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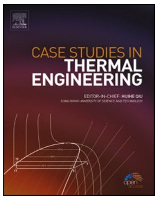

Integration of heat pipe solar water heating systems with different residential households: An energy, environmental, and economic evaluation

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HIGHLIGHTS

- Hourly-based energy, environmental, and economic evaluations of HPSWH systems.
- One, two, and four-occupant households in Perth as case studies.
- 36–51% contribution of HPSWH system in supplying required energy in winter.
- 387–1146.8 kg of CO_2 emissions avoidance by implementing the solar system.
- Most economic feasibility in houses with more occupants and electric backup system.

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ABSTRACT

This study presents a detailed methodology for evaluating the energy, environmental, and economic contributions of heat pipe solar water heating (HPSWH) systems in various households. The hot water consumption patterns of Perth residents in Australia in one, two, and four-occupant houses are extracted in hourly basis throughout a year. The annual performance of the system is evaluated based on parameters such as saved energy, solar fraction, avoided CO_2 emission, saved money, and payback period. Moreover, an experimental rig is designed, manufactured, and tested. The results show that the contribution of the solar system in meeting the hot water demand is around 99% in summer, while this contribution drops to 36–51% in winter. Almost 387–1146.8 kg of CO_2 emissions can be avoided annually in Perth if HPSWH systems are integrated with the conventional heating systems. In addition, it is shown that the HPSWH system has its most economic justification in households with higher number of occupants. Moreover, the payback period is much lower for houses with conventional electric water heating systems compared to houses with LPG systems.

1. Introduction

The households are considered as one of the main energy-intensive sectors of the economy in which around 30% of the world final energy is consumed [1]. Moreover, the consumption growth is predicted to be 1.5–2.1% per year from 2012 to 2040 due to the population growth and prosperity increase [2]. Among various applications of energy in households, domestic hot water (DHW) consumes around 25% of the total energy [3]. Various types of energy systems have been proposed to meet the DHW demand. These

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systems are mainly powered by fossil fuels which contribute greatly to the greenhouse gas emission and result in adverse environmental impacts [4].

Integration of solar water heating (SWH) systems with conventional heating systems has great potentials in decreasing fossil fuel consumption, pollutant production, and greenhouse gas emission [5]. A SWH system can operate for more than 25 years without any significant maintenance cost which turns it into a feasible investment [6]. Due to the mentioned economic and ecological advantages, the application of SWH systems has grown rapidly in the last decade [7,8]. The first type of SWH systems, which has been widely used for its simple structure and cheap price, are flat plate solar water heating (FPSWH) systems. The thermal efficiency of FPSWH systems is proven to be low, especially in cold seasons, due to its high heat loss and low convective heat transfer coefficient [9]. For instance, the thermal efficiency of 75% in summer drops to 40% when the FPSWH system is operated in winter. This type of systems are vulnerable to moisture, show high hydraulic resistances, and require sun trackers for efficiency improvement [10,11]. More information regarding the configuration and construction of FPSWH systems can be found in Ref. [10,11].

Balaji et al. [6] investigated the application of heat transfer enhancers in forced circulation FPSWH systems based on exergy, economic and environmental parameters. Kim et al. [12] studied the economic and environmental impact of a FPSWH system under the climatic conditions of China. The results indicated that solar fraction improvement of these systems can reduce CO_2 emission by up to 61%. By having energy, economic, and environmental points of view, Rosato et al. [13] studied the effects of solar circuit design as well as solar thermal technology on the efficiency of a solar district heating system.

Kalogirou [18] studied the thermal performance as well as economic and environmental justifications of a thermosiphon FPSWH system. The results showed that the payback period of the system was 4.5 years when it was operated with electrical backup. In a similar study, the technical and environmental performance of a FPSWH system was investigated by Koroneos and Nanaki [19]. Around 4280 € can be saved in Greece by implementing the solar system over its lifetime. Similar studies regarding the energy, economic, and environmental aspects of FPSWH systems can be found in Ref. [18–23].

The potentials of FPSWH systems to be applied in residential sector in Brazil were investigated based on different technical and economic aspects by Cruz et al. [14]. Initial cost, family size, and cost of energy were introduced as the most important parameters in technical and economic feasibility of these systems. In a theoretical study, two types of FPSWH systems (i.e. loop thermosiphon and conventional systems) were compared under climatic conditions of Fuzhou city, China [15]. In addition, the effects of set temperature on the annual performance were analysed in details. In another comparative study, the performances of FPSWH and conventional electric water heating systems were investigated for medium-rise residential buildings in urban Mediterranean areas [16].

The second type of SWH systems is called evacuated tube solar water heating (ETSWH) systems. This type of solar systems has higher thermal efficiency compared to the FPSWH systems even in cold environments with low solar radiation [17]. However, the possibility of overheating, vacuum loss, material problems [18], high initial costs [19], and fragile structure [18] have remained as their major drawbacks.

By having a thermo-economic viewpoint, Sokhansefat et al. [20] compared the performance of flat plate and evacuated tube solar water heaters in cold climatic conditions of Iran. The thermal efficiency and annual useful energy gain of the ETSWH system was respectively 41% and 30% higher than the FPSWH. García et al. [21] characterized the profitability of ETSDWH systems in meat industries. The results proved the profitability of the system in Europe where the solar system could provide more than half of the required energy. Yilmaz [22] developed a novel thermo-economic model to optimise the effectiveness, cost, and ecology of ETSWH systems in residential sector of Turkey. In a comprehensive review paper, Chopra et al. [23] summarized the global advancements, financial advantages and disadvantages, and research potentials of ETSWH systems.

Heat pipe solar water heating (HPSWH) systems were proposed to overcome the drawbacks of previous types of SWH systems. The advantages of HPSWH systems compared to other types include efficient solar energy absorption, low thermal and hydraulic resistances, higher heat transfer capability and lower heat transfer area and weight, efficient transition of absorbed solar energy, lower possibility of overheating, and higher lifespan [24].

The mentioned unique features and advantages of HPSWH systems, which have been evidenced in many studies [25–27], have resulted in the significant attention of researchers towards the application and efficiency improvement of these systems in recent years. Shafieian et al. [28] evaluated the efficiency of HPSWH systems to meet the residential water consumption pattern of Perth residents in cold seasons. In another experimental study, the implementation of a variable solar working fluid mass flow rates technique was proposed, tested, and verified for efficiency improvement of HPSWH systems [29].

