1581 m altitude, is on the 10th of January. The lowest temperatures for each month, which are depicted in Fig. 1, are 2.1°C, 2.2°C and 15.5°C at Sa Pa, Bao Loc and Phu Quoc island, respectively.

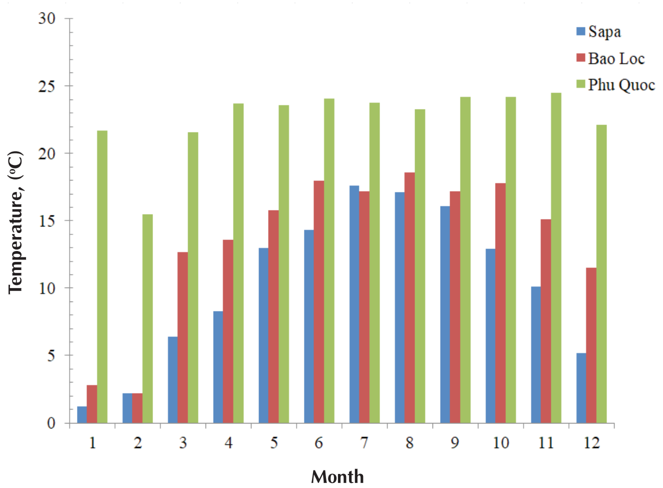


Fig. 1. The whole year lowest temperature in a month at 3 places in Vietnam.

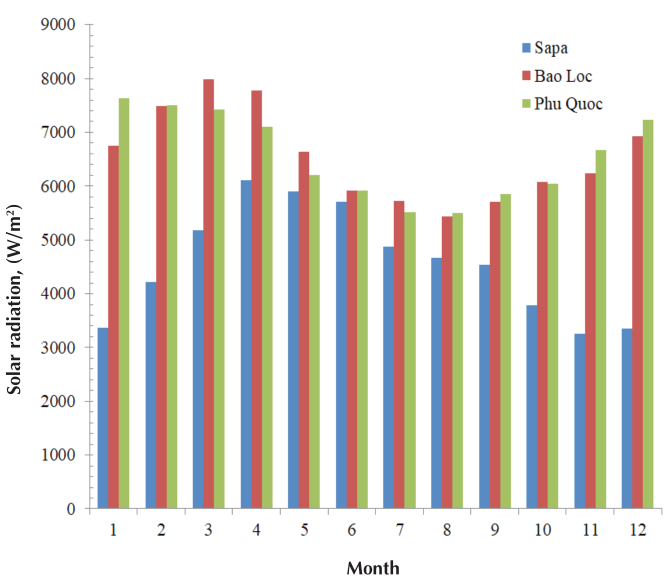


Fig. 2. The whole year solar radiation at 3 towns in Vietnam.

As depicted in Fig. 2, the solar radiation in Bao Loc and Phu Quoc island are similar with their smallest difference of 1% in June and highest difference of 13% in January. In particular, the solar radiation at Sa Pa is much lower than the other two locations. The smallest difference between Sa Pa and the other two locations is 50% in January. In order to compensate for this lack of solar radiation, a heat pump is added into the conventional water heating system. As a result, the SEF significantly increased from 14.37 to 57.47 and the SF per year increased from 93.5 to 98.3%.

Lamnatou, et al. (2015) [4] showed that solar energy remains unstable and unpredictable due to its strong dependency on climatic conditions even though it has high efficiency. In order to solve this problem, thermal energy storage equipment and an auxiliary heat supply device are installed in solar water heating systems to satisfy the fluctuating heating load [5]. Mehrpooya, et al. (2015) [6] integrated a heat pump into a solar heating system and declared that such a combined system will ensure a sufficient hot water supply and save energy. Jordan, et al. (2019) [7] carried out an experiment comparing conventional supplementary heating and the solar water heating system with heat pump and their results showed that the energy consumption of the solar system combined with heat pump was 54.9% lower than that of conventional solar water heating combined with electrical resistance. Ta Van Chuong (2017) [8] proved that the use of a heat pump is very efficient to supply 40-50°C hot water in Vietnam. Moreover, he utilized some simulation software to analyse the solar water heating system combined with heat pump and then declared that solar energy can meet 83.7% and 66% of the water heating system energy in Nha Trang and Hanoi city, respectively. In addition, their results also showed that electricity consumption is only 5% of what a conventional electrical water heating system requires when a solar water heating system is combined with a heat pump. Nguyen Van An (2015) [9] and his colleagues designed a solar water heating system combined with a heat pump whose capacity was 30000 litres at The Gioi Xanh hotel in Nha Trang; and the result showed that electricity consumption was only 7-8% of that of a conventional electrical water heating system. However, solar water heating systems in areas such as Phu Quoc island, Bao Loc, and Sa Pa have not yet been studied. Therefore, this paper will address studies in those areas.

