

Minimization of Residential Energy Costs for PV-SWH and PV-T Systems

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Abstract: Photovoltaic (PV) systems transfer solar energy into electric form. PV-T is a hybrid system that converts solar radiation into electrical and thermal energy. For residential users with limited solar panel area, there are two options to achieve economic use of solar energy. One is to install both PV and solar water heater (SWH) systems, called PV-SWH, another one is to apply the PV-T system. In this work, a residential household energy cost model is built up that includes electric vehicle (EV), energy storage system (ESS), and the back-up electricity system in PV-SWH or hybrid PV-T. The model is used to explore operation strategies to minimize user's energy cost. The case study results suggest that the hybrid PV-T system provides more benefits for the end user from long-term perspective. Compared with typical operation without optimization, the cost saving with the proposed strategy is evident.

Keywords: Photovoltaic-thermal (PV-T) system, solar water heater (SWH), energy cost optimization, residential household.

1. INTRODUCTION

Solar energy is perhaps the most important renewable energy source, in which radiant light and heat received from the sun are harnessed for energy generation (Viswanathan, 2016). Technologies such as solar water heater (SWH) and photovoltaics (PV) have been developed to utilize the solar energy. Both are suitable for household applications and can help to reduce the electricity consumption of the end user.

1.1 Review of SWH in Different Countries and Areas

Water heating is a major energy consumption all around the world (Ibrahim et al., 2014). Since SWH was invented, the potential impacts of its applications have been investigated in many countries. In Turkey, it is found the major factors influencing the popularization of SWH are government financial incentive program, payback period, availability of local dealers, and climatic conditions (Benli, 2016). The SWH systems have not been sufficiently developed in Algeria due to the availability of natural gas at low price, and the SWH devices imported from EU are expensive (Sellami et al., 2016). SWHs can be used to reduce peak electricity demand, reduce carbon emission, and improve householder's standard in South African (Curry et al., 2017). However, householders may abandon using SWH if there're no clear benefits within a few months, or if technical problems occurred. In addition, although the electricity bills can be reduced, the water usage will be increased if SWH is frequently used. This may not be an issue for areas with abundant water resources, but could be a problem for water-scarce areas. In Iran, it is found that environmental issues directly affect the use of SWH, and the largest effect is the financial support from the government (Mostafaeipour et al., 2017). Considering the potential benefits from using SWH in Zimbabwe, the electricity winter peak

demand and the final energy demand can be reduced by 13% and 27%, respectively, assuming a 50% penetration rate of SWH potential demand. In addition, SWH can help to reduce CO₂ emissions by 29% over a 25-year period (Batidzirai et al., 2009). The reduction of carbon dioxide using SWH in Brazil is assessed and compared with electric showers (Bessa and Prado, 2015). In another study for Brazil (Giglio and Lamberts, 2016), the influence of human behaviour is considered, which shows that the inefficient use of SWH is due to lack of understanding of the technique and implementation.

Pathways of using SWH and PV are investigated for China (Urban et al., 2016). Compared with PV, SWH technology received less financial and political support from the central government, nevertheless, it contributes a lot to low carbon energy since it is widely used across China, especially in rural areas. The use of PV and SWH in China is also compared in (Wei et al., 2014), where the focus is made on the costs and benefits for users. The reduction of harmful gas due to SWH application and the save of large electricity consumption for Malaysia are discussed in (Jing et al., 2015). The uses of SWH and traditional electric water heaters in Taiwan are compared and it shows that the payback period is shorter for using SWH (Lin et al., 2014). The policy measures in Japan are evaluated to promote PV and SWH in residential sector, in which factors such as installation cost and energy prices are considered (Yamaguchi et al., 2012).