Du et al. [33] experimentally studied the effect of various operational parameters on pressure drop, outlet temperature, and thermal efficiency improvement of an HPSWH system. In a theoretical study, different data-based and energy balance-based simulation methods for predicting the performance of HPSWH systems were developed and compared [30]. In another theoretical and experimental study, the thermal efficiency of an HPSWH system was investigated under climatic conditions of Sanandaj, Iran [31]. Application of HPSWH systems in households with natural gas heating systems in Pakistan was the focal point of a study by Mehmood et al. [32]. The results showed that using the solar system reduced the fuel consumption by save 23–56%. For further information regarding the latest studies, developments, and research potentials of HPSWH systems, the readers are referred to three review papers published by Shafieian et al. [17,33,34].

While the technical aspects of HPSWH systems, such as thermal efficiency, have been studied to a great extent, the annual energy, environmental, and economic contributions of these systems are completely under-researched. Besides that, the previous studies have significant deficiencies making them far from real operational conditions: (i) Only the averaged values of climatic conditions have been considered instead of real ones; (ii) Moreover, these studies have been limited to one or few days for representing the climate conditions of the year; (iii) And most importantly, lack of real hot water consumption patterns or deficient coverage of hourly hot water demand profiles are evident in these studies.

This study proposes a detailed methodology to evaluate the hourly energy, environmental, and economic contributions of HPSWH systems throughout a year in Perth, Australia. However, the proposed methodology is applicable in different countries with different climatic conditions and water consumption patterns. The hourly hot water consumption patterns of Perth residents in one, two, and four-occupant houses were extracted for all four seasons of a year. The hourly climatic data of Perth throughout a year was collected and the annual energy, environmental, and economic contributions of HPSWH systems were evaluated based on parameters such as saved energy, solar fraction, saved electricity and fuels, avoided CO_2 emission, payback period, and internal rate of return.

2. Materials and methods

2.1. Heat pipe solar water heating system

The main components of an HPSWH system include a heat pipe solar collector (HPSC), a water storage tank, a control unit, a pump, pipes and fittings; and valves (Fig. 1a). A portion of the solar radiation, which passes the evacuated glass, is absorbed and transferred to the solar working fluid using heat pipes. The pump circulates the solar working fluid in the solar loop and through the copper coil inside the storage tank. The heated solar working fluid transfers its heat to the water inside the storage tank. In a typical house in Australia, the water is extracted at the temperature of 313–333 K and replaced with cold tap water. For more information regarding the working principles of HPSWH systems, the readers are referred to the authors' previous studies [28,29].

2.2. Residential hot water consumption pattern

Extracting and applying real hot water consumption patterns play an important role in the accurate and effective energy, environmental, and economic assessment of an HPSWH system. The hot water consumption pattern depends greatly on the number of occupants and time of the year. Therefore, the hourly hot water consumption patterns of three typical residential houses, namely

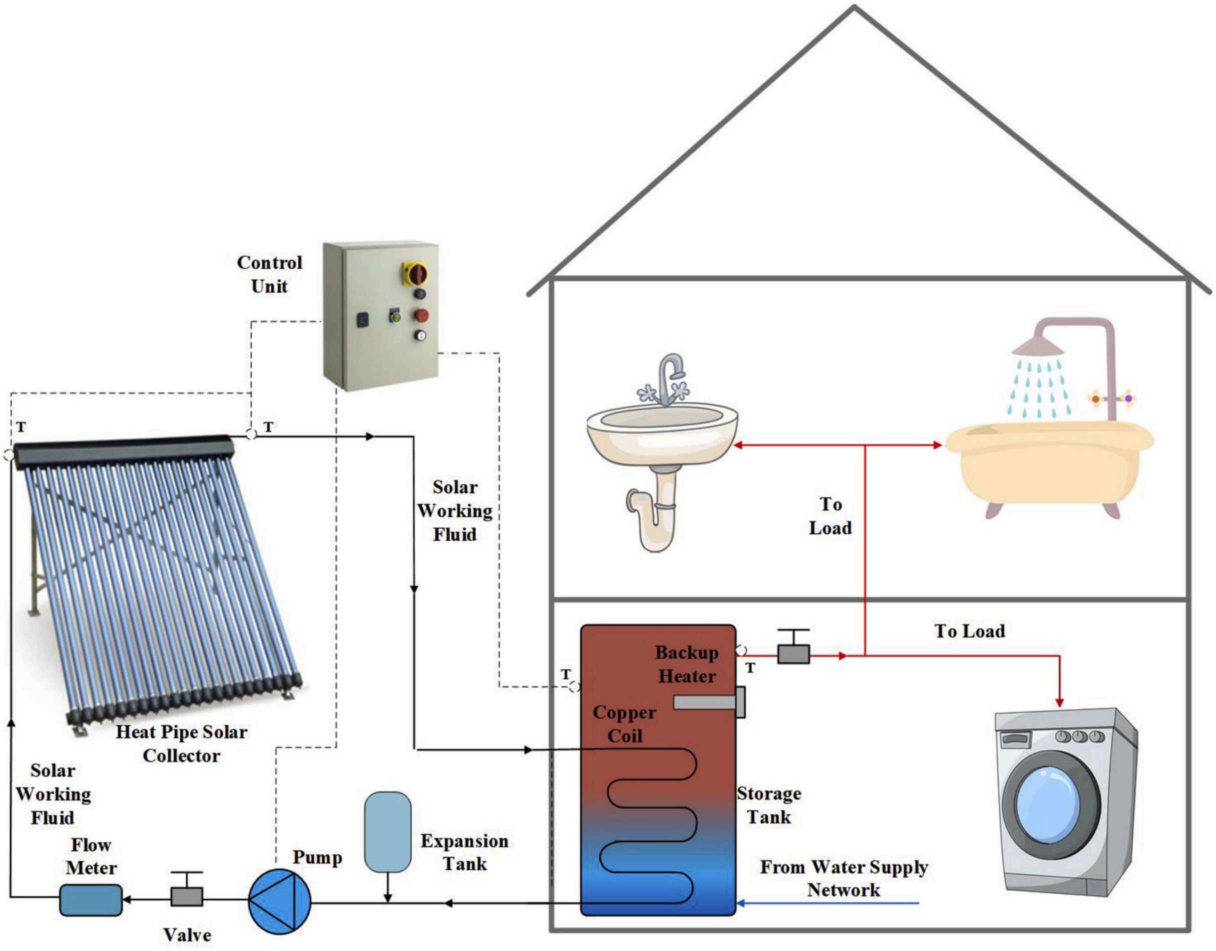


Fig. 1. Schematic of the HPSWH system.