In this paper, several solar water heating systems with heat pumps are analysed in terms of their components and operation principle. In particular, the authors calculate the hot water flowrate for a 90-room hotel in each area and all relevant parameters are analysed. The optimization of the solar collector direction was carried out by computational design in Grasshopper software. This is a new, powerful program used to analyse solar radiation as well as solar water heating systems. Finally, the optimized solar water heating system with heat pump is compared to a conventional one in order to prove its economic efficiency.

The rest of this paper is organized as follows. The fundamental concepts of a solar water heating system combined with heat pump are described in the following section. After that is an evaluation of the economic efficiency of a solar water heating system combined with heat pump is presented. The final section concludes the paper.

Fundamental concepts of solar water heating system combined with heat pump

From Refs. [10, 11], a heat pump is a device that transfers heat energy from a heat source to a heat storage tank. With a heat pump, heat energy is moved in the opposite direction of spontaneous heat transfer, which means that heat is absorbed from the cold space and released to warmer places. A heat pump uses external energy to complete the task of energy transfer from the heat source to the radiator. The most common design of a heat pump consists of four main components: condensers, expansion valves, evaporators, and compressors. Heat pumps can usually be used either in heating mode or cooling mode, as required by the user. When a heat pump is used for heating, it employs the same basic refrigeration-type cycle used by an air conditioner or a refrigerator but in the opposite direction i.e. the heat pump releases heat into the conditioned space rather than the surrounding environment. In this use, heat pumps generally draw heat from the cooler external air or from the ground.

According to Refs. [12, 13], in order to assess the heat pump efficiency, the $COP_{heatpump}$ must be used as follows:

$$COP_{heatpump} = Q_c/W \quad (1)$$

where Q_c (kW) is the heat rejected from the condenser to increase water's temperature and W (kW) is the power of the compressor used to run the heat pump.

Then, we have

$$Q_c = Q_e + W \quad (2)$$

where Q_e (kW) is the surrounding heat that is transmitted to the evaporator.

Thus,

$$COP_{heatpump} = (Q_e + W)/W \quad (3)$$

According to the 1st thermodynamic law, 1 kW of electrical energy will be theoretically transferred into 1 kW thermal energy when an electrical heater is utilized for hot water producing. However, 1 kW of electrical energy running a compressor when hot water heat pump is utilized will produce (1 + Q_e) kW of thermal energy in practice. The heat consumption $Q_{hotwater}$ (kW) for a water heating system from the initial temperature t_1(°C) to the final one t_2(°C) is the following:

$$Q_{hotwater} = G.C_p\,(t_2 - t_1) \quad (4)$$

where G and C_p are the mass water flowrate (kg/s) and water heat capacity (4.18 kJ/kg.K), respectively. G = V×δ is calculated with a flowrate volume V (m^3/s) and water density δ (1000 kg/m^3).

However, an auxiliary heater, such as electrical heater or heat pump, must be used where there is a lack of solar radiation. Thus, the efficiency of a solar water heating system combined with the heat pump must be analysed. The efficiency is evaluated by two parameters, SEF and SF, defined as the following:

Solar Energy Factor (SEF) = SWH/AHE (5)

where SEF is the ratio of the total energy provided by the solar water heating system (SWH) to the auxiliary heater energy (AHE) and

Solar Fraction per year (SF) = SWH/(SWH + AHE) (6)

where SF is the percentage of the total heat requirement that is provided by solar water heating system (SWH) for whole a year.

Evaluation of efficiency for solar hot water combined with heat pump

In this section, solar water heating systems are analysed in order to evaluate the potential for solar application. The systems are applied to a 90-room hotel in the areas of Phu Quoc island, Bao Loc, and Sa Pa. Additionally, the efficiency of a solar water heating system combined with a heat pump will be compared to the non-heat pump system in the case of a lack of sufficient solar radiation.