1.2 Hybrid Photovoltaics Thermal System (PV-T)

A PV-T system combines solar cell and solar thermal collector, and converts solar radiation into electricity and captures the remaining energy for water heating usage; it is therefore a more efficient way to use solar energy than PV or solar thermal alone (Ozgoren et al., 2013). The efficiency of

PV cells will drop with the increase in the operating temperature of PV panels; however, water circulation in PV-T system can help to carry heat away from the PV cells thereby cool down the cells and improve the electrical efficiency. Alobaid et al. (2018) developed a mathematical model of a PV-T system to calculate the system performance. In (Ozgoren et al., 2013), the conversion electrical efficiency of the PV-T system might be improved on average about 10% compared to PV system, and the maximum thermal efficiency of the system was found to be 51%. Although PV-T system is an effective way to utilize the solar energy, the thermal component of this system may become under-performed compared to the solar thermal collector. In (Agbidi et al., 2016), a 2% increase in electrical efficiency of PV cells and a 5% decrease in thermal component of PV-T system are calculated compared to traditional PV and SWH systems.

Comparisons of PV-T with SWH or PV alone are seen in a few literature above, but the comparison of PV-T with combined SWH and PV is missing. In this work, the cost reductions between PV-T and PV-SWH will be investigated for residential users. The main contributions will be on the following two aspects.

- Include the solar thermal model into the overall energy cost model; investigate the benefits for end users from the economic point of view. Parameters of the PV-SWH system such as solar panel size and storage volume of SWH will be determined.
- Calculate cost savings for different household energy supply systems. Apply the method of payback period to analyse the investment; compare the PV-SWH system with the PV-T system through case studies.

2. END USER COST MODEL

2.1 Residential Household Energy System

The residential home energy system is depicted in Fig. 1. The arrows towards the control block are defined as the positive direction of power flow.

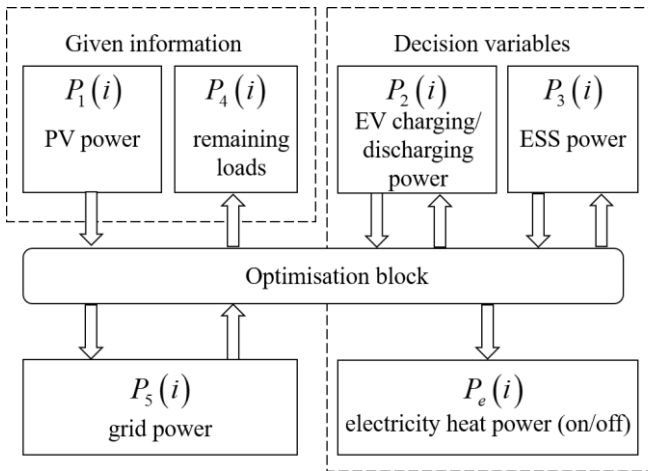


Fig. 1 Smart home energy system

In Fig. 1, P_1 is the output power of the PV system, P_2 is the EV charging or discharging power, and P_3 is the input/output power of the energy storage system (ESS). P_e is the back-up

electricity heat power of SWH which can be switched on and off. The remaining load of the residential home is represented by P_4 ($P_4 < 0$). The smart home system is connected to the grid and the power to and from the grid is represented by P_5 . Consider the length of 24 hours with the sampling rate of 1 hour, there are 24 time periods or slots, each being denoted by index i ($i = 1, 2, \dots, 24$). The initial time period is assumed to start from 8:00 am with $i = 1$. The power balance equation of the smart home system can be described as:

$$\sum_{j=1}^5 P_j(i) + P_e(i) = 0 \quad (i = 1, 2, \dots, 24) \quad (1)$$

The status of P_2 , P_3 and P_e are the three decision variables that can be controlled through optimisation. The controlling status of these variables are represented as follows:

$$\tilde{P}_2(i) = \begin{cases} +a \cdot \tau, & \text{if EV is discharging} \\ -a, & \text{if EV is charging} \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

$$P_3(i) = \begin{cases} +a \cdot \tau, & \text{if ESS is discharging} \\ -a, & \text{if ESS is charging} \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

$$P_e(i) = \begin{cases} -\kappa, & \text{if water heated by backup system} \\ 0, & \text{otherwise} \end{cases} \quad (4)$$

where a (kW) is a positive real number used for both EV and ESS; τ is the discharging efficiency accounting for the energy conversion loss, which is selected as 90% according to (Tesla, 2018). An intermediate term \tilde{P}_2 is used in (2) to represent EV charging and discharging power when the vehicle is parking at home. P_2 can be expressed as in (5) when considering the probability of driving usage (Sun et al., 2018).