House I, II, and III, in four seasons were considered in this study. Houses I, II, and III have respectively one, two, and four occupants, and their hot water consumption patterns in various seasons were extracted from the Residential End Use Monitoring Program (REMP) Report presented by the government of Australia in 2012 (Fig. 2) [35].

2.3. Climatic data

The climatic data (i.e. solar radiation and ambient temperature) was continuously recorded in 1-min intervals from the weather station at Edith Cowan University. The climatic data over a year from the beginning of March 2018 to the end of February 2019 was collected and used in this study. Based on the geographical conditions of Perth which is located in the southern hemisphere, spring, summer, autumn, and winter are approximately from September to November, December to February, March to May, and June to August, respectively.

2.4. Experimental setup and instrumentation

In order to validate the developed theoretical methodology (which will be explained in Section 2.5), an experimental rig was designed, manufactured, and experimented under different operational and climatic conditions. A pump (Davey Company) was circulating the solar working fluid and its flow rate was regulated by installing a valve after the pump. The solar working fluid (low-temperature) entered the HPSC, received the absorbed energy, and left the solar collector at a higher temperature. The solar working fluid then passed through the copper coil inside the storage tank and transferred its heat to the water inside the tank. The residential hot water consumption patterns were the basis for hot water extraction from the storage tank. This water was then replaced by tap water from a valve located at the bottom of the tank which was connected to water network.

The central control unit used in the system consisted of a National Instrument Data Acquisition (NI-DAQ) system, a control unit, and a computer. Seven Type T- Class1 thermocouples made by TC Ltd. were purchased and installed to measure temperatures at various locations of the system. These thermocouples were monitored using the NI-DAQ system. The experimental data in this study was recorded at the intervals of 10 s. This was facilitated using an Application Program Interface (API) whose code was written in the LabVIEW 2014 software. To avoid making the paper lengthy, the readers are referred to the authors' previous publications [28,29] for further information regarding the components, working principles, and control and operational parameters of the system.

2.5. Mathematical modelling

2.5.1. Required energy for water heating

The amount of energy which is required to increase the temperature of water to a specified temperature (Q_{req}) can be calculated by:

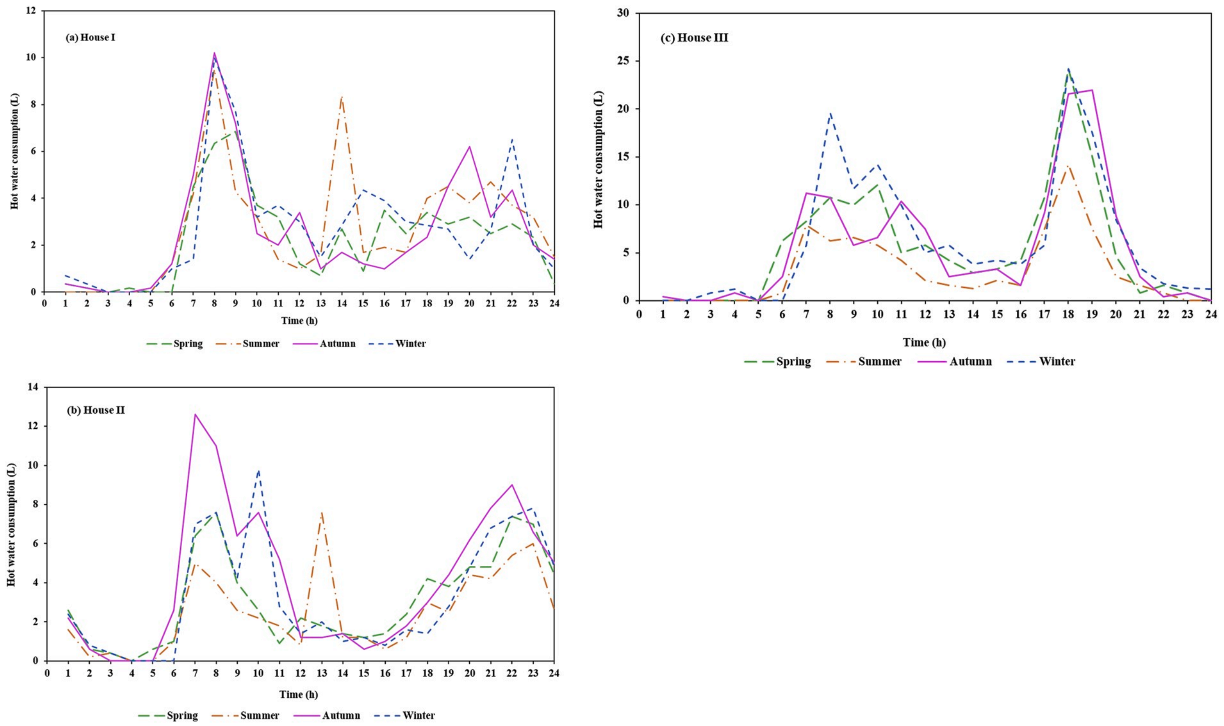


Fig. 2. Seasonal domestic hot water consumption patterns: (a) Houses I, (b) House II, and (c) House III.

$$Q_{req} = m_{w,h} Cp_w (T_{w,user} - T_{w,network}) \tag{1}$$

where $m_{w,h}$ (kg) is the hot water mass based on the consumption pattern and Cp_w (J/kgK) is the specific heat capacity. $T_{w,user}$ (K) and $T_{w,network}$ (K) are respectively the temperature of the hot water and the water temperature of the municipal water network.

2.5.2. *Useful absorbed solar energy*

The calculation process of useful absorbed solar energy consists of four steps. The first step is determining the solar energy which is absorbed by the HPSC (Q_{ab}). The second step is determining the thermal energy which is transmitted by the heat pipes (Q_{hp}), while the third step is regarding the thermal energy exchange inside the manifold section of the HPSC between the heat pipes condensers and the solar working fluid (Q_{sun}). The final step is calculating the amount of thermal energy which is transferred to the water inside the storage tank ($Q_{sun,u}$).

