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A solar-driven membrane-based water desalination/purification system

Abdellah Shafieian Dastjerdi
Edith Cowan University

A solar-driven membrane-based water desalination/purification system

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Abdellah SHAFIEIAN DASTJERDI

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Dedication

This PhD thesis is proudly dedicated to my beloved supervisor, teacher, and friend **Dr Ataollah Nosrati** who sadly passed away in May 2019. Ata was a chemical engineer and metallurgist with over 15 years of industrial and academic research experience in chemical engineering, materials science and mineral processing. He was involved in multiple applied and fundamental project activities at Edith Cowan University and the University of South Australia, all with problem solving and process optimization nature. Ata was very passionate about training high quality chemical engineers and research scientists through teaching and supervision of undergraduate and HDR students and also strove for novel and multidisciplinary research projects in collaboration with different industry and academic partners.

I believe that those we love do not go away. They walk beside us every day, unseen, unheard, but always near. Still loved, still missed, and very dear.

Abstract

Lack of fresh water has turned into one of the major challenges of the world in the present century. Desalination of brackish or seawater has been proven to be one of the best solutions to cope with this global challenge. Among all the desalination methods, Membrane Distillation (MD) is well known as a cost effective and profitable technology for treating saline water. However, higher energy consumption compared to other separation techniques has been reported as MD's main drawback. That is why the application of solar energy to provide the thermal energy requirement of MD modules has been the focal point of research in this field in recent years.

Despite many studies and efforts that have been conducted to date, solar driven membrane-based systems have still many undiscussed aspects. Integrating solar energy and membrane technology is not yet a straightforward matter and has many opportunities for technical and economic improvements. Utilizing new solar technologies, their combination with thermal-driven membrane modules, and trying to improve thermal and overall efficiency of this integration can be the bedrock of novel researches. Furthermore, most of the previous studies and research activities have been focused on desalination systems, while the proposed systems have been either inefficient or energy intensive, and other sources for improving water quality such as wastewater is completely under-researched. That is why, this study proposed a novel integrated solar membrane-based desalination and wastewater treatment system taking advantage of technologies such as heat pipes, vacuum tubes, and direct contact membrane distillation (DCMD) modules.

A theoretical study was considered to firstly investigate the performance and feasibility of the proposed system and secondly to obtain the optimum physical and operational characteristics of both solar and desalination systems. The theoretical analysis was performed by using appropriate energy and exergy equations which were solved in Matlab software. Heat and mass transfer equations along with energy and mass balance equations were considered in this study. A new multi-step theoretical approach was proposed and developed to model the DCMD unit, while the thermal resistance network method was applied in the simulation of the solar system including vacuum glasses, heat pipes, and manifold.

Based on the optimum data obtained from the mathematical models, an experimental rig was designed, manufactured, and tested under different climatic and operational conditions. The

system was controlled using a central control unit including a control unit, a National Instrument Data Acquisition (NI-DAQ) system, and a power unit. An application program interface (API) was programmed in the LabVIEW 2014 software to record the data at 10-second intervals. Climatic data including solar radiation, ambient temperature, and wind velocity were collected from the weather station located at Edith Cowan University, Joondalup Campus which is located 23 km north of Perth business district.

The comparison of the theoretical and experimental results revealed the capability of the developed model to accurately predict the performance of the proposed system. In addition, the optimum characteristics of the system, including the optimum solar collector's surface area, feed and permeate streams mass flow rates and temperatures, were determined. The results revealed that the application of this nanofluid as the solar working fluid along with implementing a variable mass flow rate technique significantly improved the overall efficiency of the solar system. Sodium Dodecyl BenzeneSulfonate (SDBS) at 0.1 wt.% was the optimum concentration of SDBS for 0.05 wt.% Al_2O_3/DI water nanofluid exhibiting the highest stability and thermal conductivity enhancement. The results also showed the high dependency of the DCMD module to the physical (e.g., length) and operational (e.g., feed and permeate mass flow rates) parameters, while its performance was independent of salinity. The highest freshwater production rates in hot and cold seasons were observed to be 3.81 and 2.1 L/m^{2}h, respectively. Moreover, the maximum gained output ratios of the system were around 0.79 and 0.58 in hot and cold seasons, respectively.