$$P_2(i) = \tilde{P}_2(i) \cdot p_{k1}(i) - \frac{Q_{EV}}{T} \cdot p_{k2}(i) \cdot \sum_{l=1}^{N_d} \frac{d(l) p_l}{d_{total}} \quad (5)$$

where d_{total} is the total distance (km) the EV can drive with a fully charged battery; Q_{EV} is the EV battery capacity (kWh). The total number of driving periods is given by N_d . $d(l)$ ($l = 1, \dots, N_d$) is the l -th driving distance; p_l is the probability corresponding to $d(l)$; T is the sampling length, which is 1 hour in this work. $p_{k1}(i)$ is the probability of EV parking and plug in at home within time slot i ; $p_{k2}(i)$ is the probability that the EV is under driving outside within time slot i .

The PV output power is calculated by:

$$P_1(i) = \xi \cdot S(i) \cdot A \quad (6)$$

Here $S(i)$ is the absorbed solar irradiance (kW/m^2); ξ ($0 < \xi < 1$) is the conversion efficiency of solar irradiance to electricity which is selected as 15% in this paper; A is the solar panel area for PV (m^2). Those remaining loads in P_4 is considered to be known and constant. The grid power can be calculated by (1) when other power terms are available.

2.2 Solar Thermal Model for Water Heating

The heat collector, storage tank, loads and heat losses have been considered in this model as in (Kalogirou, 2013). Hot water in the storage tank is assumed to be fully mixed or non-stratified. It is also assumed the supplying flow rate of hot water is fixed, the make-up water temperature is constant and the heat exchanger and pipe losses are ignored. The energy balance of the storage tank is given as:

$$M \cdot C_p \frac{dT_s}{dt} = P_u(t) + P_e(t) - P_l(t) - P_{tl}(t) \quad (7)$$

where T_s is the temperature inside the tank; M is the mass of storage capacity (kg); C_p is the specific heat of water, which is $4,187 J/(kg \cdot ^\circ C)$. The collected solar power delivered to the storage tank is represented by P_u and the power removed from the storage tank to load is P_l . P_{tl} is the power loss from storage tank, and P_e is the auxiliary electricity heat power as in (4). Taking sampling time to be 1 hour, at time instance i , (7) can be written in a discrete form as:

$$M \cdot C_p \cdot (T_s(i+1) - T_s(i)) = P_u(i) + P_e(i) - P_l(i) - P_{tl}(i) \quad (8)$$

The collected solar power delivered to the storage tank can be given by (Kalogirou, 2013), and the heat loss area is assumed to be the same as the solar collect area:

$$P_u(i) = A_c \cdot F_R \cdot (S(i) - U_L \cdot (T_s(i) - T_a(i))) \quad (9)$$

where A_c is solar collect area (m^2), $S(i)$ is absorbed radiation at time i , F_R is the heat removal factor, which is 0.88 following (Sayigh, 2014), and U_L is the overall heat loss coefficient which is selected as $6.6 W/(m^2 \cdot ^\circ C)$ (Kalogirou, 2013). $T_a(i)$ is the environment temperature written as:

$$S(i) = \rho \cdot \lambda \cdot I(i) \quad (10)$$

where $I(i)$ is solar irradiance, and $\rho \cdot \lambda$ is transmittance absorbance product which is selected as 0.86 (Symons, 1984).