Following the standard in Ref. [14], a hot water flowrate of 53.1 litres per room per day and 60°C hot water temperature were chosen for the 90 rooms. As a result, during 8 h of working time that starts at 7:00 AM every day, the maximum hot water flowrate is 4779 litres per day.

The authors design the solar water heating system with the above initial conditions. In addition, other parameters are obtained by the Grasshopper simulation software such as the initial water supply temperature, water heating system energy, and solar collector area.

Schematic diagram of system (Fig. 3)

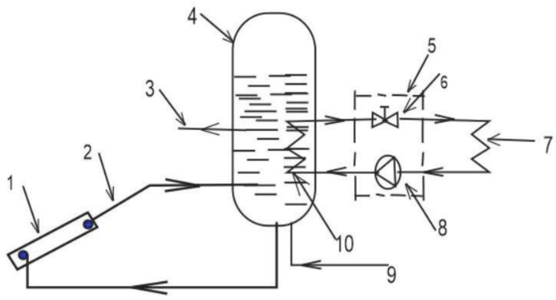
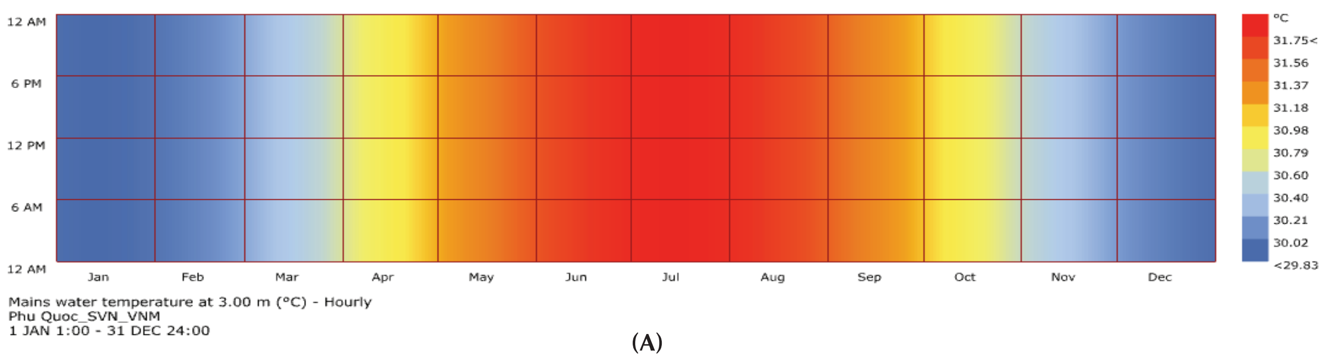


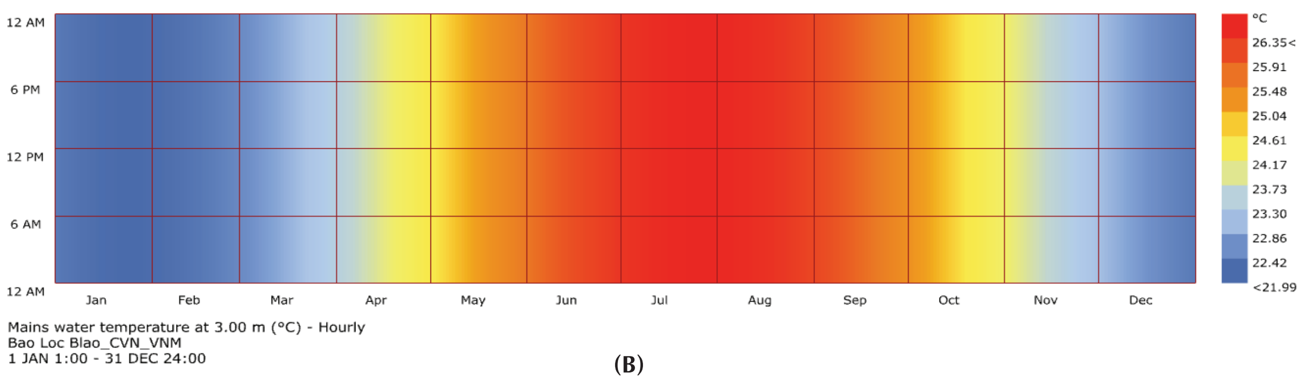
Fig. 3. The schematic diagram of system.
1: solar collector; 2: piping system; 3: hot water supply to the resort; 4: hot water tank; 5: heat pump system; 6: expansion valve; 7: evaporator; 8: compressor; 9: cold water supply; 10: condenser.