The results also indicated that the gained output ratio and overall efficiency of the system improved upon application of a cooling unit in the permeate flow loop of the system, indicating the effectiveness of the proposed configuration. In addition, the freshwater production increased up to 37% when the system was equipped with a cooling unit. However, the economic feasibility of implementing the cooling unit needs further investigations. Moreover, the proposed system effectively removed the contaminating metals from wastewater by showing the removal percentage of 96, 89, 96, 100, 100, and 94% for Fe, Mn, Cu, Na, K, and Ca, respectively.

Keywords: Heat pipe solar collector; Direct contact membrane; Desalination; Wastewater treatment

Declaration

I certify that this thesis does not, to the best of my knowledge and belief:

i. Incorporate without acknowledgement any material previously submitted for a degree or diploma in any institution of higher education;

ii. Contain any material previously published or written by another person except where due reference is made in the text; or Contain any defamatory material.

iii. I also grant permission for the Library at Edith Cowan University to make duplicate copies of my thesis as required.

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Data: 10/06/2020

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List of Journal Publications Arising from this Candidature

Published Journal Papers

1- A. Shafieian, M. Khiadani, A. Nosrati, A review of latest developments, progress, and applications of heat pipe solar collectors, Renewable & Sustainable Energy Reviews, 95 (2018) 273-304. https://doi.org/10.1016/j.rser.2018.07.014

2- A. Shafieian, M. Khiadani, A novel solar-driven direct contact membrane-based water desalination system, Energy Conversion and Management, 199 (2019) 112055. https://doi.org/10.1016/j.enconman.2019.112055

3- A. Shafieian, M. Khiadani, A. Nosrati, Strategies to improve the thermal performance of heat pipe solar collectors in solar systems: A review, Energy Conversion and Management, 183 (2019) 307-331. https://doi.org/10.1016/j.enconman.2018.12.115

4- A. Shafieian, M. Khiadani, A. Nosrati, Thermal performance of an evacuated tube heat pipe solar water heating system, Applied Thermal Engineering,149 (2019) 644-7. https://doi.org/10.1016/j.applthermaleng.2018.12.078

5- A. Shafieian, J.J. Osman, M. Khiadani, A. Nosrati, Enhancing heat pipe solar water heating systems performance using a novel variable mass flow rate technique and different solar working fluids, Solar Energy 186 (2019) 191–203. https://doi.org/10.1016/j.solener.2019.05.016

6- A. Shafieian, M. Khiadani, Performance analysis of a thermal-driven tubular direct contact membrane distillation system, Applied Thermal Engineering 159 (2019) 113887. https://doi.org/10.1016/j.applthermaleng.2019.113887

7- A. Shafieian, M. Khiadani, A. Nosrati, Theoretical modelling approaches of heat pipe solar collectors in solar systems: A comprehensive review, Solar Energy, 193 (2019) 227-243. https://doi.org/10.1016/j.solener.2019.09.036

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9- A. Shafieian, MR Azhar, M. Khiadani, Performance improvement of solar membrane-based desalination systems using nanofluid in the feed stream, Sustainable Energy Technologies and Assessments 39 (2020) 100715. https://doi.org/10.1016/j.seta.2020.100715

10. A. Shafieian, M. Khiadani, Integration of heat pipe solar water heating systems with different residential households: An energy, environmental, and economic evaluation, Case Studies in Thermal Engineering 21 (2020) 100662. https://doi.org/10.1016/j.csite.2020.100662

11- A. Shafieian, M. Khiadani, MR Azhar, A novel solar direct contact membrane-based treatment system for multi-metals removal from wastewater, Energy. (In press)

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List of Symbols

Nomenclature

A	area (m^2)
A_c	collector area (m^2)
a	air
ab	absorber
amb	ambient
C	specific heat capacity (J/kg K)
C_f	heat capacity of saline feed stream (kJ/kgK)
C_m	membrane specific mass transfer coefficient (kg/m^2sPa)
C_{wf}	Heat capacity of the solar working fluid (kJ/kgK)
c	collector/condenser
cv	control volume
D	diffusion coefficient
D_h	hydraulic diameter (m)
D_m	molecular diffusivity (m^2/s)
D_{w-a}	water vapour diffusion coefficient
d	diameter (m)/ pore dimension (m)
d_e	Vapour and air collision diameter (m)
dest	destroyed
dist	distilled
E	Energy rate (W)
Ex	exergy rate (kW)
e	evaporator
F	radiation view factor
f	feed
G	solar radiation intensity (W/m^2)
GOR	Gained output ratio
gi	inner glass
go	outer glass
H	Heater
H_v	evaporation enthalpy (J/kg)
h	heat transfer coefficient (convection) (W/m^2.K)/ specific enthalpy (kJ/kg)
h_{fg}	latent heat of evaporation (J/kg)
h_p	heat pipe
i	internal/inner/inlet
i/in	inlet
J	Transmembrane water flux (kg/m^2s)
K_b	Boltzmann constant
K_g	Water vapour thermal conductivity inside the pores (W/m.K)
k_m	Membrane module thermal conductivity (W/m.K)
k	thermal conductivity (W/mK)/ location
k_m	Membrane module thermal conductivity (W/m.K)
L	length (m)/liter
l	liquid
M	Molecular weight (kg/mol)