The power removed from the storage tank to load can be written as

$$P_l(i) = \dot{m} \cdot C_p \cdot (T_s(i) - T_{mu}(i)) \quad (11)$$

where \dot{m} is the mass flow rate (kg/s), T_{mu} is the make-up water temperature. The storage tank power loss is given by (Kalogirou, 2013)

$$P_{tl}(i) = U \cdot A \cdot (T_s(i) - T_a(i)) \quad (12)$$

where U is the storage tank loss coefficient and A is tank area. The product of U and A is $2.8 W/^\circ C$ on operation status and $1.9 W/^\circ C$ on stand-by status (Furbo, 2004). Taking (4), (9)-(12) into (8) will give the full description for the storage tank hot water temperature.

2.3 Overall Energy Cost Function for Optimisation

The developed model is used to minimize the total operational cost of the energy system, over a 24 hours' time period. The cost function, C_{total} , consists of the following parts: the cost to purchase electricity from the grid ($C_{purchase}$), the degradation cost of the EV battery (C_{EV}), the cost of the ESS battery (C_{ESS}), and also the income from selling electricity to the grid, C_{income} . The battery degradation cost models of EV and ESS are developed in our previous work (Sun et al., 2018).

The electricity purchasing cost and the income from selling electricity to the grid depend on the values of P_5 .

The overall daily cost function can be written as

$$C_{total} = \sum_{i=1}^{24} [C_{EV}(i) + C_{ESS}(i) + C_{purchase}(i) - C_{income}(i)] \quad (13)$$

The following two constraints are considered for the state of charge (SOC) of EV and ESS.

$$SOC_{min}^{EV} \leq SOC_{EV}(i) \leq SOC_{max}^{EV} \quad (14)$$

$$SOC_{min}^{ESS} \leq SOC_{ESS}(i) \leq SOC_{max}^{ESS} \quad (15)$$

To ensure that the EV has sufficient power for the next driving period, the minimal terminal SOC constraint should be given as well, which is expressed as follows:

$$SOC_{EV}(24) \geq SOC_{LB}^{EV} \quad (16)$$

The constraint of the hot water temperature in storage tank is written as

$$|T_s(i) - T_{expected}(i)| \leq Z \quad (17)$$

where Z is the permissible error range of the temperature; $T_{expected}(i)$ is the expected hot water's temperature at time period i . According to the model in Section 2.2, the hot water temperature in the storage tank is a function of P_e as shown in (8). Taking all the above factors into account, the optimisation problem can be formulated as shown below:

$$\min C_{total}$$

$$\text{subject to: } SOC_{min}^{EV} \leq SOC_{EV}(i) \leq SOC_{max}^{EV}$$

$$SOC_{min}^{ESS} \leq SOC_{ESS}(i) \leq SOC_{max}^{ESS}$$

$$SOC_{EV}(24) \geq SOC_{LB}^{EV} \quad (18)$$

$$\sum_{j=1}^5 P_j(i) + P_e(i) = 0$$

$$|T_s(i) - T_{expected}(i)| \leq Z$$

As can be seen from (2), (3) and (4) the decision variables can be considered as the 0, 1 and -1, and the optimization is an integer programming problem. In this work, a GA algorithm has been applied to solve the optimization problem.

3. CASE STUDIES UNDER DIFFERENT SCENARIOS

3.1 System Specifications

In this work, both the flat electricity tariff and the time-of-use (TOU) tariff are considered in the following case studies. The solar PV's generation tariff and the FITs are taken from (Ofgem, 2018), and the solar PV rating is selected as less than 10kW. The brand and type of the EV is Tesla Model S P100, the battery capacity is 100kWh. The battery price of this EV is taken as £25,860. Furthermore, another product of Tesla, which is Powerwall, is selected as the ESS battery storage. Each Powerwall has the capacity of 6.4kWh and the cost of \$3,000 (approximately £2,400). The grid voltage is standard household AC voltage of UK which is 240V, and the charging / discharging current of EV and ESS are all assumed to be 10A.