The initial water supply temperature

This parameter is significant because it affects the water heating system energy and depends on environmental temperature, soil thermal diffusivity, and buried depth. In order to obtain the initial water supply temperature, three initial conditions are required for the simulation process: the hourly surrounding temperature of each area, a 3-m buried depth, and dry clay soil. The input and output parameters for the initial water temperature simulation in Fig. 4 are shown in Table 1.



(A)



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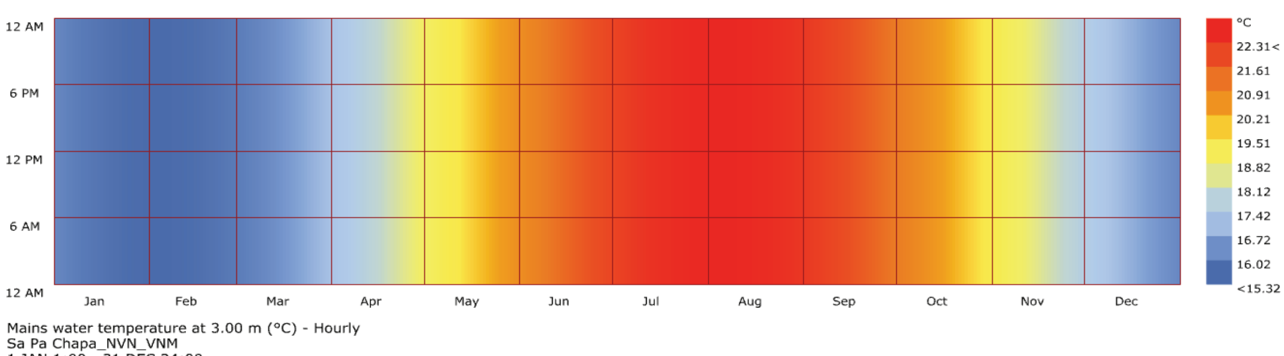

(C)

Fig. 4. The initial water supply temperature during a year in: (A) Phu Quoc island, (B) Bao Loc town, (C) Sa Pa town.

Table 1. The input and output parameters for the initial water temperature.

Input parameters	Output parameter
Weather data	The initial water supply temperature during a year
Soil thermal diffusity for dry cray: $2.5.10^{-7}$(m^2/s)	
Pipe depth : 3 meters	

Table 2. The average and lowest intitial water supply temperature of each area.

Location	Average temperature a year (°C)	The lowest temperature (°C)
Phu Quoc island	30.79	29.8
Bao Loc town	24.17	22
Sa Pa town	18.8	15.32

Water heating system energy

Using Eq. (4) with the water flowrate of 597.38 litres/h, the lowest initial water temperature supplied from Table 2 and the final hot water temperature of 60°C produce a maximum water heating system energy of 20.93 kW, 26.35 kW, and 30.85 kW for Phu Quoc island, Bao Loc, Sa Pa, respectively.

In addition, with the water flowrate of the hourly initial water supply temperature analysed in an earlier section, the final hot water temperature and water heating energy for a year are displayed in Fig. 5. The input and output parameters for the simulation are shown in Table 3.