m	water flow rate (kg/s)
$\dot{m}$	Mass flow rate (kg/s)
$\dot{m}_{DCMD}$	mass flow rate through the membrane (kg/s)
$\dot{m}_f$	mass flow rate of feed stream (kg/s)
$\dot{m}_{wf}$	solar working fluid mass flow rate (kg/s)
N	number
n	number/step/section number/ number of error sources
o	outer/ outlet
out	outlet
P	pressure (Pa)
p	pipe/ permeate/pump
Q	heat transfer rate (W)/ heat flux (W/m^2)
R	thermal resistance (K/W)/ gas constant (J/kg.K)
Re	Reynolds number
r	pore radius (m)
S	salinity
Sh	Sherwood number
s	specific entropy (kJ/kg K)
sc	solar collector
T	temperature (K)/ temperature (°C)
T_0	temperature at dead state (K)
T_{sr}	solar radiation temperature (K)
$T_{wf,i}$	collector inlet temperature (°C)
$T_{wf,o}$	collector outlet temperature (°C)
t	total/thickness (m)/time
u	useful
V	Velocity (m/s)
v	vapor
W	work rate (W)/ transferred molecules mean free path (m)
w	wick/water
Y	specific enthalpy (J/kg)

Greek Letters

φ	physical exergy flow (kJ/kg)
ε_s,	systematic errors
ε_r	random errors
η	efficiency
ε	emissivity/effectiveness/porosity
τ	transmittance/ membrane tortuosity
ρ	density (kg/m^3)
σ	Stefan Boltzman constant (5.670367×10^{-8} kg/s^{3}K^4)
µ	dynamic viscosity (Pa.s)
α	absorptivity
θ	angle
δ	thickness (m)
$\emptyset$	average value of measurements

Chapter 1

General introduction

1.1. Background

According to the reports published by the World Health Organization, 20% of the world's population do not have access to enough potable water. Considering population increase and growing fresh water demand, it is also predicted that the situation will become worse. By 2025, more than 60% of the people will struggle with water shortage and its drawbacks [1]. Although a significant portion of earth is covered by water, majority of it is non-potable (seawater), unhealthy (e.g., arsenic contaminated) or unreachable (poles) [2]. This problem can be solved by removing salt from saline water and extracting potable water from contaminated water resources as well as different waste waters.

To accomplish abovementioned solution, different methods have been proposed (e.g., MED, MSF, RO, and MD). However, they have different practical and economic complications: (i) Designed systems are energy intensive by requiring great amounts of heat (i.e. thermal processes) and high pressures (e.g. reverse osmosis); (ii) Higher energy consumption means higher production of pollutants, toxins, emissions, and greenhouse gas emissions resulting in more environmental impacts; (iii) These systems are not economically feasible [3]. Because of the mentioned drawbacks, the economic feasibility of these systems has gone under question which shows the importance of exploring alternative, cost-effective, and more environment friendly solutions.

In recent years, significant attention has been given to the application of solar energy in desalination systems. The abovementioned challenges can be overcome by using solar energy technologies to provide the required thermal energy for driving these systems [4]. Also, the thermal-driven membranes are a growing and promising new-comer that can be integrated with solar energy because of having the ability to be driven by low-grade energy resources [2]. However, in spite of all the valuable efforts and studies that have been done to integrate these two technologies, there are still significant technological, environmental and economic challenges faced. For instance, a group of the proposed solar systems are still high energy demand [5]. Low thermal efficiency and low productivity are also evident in some of the proposed solar desalination systems [2]. The situation becomes even worse if the

environmental conditions become non-ideal. Also, in all of the proposed systems, water is circulated inside the collector or is in direct contact with the heat exchangers which causes fouling and reduction in system's long term thermal efficiency. Finally, the performance of the proposed systems depends highly on the climatic conditions, hence, their efficiency decreases in non-ideal weathers and cannot be used throughout the year [6].