The solar energy absorption and heat loss of the HPSC can be simulated using the thermal energy balance [36]:

$$Q_{ab} = Q_{en} - Q_{loss} \tag{2}$$

where Q_{ab} (W) represents the absorbed thermal energy by the HPSC. Q_{en} (W) is the solar energy passing through the evacuated glass, while Q_{loss} (W) is energy dissipating back to the surroundings. These thermal energies can be determined by Ref. [37,38]:

$$Q_{en} = \tau_{go} \tau_{gi} \alpha_c A_{ab} N_{hp} G \tag{3}$$

$$Q_{loss} = \frac{T_{ab} - T_{amb}}{R_{t,ab}} \tag{4}$$

where α_c represents the absorptivity of the absorbing surface. τ_{gi} in this equation is the transmittance of the inner glass while τ_{go} stands for the transmittance of the outer glass. The absorber and the ambient temperatures are shown by T_{ab} (K) and T_{amb} (K), respectively. The most important parameter in the abovementioned equations is the overall thermal resistance $R_{t,ab}$ (K/W) of the absorbing section (which includes the evacuated glass and the absorbing surface). This parameter comprises the absorber-inner glass natural convection and radiation resistances, the inner glass conduction resistance, the inner-outer glasses radiation resistance, the outer glass conduction resistance, and the outer glass-ambient forced convection and radiation resistances. More information about these resistances and equations to calculate them can be found in details in authors' previous work [28].

The thermal energy which is transmitted by the heat pipes (Q_{hp}) can be calculated by Ref. [39]:

$$Q_{hp} = \frac{T_{ab} - T_{con}}{R_{t,hp}} \tag{5}$$

The total thermal resistance of a heat pipe ($R_{t,hp}$) comprises the evaporator wall conduction and phase change resistances, the wick conduction resistance, heat pipe internal resistance, the condenser conduction and phase change resistances. More information about these resistances and equations to calculate them can be found in details in authors' previous work [28].

The effectiveness-NTU (i.e. Number of Transfer Units) technique [40] was implemented in this study to determine the HPSC outlet temperature:

$$T_{o,n} = T_{i,n} + \varepsilon_n (T_{c,n} - T_{i,n}) \tag{6}$$

where $T_{o,n}$ (K) represents the temperature of the solar working fluid after it passes through the condenser section of each heat pipe. $T_{i,n}$ (K) is the inlet temperature while $T_{c,n}$ (K) stands for the condenser temperature. ε_n in this equation represents the heat pipes effectiveness in the manifold section. Then, the amount of thermal energy which is exchanged in the manifold section between the heat pipe condensers and the solar working fluid (Q_{sun}) can be calculated by:

$$Q_{sun} = m_{swf} C_{swf} \left(T_{swf,o-} T_{swf,i} \right) \tag{7}$$

The amount of transferred energy to the water inside the storage tank ($Q_{sun,u}$) is obtained from:

$$Q_{sun,u} = Q_{sun} \varepsilon_{HE} \tag{8}$$

where ε_{HE} in this equation represents the effectiveness of the copper coil in contact with the water inside the storage tank.

A higher amount of useful absorbed solar energy ($Q_{sun,u}$) compared to the required energy (Q_{req}) means that the solar system is capable of meeting all the energy demand. In this case, the energy provided by other sources or the conventional water heating systems (i.e. electricity or LPG), which act as the backup for the solar system, equals to zero ($Q_f = 0$) and saved energy (Q_{saved}) can be obtained from:

$$Q_{saved} = Q_{req} \tag{9}$$

The extra energy is absorbed by the water inside the storage tank resulting in its temperature increase. The extra energy and temperature of water inside the tank (T_t) can be calculated as follows:

$$Q_{extra} = Q_{sun,u} - Q_{req} \tag{10}$$

$$T_{tank,i+1} = T_{tank,i} + \frac{Q_{extra}}{m_{tank} Cp_w} \tag{11}$$

where $T_{tank,i}$ (K) and T_{tank} (K), and m_{tank} (kg) are the former and new temperatures and mass of the water inside the storage tank, respectively.

However, if $Q_{sun,u}$ is less than Q_{req}, required backup energy (Q_f) and saved energy (Q_{saved}) can be calculated by:

$$Q_f = Q_{req} - Q_{sun,u} \tag{12}$$

$$Q_{saved} = Q_{sun,u} \tag{13}$$

In this case, there is no extra energy and the water temperature inside the storage tank equals the temperature of the water network ($T_{w,network}$):

$$Q_{extra} = 0 \tag{14}$$

$$T_{tank,i+1} = T_{w,network} \tag{15}$$

2.5.3. Saved electricity

The following equations are applied to determine the amount of saved fuel (kg) and electricity (kWh) using the HPSWH system:

$$Saved\ fuel = \frac{Q_{saved}}{\eta_{boiler} PC_f} \tag{16}$$

$$Saved\ electricity = \frac{Q_{saved}}{\eta_{boiler} CF_{electricity}} \tag{17}$$

where PC_f (MJ/kg) is the caloric power of LPG and $CF_{electricity}$ represents the energy-electricity conversion factor.

2.5.4. Environmental analysis

The environmental analysis mainly consists of studying the amount of CO_2 emission avoided by implementing the HPSWH system:

$$Avoided\ CO_2 = Saved_{fuel/electricity}\ F_{fuel/electricity} \tag{18}$$

where $F_{fuel/electricity}$ represents the amount of emitted CO_2 to the environment per each unit use of LPG or electrical energy.

2.5.5. Economic analysis

The amount of money saved by applying the HPSWH system can be determined by:

$$Saved\ money = Saved_{fuel/electricity}\ \$_{fuel/electricity} \tag{19}$$

where $\$_{fuel/electricity}$ represents the cost of fuel or electricity used in the conventional boiler.

The net present value (NPV) is defined as the investment worth in today's money and can be calculated by:

$$NPV = -C_T + \sum_{x=1}^{x} \frac{A_{annual,x}}{(1 + I_{bm})^x} \tag{20}$$

where C_T is the initial cost of the system, x represents the lifespan of the system, $A_{annual,x}$ is the annual saved money, and I_{bm} represents the annual inflation rate.