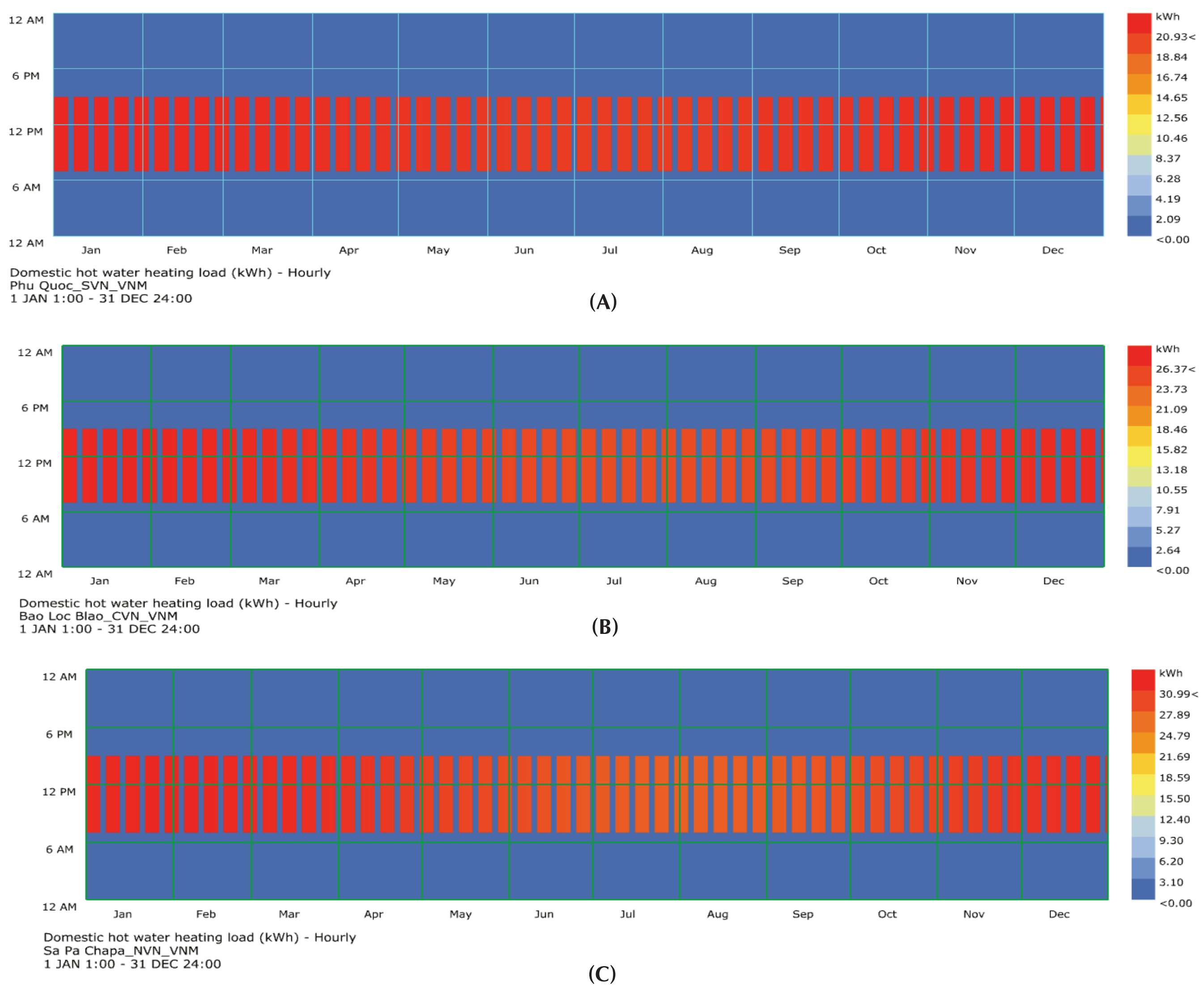

Fig. 5. The water heating energy during a year in: (A) Phu Quoc island, (B) Bao Loc town, (C) Sa Pa town.

Table 3. The input and output parameters for the water heating energy during a year.

Input parameters	Output parameter
Weather data	The water heating energy during a year
Chosing : type "Hotel from 61 to 99 rooms"	
90 rooms	
53.1 liters per room per day	
Delivery water temperature: 60°C	
The initial water supply temperature during a year	

Obviously, the water heating energy in Sa Pa is the largest as a result of the cold initial water supply temperature. Therefore, its solar collector area for that location will be the largest. In the following section, the solar collector area and its optimum direction will be chosen.

Solar collector area

The solar collector area will be chosen to meet the water heating system energy requirements in each area. Thus, the authors optimized the solar collector area until the final energy that is collected by solar energy meets the calculated water heating system energy. Apart from the solar collector area, another parameter that strongly affects solar energy is azimuth angle of the solar collector. When this angle is changed, the efficiency of solar energy also changes, which is represented by the tilt and orientation factor (TOF). TOF is the solar radiation at the actual tilt and azimuth divided by solar radiation at the optimum tilt and azimuth. In this paper, authors chose the tilt of the solar collector to be 30° with respect to the horizon plane and changed its direction from North (azimuth angle = 0°) to West (azimuth angle = 270°).

The results obtained after simulation are presented in Table 4. The input and output parameters for the simulation are shown in Table 5.

Table 4. TOF of Solar collector.