Overall, to propose an effective solar membrane-based system, many operational and technical aspects should be considered. Furthermore, new technologies and efficient components should be implemented and their combination should be investigated in detail.

1.2. Solar collectors

Fundamentally, there are three types of solar collectors: (i) Flat plate solar collectors; (ii) Evacuated tube solar collectors, and (iii) Heat pipe solar collectors. This section will briefly introduce these three types along with their advantages and disadvantages.

1.2.1. Flat plate collectors

Flat plate collectors are widely used and have been designed in a wide range of forms and materials. They are durable, cheap and manufactured easily; however, they are technically and economically feasible only in sunny warm climates and in summer [7]. They are vulnerable to cold climatic conditions, cloudy, and windy days [6]. Another considerable drawback of flat plate collectors is that they are not suitable for applications with high operating temperature. Increasing operating temperature, increases thermal losses and hence significantly decreases the efficiency of the collector [8]. Also, this type of collectors lacks sun tracking and their efficiency varies with position of sun. They can be applied by external sun trackers; however, this increases their operational and maintenance cost [9].

1.2.2. Evacuated tube collectors

An evacuated tube collector consists of a number of evacuated glass pipes that are placed in parallel arrangement. Each evacuated glass pipe contains one inner and one outer tube with least sunrays reflection properties (Figure 1.1). The inner tube acts as the absorbing surface; while the outer tube acts as the transparent glass. To create a thermal insulation, air between the two tubes is extracted and a vacuum is present near the absorber which significantly decreases heat loss [10].

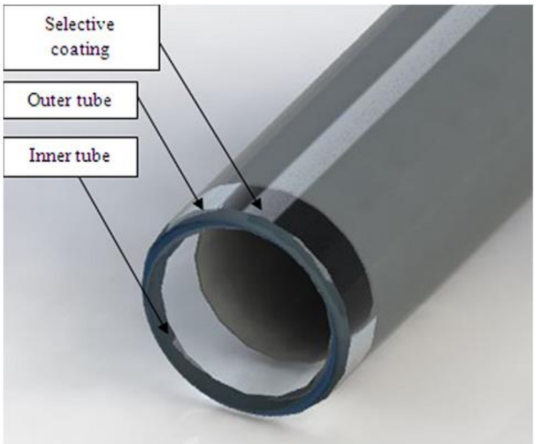

Figure 1.1. Evacuated glass pipe

Evacuated tube collectors have cylindrical absorbing surfaces and because of that, they track sun passively during the day. The maintenance costs of evacuated tube collectors are low and unfavourable climatic conditions (e.g., low radiation, cold temperature and high wind velocity) affect their performance less than flat plate collectors [11].

1.2.3. Heat pipe solar collectors

Heat pipe is a sealed tube with a fixed volume of fluid inside it that acts as the working fluid [12]. Heat pipes include three main sections: evaporator, adiabatic section, and condenser. Figure 1.2 shows the cross section of a typical heat pipe [13]. Heat passes through the wall of the evaporator section and provides the required thermal energy for evaporation. Produced vapour then starts moving through the adiabatic section towards the condenser section to lose its thermal energy and return to liquid form. Liquid working fluid then returns to the evaporator section by capillary wick structure and the cycle goes on [14].

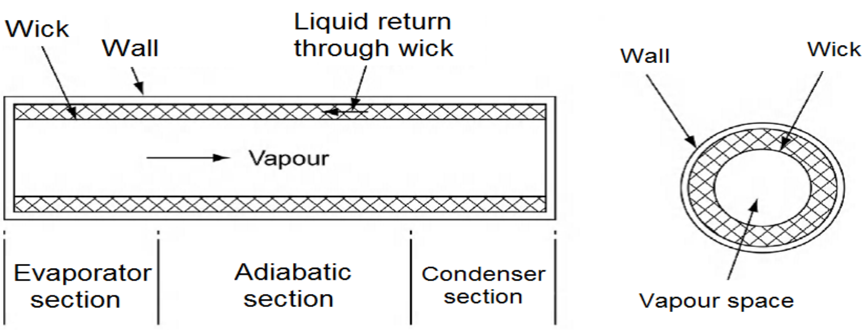

Figure 1.2. The cross section of a typical heat pipe

Heat transfer coefficients of boiling and condensation processes are significantly higher than other typical heat transfer processes [15]. Taking into account that the functioning principle of a heat pipe is repetitive boiling and condensation, heat pipes are extremely effective heat transfer devices [16]. Furthermore, heat pipes have no pumping or moving parts and can operate in wide range of temperatures, depending on the working fluid type [17].