The internal rate of return (*IRR*) is considered as an effective factor to evaluate the economic justification of the HPSWH system. The following equation should be solved to calculate the IRR:

$$C_T = \sum_{x=1}^{x} \frac{A_{annual,x}}{(1 + IRR)^x} \tag{21}$$

The payback period (*PP*) of the HPSWH system can be determined by:

$$PP = N + \left[1 + \frac{A}{B}\right] \tag{22}$$

where N is the number of years after which the last negative cumulative cash flow is observed. A and B in this equation represent the cumulative cash flow value at which the last negative and positive cumulative cash flow is observed, respectively.

2.5.6. Computational process

The computational process starts with reading the annual climatic data and seasonal hot water consumption patterns. Then, the computer program considers the first hour of the first day and performs the calculations for the first day. The results of the computational process of each hour are stored, and some outlet parameters such as tank temperature are considered as inputs for the computational process of the next hour. The mentioned process is iterated and the results are analysed for the whole year. In addition, Table 1 provides information regarding the input parameters as well as their values.

According to the standards and guidelines, the characteristics of the solar system should be designed based on the number of occupants and their consumption requirements. By following the guidelines provided by manufacturers and the data presented in standard handbooks, three types of hot water system, as presented in Table 2, were considered in this study.

3. Results and discussions

3.1. Energy analysis

3.1.1. Solar fraction

The solar fraction is widely used to evaluate the contribution of the solar system in meeting the hot water demand of a household. It is defined as the ratio of the energy provided by the HPSWH system by the total required energy. Fig. 3 shows the distribution of the seasonal and annual solar fractions of the HPSWH system in Houses I, II, and III.

The contribution of the HPSWH system is very significant in summer when the system reached the solar fractions of 0.98, 0.99, and 0.98 in Houses I, II, and III, respectively. Although the absorbed solar energy in this season is higher than the required energy, the peaks in hot water demand and available solar energy do not match. The former occurs in the early morning and late afternoon while the latter occurs around noon. In fact, the highest requirement for hot water in all Houses occurs when the least solar energy is available. Due to this fact, a part of the required energy should be provided by the backup system even in summer.

Besides having shorter days in winter, the solar radiation is much lower in this season compared to summer. On the other hand, the hot water demand in this season is relatively high compared to other seasons. This results in a lower contribution of the HPSWH system in hot water supply in this season. The solar fractions in winter are 0.41, 0.51, and 0.36 for Houses I, II, and III, respectively. The solar fractions of the HPSWH system in Houses I, II, and III are respectively 0.93, 0.95, and 0.91 in spring and 0.6, 0.58, and 0.57 in autumn. Overall, the average annual solar fraction of the HPSWH system is in the range of 0.71–0.76 depending on the operational and climatic conditions.

3.1.2. Required, absorbed, and backup energy

Fig. 4 shows the seasonal and annual energy which is required to meet the hot water demand (Q_{req}) in Houses I, II, and III. This figure also includes the amount of the absorbed solar energy as well as the amount of the energy provided by the backup system. The required energy to meet the hot water demand depends greatly on the number of occupants and their consumption patterns. That is why the required energy varies from 3.6 GJ in House I to 4.49 GJ in House II, and 7.06 GJ in House III.

The amounts of annual absorbed solar energy are 2.84, 4.23, and 5.61 GJ for Houses I, II, and III, respectively. These values depend significantly on weather data and characteristics of the solar system. Around 1.04 GJ of the annual energy in House I should be supplied by external fuel sources while these values are 1.21 and 2.4 GJ in Houses II and III, respectively.

The highest hot water energy demand occurs in winter followed by autumn, while the lowest available solar energy occurs in these seasons resulting in higher usage of backup systems. The hot water energy demand is comparatively lower in summer and spring when the availability of solar energy is rather high. For instance, the hot water energy demand of House III in winter is two times more than that in summer (i.e. 2.19 GJ in winter and 1.06 GJ in summer), while, the absorbed solar energy is less than half (i.e. 0.78 GJ in winter and 2 GJ in summer). As a result, the Houses are highly dependent on backup heating systems in cold seasons.

3.2. Environmental analysis

3.2.1. Saved electricity

The distribution of seasonal and annual saved electricity by applying the HPSWH system along with the consumed electricity by the backup system are shown in Fig. 5. The implementation of the HPSWH system results in electricity consumption reduction of 774, 980, and 1435 kWh in Houses I, II, and III, respectively. This reduces the hot water electricity consumption in Houses I, II, and III by 70%, 72%, and 66%, respectively. Taking the overall energy consumption into account, around 69% of the electricity consumption for water heating can be eliminated by applying the HPSWH system.

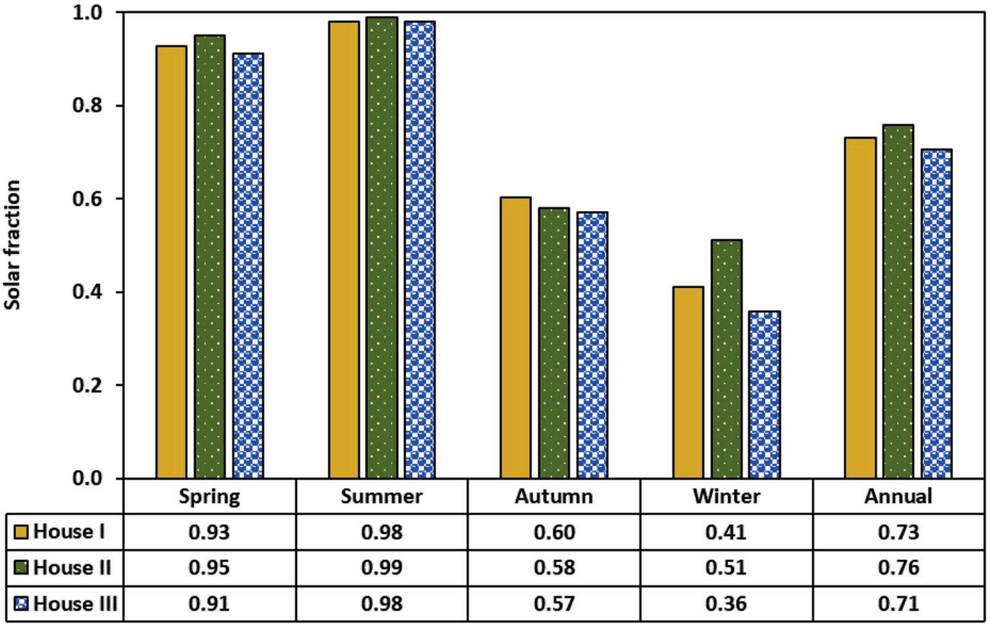
The consumed electricity in spring and summer in all Houses are comparatively insignificant compared to the saved electricity. In

Table 1
Input parameters of the computational process.