Location	East	West	South	North
Phu Quoc island	86.7%	92.4%	100%	80.3%
Bao Loc town	85.8%	92.8%	100%	80.3%
Sa Pa town	87%	93.9%	100%	81%

Table 5. The input and output parameters for TOF.

Input parameters	Output parameter
Weather data	TOF
The actual collector's tilt : 30°	Optimal tilt
The actual collector's Azimuth: from 0° to 270°	Optimal Azimuth
Annual shading: 0%	

From Table 4, the optimum azimuth angle of the solar collector is 180° (South) because it creates the largest amount of solar energy during a year. In order to generate enough water heating energy, the sufficient solar collector area is also chosen. Moreover, the collected solar energy for each solar collector area, is shown in Fig. 6. In this simulation, a vacuum solar collector is chosen. In addition, its surface area is changed to match the water heating energy demand found from Fig. 5. In these results, the surface areas are 120 m^2, 138 m^2, and 314.5 m^2 for the locations of Phu Quoc island, Bao Loc, and Sa Pa, respectively.

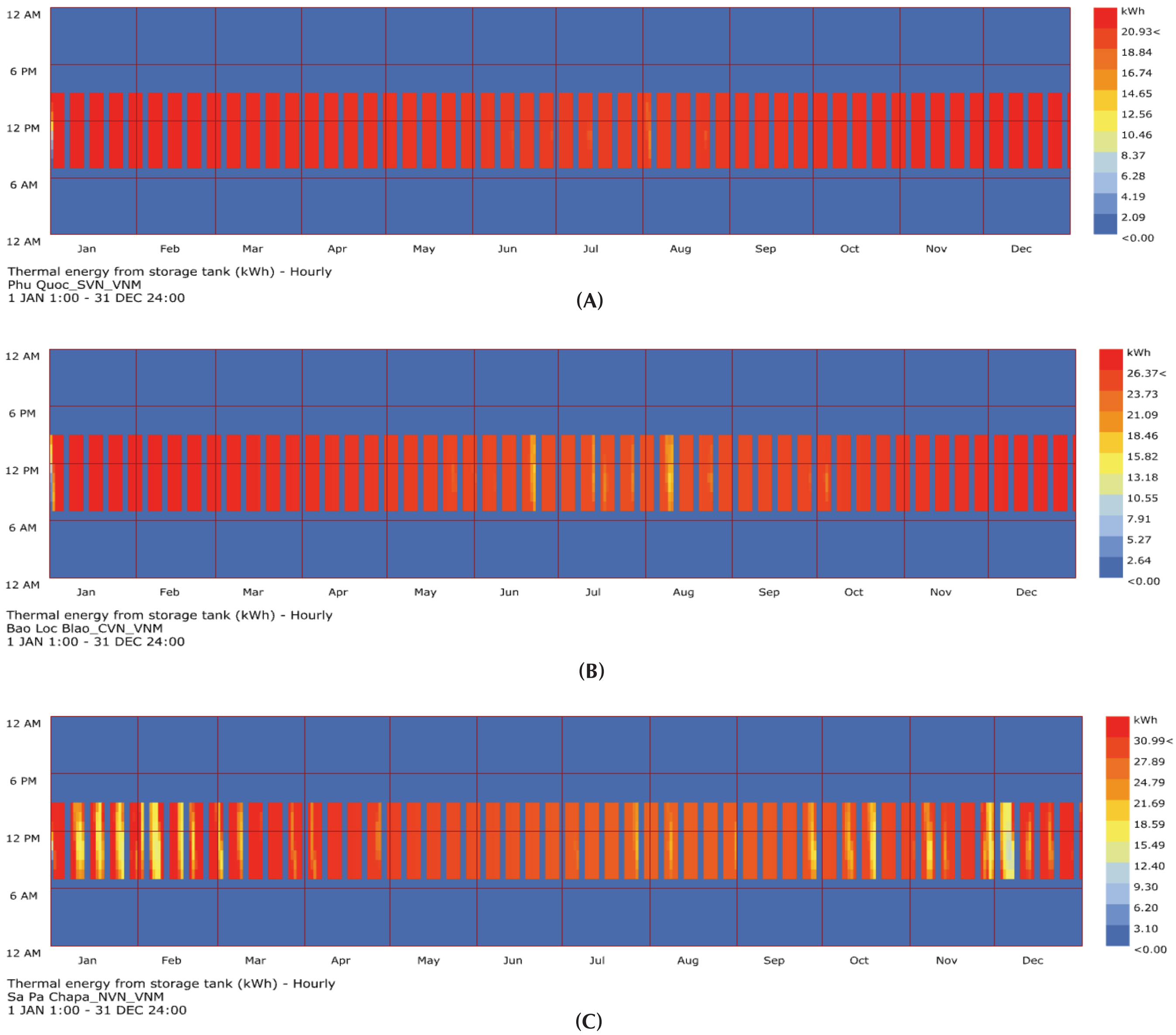

Fig. 6. The obtained solar energy correspondence with its collector area: (A) Phu Quoc island, (B) Bao Loc town, (C) Sa Pa town.

The daily solar water heating (DSWH) energy and the whole year solar water heating (SWH) energy which are collected by solar collector in each area are displayed in Table 6.

Table 6. The DSWH energy and the whole year SWH energy.

Location	DSWH (kWh)	SWH (kWh)
Phu Quoc island	115.56	42180
Bao Loc town	140.8	51401
Sa Pa town	157.79	55769

The input and output parameters for the simulations in Figs. 6, 7 and in Table 6 are shown in detail in Table 7.

Table 7. The input and output parameters for the obtained solar energy with its collector; the auxiliary heater energy and the daily solar water heating energy and the whole year solar water energy.

Input parameters	Output parameter
Weather data	Solar energy for water heating per hour
The water heating energy during a year	The Auxilary heater energy
SWH area	DSWH
SWH surface percent: 100%	
"Direct " hot water loop	
Collector type: "Evacuated collector tube"	The whole year SWH
The tilt and direction of solar collector	
Sky Exposure Factor: choosing 1	