The back-up electricity heat power is 1.1kW, the rated voltage is the same as the standard home voltage and the current is 5A. According to the Solar Energy Calculator Sizing Guide (2015), the smallest area of solar panel is around $16m^2$, thus the maximum radiation absorbed area for both SWH and PV systems are set as $A_c + A = 16m^2$ in the case studies.

The average hourly residential load curve (Fig. 2) is sourced from the UK official government report (Zimmermann et al., 2012). The average hourly solar irradiance data is taken from the report of PV geographical information system (2017), where the site is near Glasgow, and the selected months are January in Fig. 3 for winter and July for summer case. The average hourly hot water consumption data (Fig. 4) is taken from (Blumsack et al., 2009). The make-up water temperatures for the SWH system are usually $8^\circ C$ in winter and $15^\circ C$ in summer. According to (Hulme et al., 2013), the average daily indoor ambient temperatures are $18.3^\circ C$ in winter and $21^\circ C$ in summer. The expected temperature of the hot water is set to be $50^\circ C$.

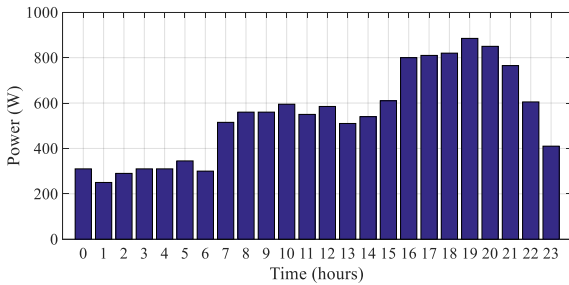


Fig. 2 Average hourly load profile during a day

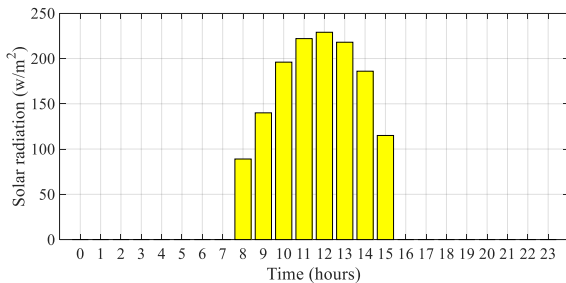


Fig. 3 Average hourly solar radiation daily profile in January

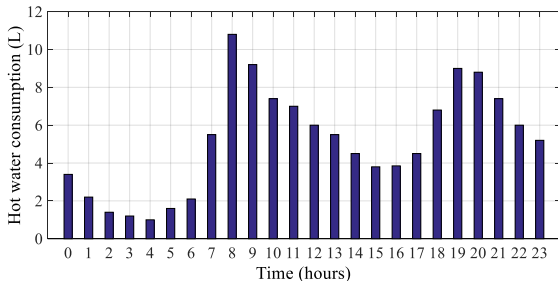


Fig. 4 Average daily profile for hot water consumption

3.2 Daily Costs under Different SWH and PV Areas

In this section, the impact of SWH area (A_c) and PV area (A) are investigated. The initial SOC value is set to be 80%, and it is the same as the minimal terminal SOC constraint, SOC_{LB}^{EV} .

Under each set of A_c and A , the optimization in (18) is conducted to reach the minimum cost. First select the winter season and the fixed tariff. The impacts of PV and SWH are tested separately. Fig. 5 shows that when the PV area is kept constant as zero, the cost is decreased when the area of SWH is increased.

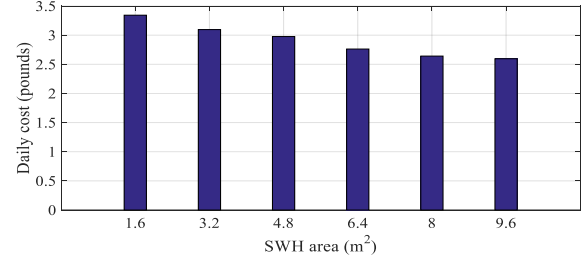


Fig. 5 Daily costs with different areas of SWH in winter

Then the SWH's area is kept constant at $9.6m^2$, and the PV's area is varied. Fig. 6 shows that the cost decreases with the increase of PV area.