Parameter	Value	Parameter	Value
Needed hot water temperature (K)	333	Storage tank volume (L)	110–220
LPG boiler efficiency (%)	87	Electrical boiler efficiency (%)	90
LPG caloric power (MJ/kg)	46.16	Electricity conversion factor (MJ/kWh)	3.6
CO_2 emission avoided (LPG) (kg CO_2/kg)	3	CO_2 emission avoided (electricity) (kg CO_2/kWh)	38.1
LPG cost (AUD/kg)	1	Electricity cost (AUD/kWh)	0.35

Table 2
Characteristics of the HPSWH system.

House Type	Number of heat pipes (pipe)	Absorber area (m^2)	Volume of hot water storage tank (L)
I	12	0.96	110
II	18	1.44	150
III	25	1.92	220



	Spring	Summer	Autumn	Winter	Annual
🟨 House I	0.93	0.98	0.60	0.41	0.73
🟩 House II	0.95	0.99	0.58	0.51	0.76
▨ House III	0.91	0.98	0.57	0.36	0.71

Fig. 3. Distribution of seasonal and annual solar fraction of the HPSWH system.

autumn, the consumed electricity gets closer to the saved one and it becomes almost equal to or passes the saved electricity in winter. The highest dependency on the backup heating system occurs in winter for Houses I and II, and in autumn for House II.

3.2.2. Avoided CO_2 emission

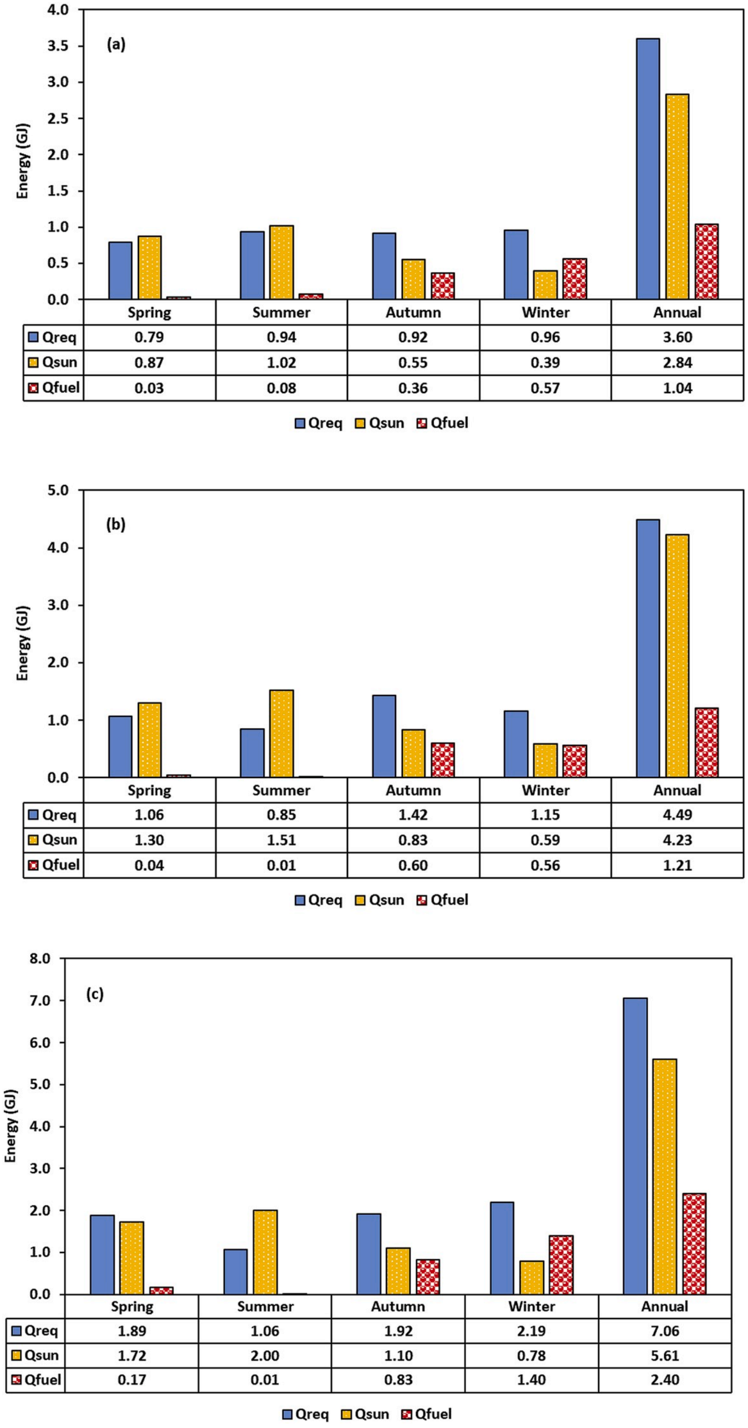
The distribution of the seasonal and annual CO_2 emissions which can be avoided by applying the HPSWH system is shown in Fig. 6. The annual avoided CO_2 emissions, when the conventional heating system is operated by LPG, are 209, 264.8, and 387 kg for Houses I, II, and III, respectively. These parameters are respectively 619.3, 784.7, and 1146.8 kg for Houses I, II, and III if the conventional heating system is operated by electricity. The main reason for this difference is that LPG is a much cleaner fuel compared to electricity. LPG is a low carbon fuel which emits virtually no black carbon and results in less environmental impacts compared to the process of electricity generation and consumption.

The seasonal CO_2 emissions which can be avoided by applying the HPSWH system are higher in hot seasons compared to cold ones. For instance, the CO_2 emissions avoided in House III in spring are 143 and 425 kg in LPG and electricity modes, respectively. These values drop to respectively 65.4 and 193.7 kg in House III in winter. This is because the contribution of the HPSWH system in supplying the energy for hot water demand is more significant in spring and summer compared to cold seasons, resulting in higher amounts of saved energy and less fuel consumption.