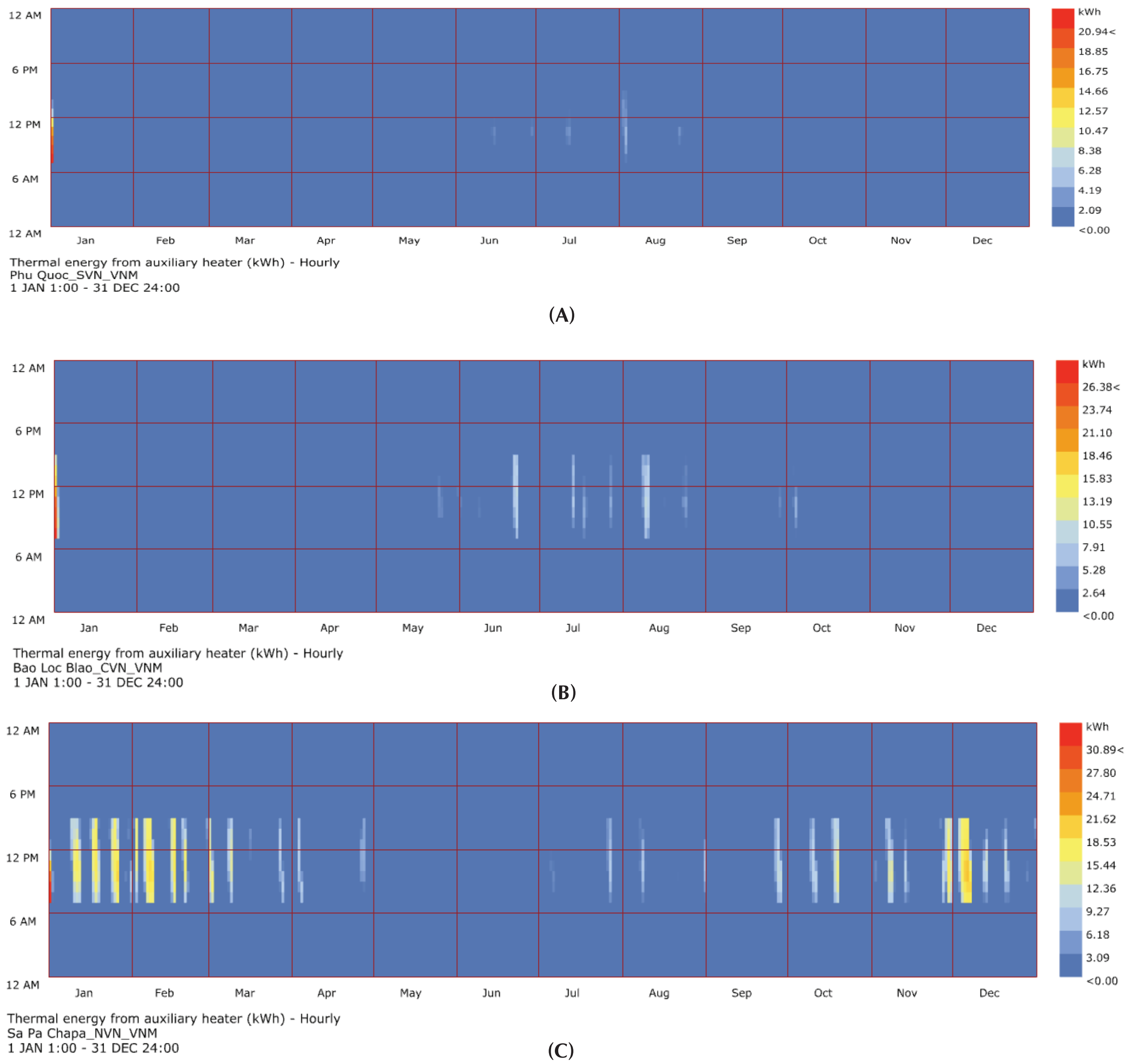

Fig. 7. Auxiliary heater energy in: (A) Phu Quoc island, (B) Bao Loc town, (C) Sa Pa town.

In general, solar energy can satisfy water heating energy. However, it cannot supply enough energy to the water heating system over some time periods. This phenomenon is displayed in Fig. 7. As a result, the auxiliary heater is used for supplementary energy.

Auxiliary heater

The supplementary energy from auxiliary heater during a year is displayed in Fig. 7.

In Fig. 7, the lack of solar radiation can be recognized in some period times and auxiliary heater is used to satisfy system's demand. Hence, the whole year auxiliary heater energy (AHE) is obtained from the simulation and it is generated by electricity, gas, oil or heat pump.

Economic efficiency of solar water heating combined with heat pump

In order to calculate the efficiency of the solar water heating system, Eqs. (5) and (6) are used. The results are shown in Table 8.

Table 8. Efficiency of solar water heating evaluation.

Location	SWH (kWh)	AHE (kWh)	SEF	SF(%)
Phu Quoc island	42180	124.36	340	99.7
Bao Loc town	51401	493.38	104.18	99.04
Sa Pa town	55769	3881.48	14.37	93.5

The input and output parameters for Table 8 are shown in details in Table 9.

Table 9. The input and output parameters for Efficiency of solar water heating evaluation.

Input parameters	Output parameter
Solar energy for water heating per hour	SEF
The Auxiliary heater energy	SF per year
SWH surface percent: 100%	
The water heating energy during a year	
Solar water system settings	
Pump energy: 0 kWh	