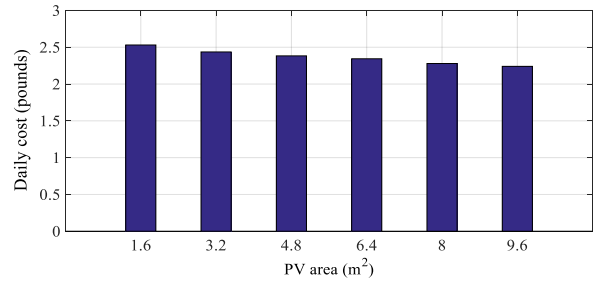


Fig. 6 Daily costs with different areas of PV in winter

The above results are obtained without considering limit on the total area for collecting solar radiation. However, it should be noted that the total area for collecting solar radiation is limited by $16m^2$. There is a trade-off between the SWH area and the PV area. Comparing Fig. 5 with Fig. 6, it can be observed that the change of SWH's area is slightly more sensitive than PV. However, larger area of SWH does not necessarily assure more cost savings. The daily hot water consumption also needs to be considered, i.e. excessive area of SWH is not helpful when the demand of hot water consumption has been satisfied.

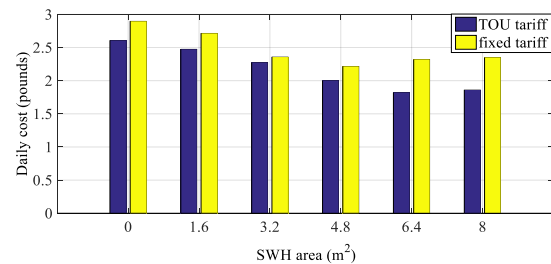


Fig. 7 Cost comparison of different SWH areas in winter

When considering the total area constraint, Fig. 7 shows the comparison of the costs with different areas of SWH under two electricity tariffs for the selected winter season. With the selected fixed tariff, the minimum cost obtained is $\text{£}2.20$ when the area for SWH $4.8m^2$ (PV area $11.2m^2$). With the TOU tariff, the minimum cost is calculated to be $\text{£}1.82$ when the area of SWH is $6.4m^2$ (PV $9.6m^2$).

Fig. 8 shows the optimised results when the selected season is summer. Under both tariffs, the optimal areas are found to be 1.6m^2 for SWH and 14.4m^2 for PV. Comparing the costs between the two tariffs in both Fig. 7 and Fig. 8, users will obtain more profits when the TOU tariff is applied.

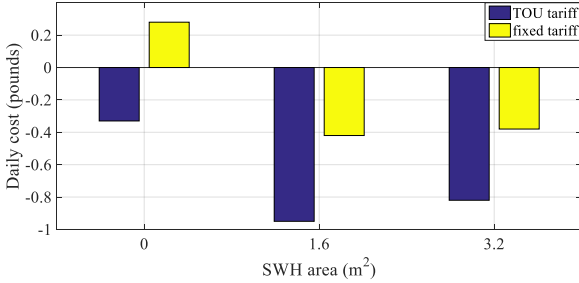


Fig. 8 Cost comparison of different SWH areas in summer

3.3 Comparison with Photovoltaic Thermal Hybrid Solar Collectors (PV-T) and non-Optimized Baseline

In this study, the storage tank's volume is 80L, the selected EV is TESLA MODEL S 100. The thermal part of the PV-T system model is assumed to be similar to the SWH model in Section 2.2. The conversion electrical efficiency of the PV-T system is selected as 10% higher than the PV system following (Ozgoren et al., 2013). The thermal efficiency of the PV-T system is set as 5% lower than the SWH system (Agbidi et al., 2016). Therefore, for the PV-T model, the PV electricity output power and the thermal solar radiation should be written as $P_1(i) = \xi \cdot S(i) \cdot A \cdot 110\%$ and $S(i) = \rho \cdot \lambda \cdot I(i) \cdot 95\%$. Other parameters are the same as in Section 3.2, and the minimum daily cost of the end user is obtained by optimization in (18). Table 1 shows the annual costs for two different hybrid systems, in which the variation of solar radiation on monthly basis are considered. It can be seen that user profit is made if the PV-T system is installed. Since the initial investment cost of PV-T is much higher than the traditional PV or SWH system, whether the PV-T system can benefit the end user from long-term perspective needs to be further examined.