3.3. Economic analysis

The economic analysis is performed by having the results of the annual saved energy using the HPSWH system, the initial cost of the system, the cost of fuel, and inflation rate. Fig. 7 shows the distribution of the payback period in different Houses having LPG and electricity conventional heating systems. The initial investment on an HPSWH system is covered over a period of 22–27 months if the conventional heating system in the house is electrical. In case the conventional hating system relies on LPG, this period is in the range of 57–74 months. As a result, the HPSWH system has more economic justification in places with electrical heating systems.

In addition, the payback period in House III is lower than the other two Houses. For instance, the payback periods of an HPSWH system, if the conventional heating system is electrical, are 27, 24, and 22 for Houses I, II, and III, respectively. These values are 74, 63, and 57 months for Houses I, II, and III, respectively. Overall, the HPSWH system has its most economic justification in House III, where the number of occupants is higher, followed by House II and I.



(a)

	Spring	Summer	Autumn	Winter	Annual
Qreq	0.79	0.94	0.92	0.96	3.60
Qsun	0.87	1.02	0.55	0.39	2.84
Qfuel	0.03	0.08	0.36	0.57	1.04

(b)

	Spring	Summer	Autumn	Winter	Annual
Qreq	1.06	0.85	1.42	1.15	4.49
Qsun	1.30	1.51	0.83	0.59	4.23
Qfuel	0.04	0.01	0.60	0.56	1.21

(c)

	Spring	Summer	Autumn	Winter	Annual
Qreq	1.89	1.06	1.92	2.19	7.06
Qsun	1.72	2.00	1.10	0.78	5.61
Qfuel	0.17	0.01	0.83	1.40	2.40

Fig. 4. Seasonal and annual energy required, supplied by the sun, and backup energy to meet the hot water demand of (a) House I, (b) House II, and (c) House III.

3.4. Validation

The most important parameter in analysing the annual performance of an HPSWH system is the amount of absorbed solar energy and all other parameters are calculated based on this parameter. Hence, the amount of the absorbed energy was chosen for the purpose of model validation. One day in each season was chosen and the experimental and theoretical data were compared in these days, as specified in Table 3. It is worth noting that as the experimental rig was manufactured to meet the hot water requirements of House III

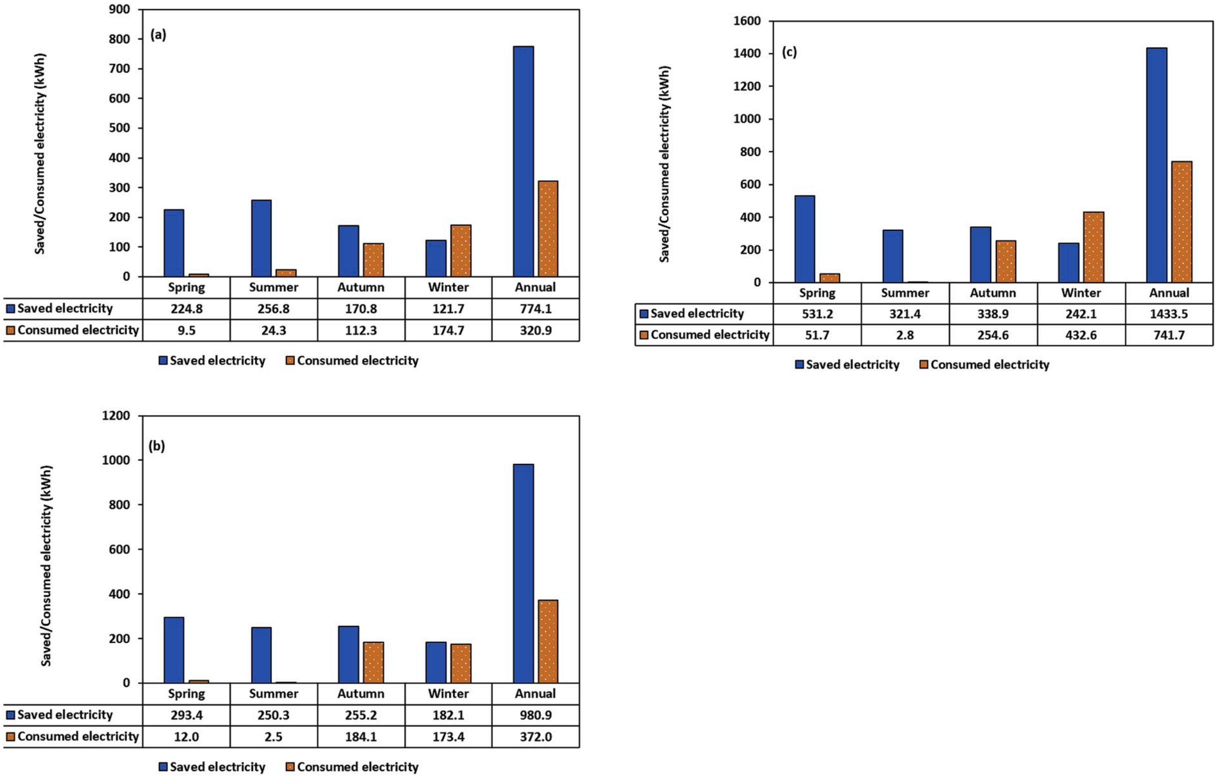


Fig. 5. The seasonal and annual saved electricity using the HPSWH system and the consumed electricity by the backup system in (a) House I, (b) House II, and (c) House III.