The greater the increase of SEF, the more economic efficiency from the solar water system. In this table, the SEF of the solar water heating system in Sa Pa is the smallest because it must use the auxiliary heater more than in the other locations. In order to increase the SEF, the use of a heat pump is a solution that must be considered. If using heat pump with a $COP_{heatpump} = 4$, following Eq. (3), the new AHE = 3881.48/4 = 970.37 kWh. Therefore, the new SEF and SF in Sa Pa are 57.47 and 98.3%, respectively.

Conclusions

This paper has briefly presented the fundamentals of a solar water heating system combined with a heat pump. The solar water heating system is designed by Ecotect and Grasshopper software applications in three famous tourist areas in Vietnam. The optimum azimuth angle for the solar collector is chosen. A comparison of the efficiency between solar heating system with and without heat pump is presented. The main ideas of this work can be summarized as follows:

• The solar radiation in Bao Loc is nearly equal to Phu Quoc island. However, as a result of the low initial water supply temperature, solar water heating energy must be about 26% higher in Bao Loc than Phu Quoc island and the solar collector surface area is also 15% higher than that of Phu Quoc island.

• The solar radiation and initial water temperature supply in Sa Pa are the lowest and, thus, greater than 2.62 times collector surface area is required for Sa Pa than that of Phu Quoc island.

Over some periods of time, obviously, solar energy is not able to meet the hot water energy demand to heat water, so an auxiliary heater is needed. However, this leads to more electric energy usage, therefore a heat pump is the best solution to cope with this unavoidable problem.

The authors declare that there is no conflict of interest regarding the publication of this article.

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