Table 1 Annual costs for PV-T and PV-SWH

PV-T Annual cost (£)	-215.4
PV-SWH Annual cost (£)	175.2
Non-optimised Cost (£)	890.4

For non-optimized calculations, on each time period, simply add each power consumption and power generation with the PV input, and then multiply this with the electricity tariff or FIT. The initial input data for the non-optimized calculation are the same as the previous settings for the optimized calculation, such as solar radiation, load curve, electricity tariff and so on. The SWH is ignored, only the PV system is included in the non-optimized model, thus all solar panel area is utilized for PV system. Following (Zimmermann et al., 2012), the power consumption for water heating with an electric heater has been included. In addition, ESS is not included and EV control is not considered in the non-optimized model. The initial investment of smart home system is mainly from the installation costs, which is shown in Table 2.

Table 2 Initial investment for a smart home system

	PV	ESS	EV charging device	Smart home system
Installation cost (£)	1,505/kW	2,300/pack	647	1,181

According to the solar water heater product list (2018), the cost of a typical SWH system is around £500. In addition, when the SWH system is installed, the area for installing PV panel will be decreased, so the PV system is decreased to 2kW. The initial investment for setting a smart home system with a 2kW PV system, one pack of Tesla Powerwall and a typical SWH system will be £7,638. If the hybrid PV-T system is applied, the total roof area can be utilized for the solar panel. In this case, it is assumed that the electricity output of PV-T can be increased to 3kW. The installation cost of PV is £1,505/kW. According to the solar PV-T hybrid solar thermal/PV panels report (2014), the PV-T installation cost is 10% higher than the traditional PV system, the associated cost will be $1,505 \times 3 \times 110\% = £4,966$. The overall cost of the smart home system will be £9,094. From these estimations, the payback periods (PB) for PV-SWH system, PV-T system and PV system can be obtained as shown in Table 3

Table 3 Payback periods of different systems

PV-SWH (years)	PV-T (years)	PV (years)
3.56	3.62	5.10

As can be seen from Table 3, the payback period of the residential system with solar thermal collectors (either PV-SWH or PV-T), will be much shorter than the non-solar thermal collector system. Comparing PV-T with PV-SWH, the PB is slightly longer. However, according to the results in Table 1, end users can make more profits after return the initial investment; therefore, PV-T system is recommended from long-term perspective to achieve best economic benefit.

4. CONCLUSIONS

An energy cost model is established with the aim to minimize the household user's energy cost. It includes EV, ESS, PV, SWH or hybrid PV-T system. The optimization is performed by setting up different split of SWH area and PV area when the total area for collecting solar radiation is kept constant. Comparing SWH with PV, the results show that SWH is more efficient than PV for utilizing solar energy for water heating. It appears solar thermal water heater is still necessary to achieve the best economic benefit for the end users. Through the proposed strategy, the suitable area split between SWH and PV can be determined. The hybrid PV-T system is compared to the PV-SWH system. Case study results show that the PV-T system can achieve more cost savings than the PV-SWH system.

The costs which are obtained through the optimization have been compared with the non-optimized case. The improvement in cost savings with optimization is apparent, and the PB because of the cost savings can be achieved. The average payback period of the residential system, which includes solar thermal collector (either PV-SWH or PV-T),

will be much shorter than a non-SWH system. This is mainly resulted from the cost reduction from the solar thermal system.

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