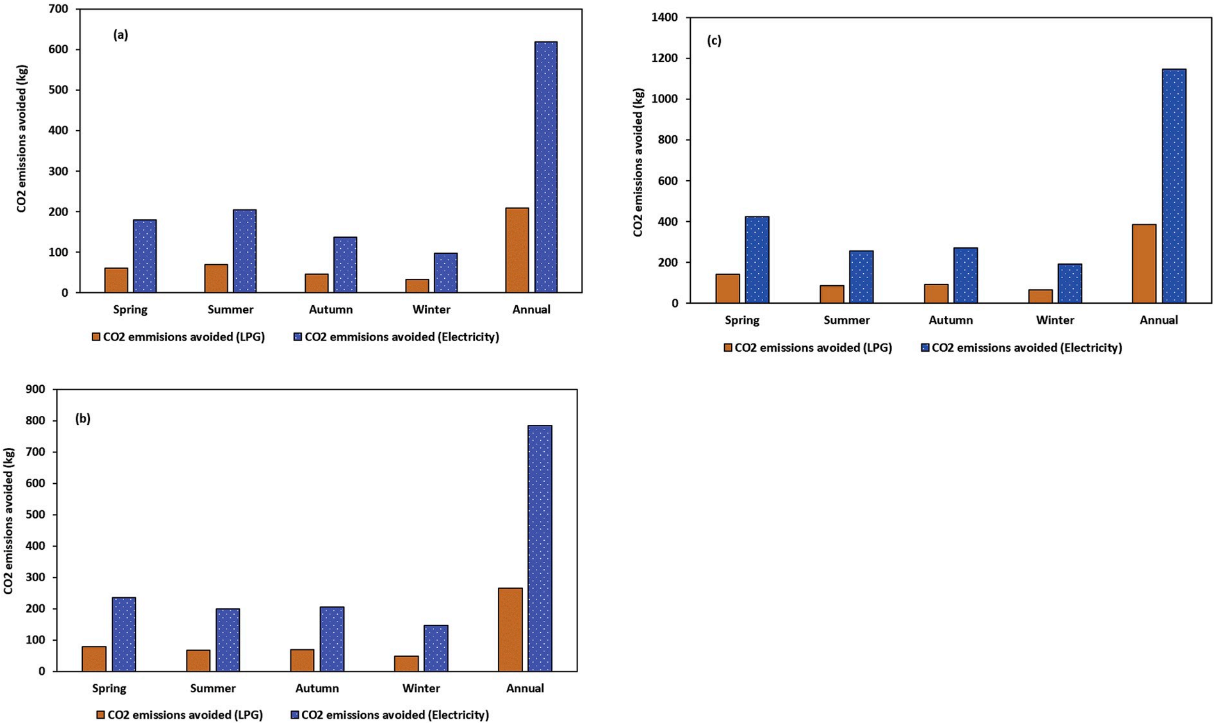


Fig. 6. The seasonal and annual CO_2 emissions avoided by using the HPSWH system in (a) House I, (b) House II, and (c) House III.

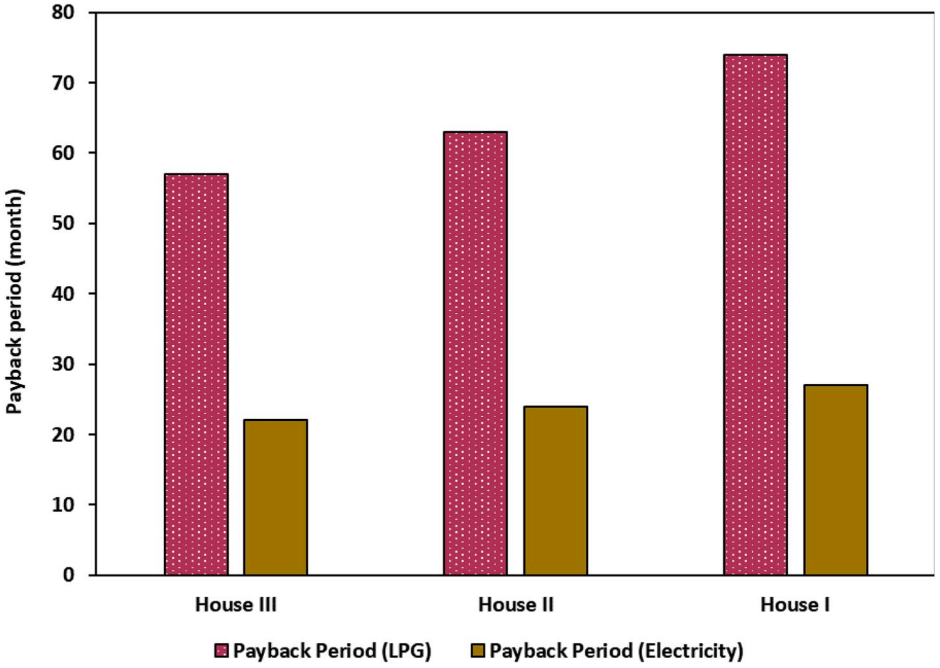


Fig. 7. The payback period of the HPSWH system in different Houses.

Table 3
Theoretical and experimental absorbed energy in different seasons for House III.

Day	Season	Theoretical absorbed energy (MJ)	Experimental absorbed energy (MJ)	Difference (%)
May 21, 2018	Autumn	11.9	11.5	3.8
July 10, 2018	Winter	8.5	7.9	7.1
October 17, 2018	Spring	18.9	18	4.7
January 15, 2019	Summer	22.3	20.9	5.9

(specified in Table 2), the theoretical and experimental data in Table 3 are for this type of household.

The comparison of the results shows that the maximum difference between the theoretical and experimental data, which is 7.1%, occurs in winter. This is followed respectively by summer, spring, and autumn. Overall, the model can be considered as relatively accurate in predicting the performance of HPSWH systems.

4. Conclusions

The energy, environmental, and economic contributions of heat pipe solar water heating systems in one, two, and four-occupant houses (i.e. House I, II, and III, respectively) in Perth, Australia are investigated. The results show that the system reaches the solar fractions of 0.98, 0.99, and 0.98 in summer in Houses I, II, and III, respectively. In winter, these values are respectively 0.41, 0.51, and 0.36 in Houses I, II, and III showing the greater contribution of the HPSWH system in meeting the hot water demand in hot seasons. The annual avoided CO_2 emissions when the conventional heating system is operated by LPG are 209, 264.8, and 387 kg for Houses I, II, and III, respectively. These parameters are respectively 619.3, 784.7, and 1146.8 kg in Houses I, II, and III, if the conventional heating system is operated by electricity. In addition, the payback period is 22–27 months in houses with electrical heating system and 57–74 months when LPG systems are used. Moreover, the solar system shows its most economic justification in houses with higher number of occupants as well as in houses with electrical water heating systems.

Declaration of competing interest

There is no Declaration of Interest for this manuscript.

CRediT authorship contribution statement

Abdellah Shafieian: Investigation, Methodology, Formal analysis, Visualization, Writing - original draft. **Mehdi Khiadani:**

Supervision, Conceptualization, Writing - review & editing.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.csite.2020.100662.

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