Heat pipe solar collectors are the combination of evacuated tubes collectors and heat pipes (Figure 1.3). Having the advantages of both, heat pipe collectors can absorb and transfer solar energy more efficiently [18]. The typical function of heat pipe collectors consists the following steps: (1) Solar radiation passes through the glass and reaches the absorber surface and turns into heat; (2) Produced heat reaches the evaporator section of the heat pipes and vaporises the working fluid; (3) The generated vapour moves toward the condenser section and transfers its heat to the solar loop working fluid through the manifold, and at the same time returns to liquid form; (4) The liquid then returns to the evaporator section to repeat a new cycle. The readers are referred to Appendix section for further information regarding the concepts and applications (Appendix A), thermal efficiency improvement strategies (Appendix B), and theoretical modeling approaches (Appendix C) of heat pipe solar collectors.

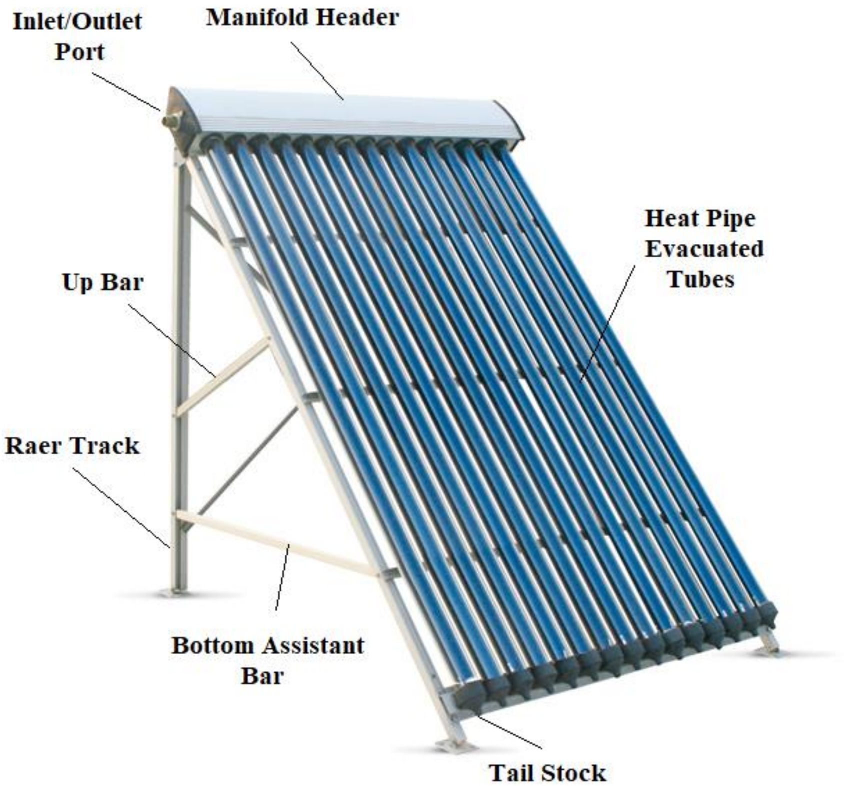

Figure 1.3. Heat pipe solar collector’s components

1.3. Thermal-driven membranes

Membrane modules involve two channels for hot and cold (product) streams separated by a micro porous membrane [19]. Vapour molecules transfer from the hot channel with higher vapour pressure to the cold one with lower vapour pressure. The vapour pressure difference, created by the temperature difference, acts as the main driving force for mass transfer through the pores from the hot surface of the membrane towards the cold side [2]. In direct contact membrane desalination systems, liquids have direct contact with both the hot and the cold surfaces of the membrane module. Hot liquid flows inside the membrane's feed channel to provide the required heat for evaporation at the feed side of the membrane. Once the evaporated water in feed channel passes through the membrane, it condenses to liquid with the condensation heat being absorbed by the cold liquid at the permeate side of the membrane (product channel). This evaporation and condensation is the main reason for the existence of the temperature gradient in the liquid films near the membrane which leads to creation of thermal layers. Consequently, the temperatures of the membrane sides differ from those of the mean flow streams inside the cold and hot channels. Figure 1.4 shows the heat and the mass transfer process of a direct contact membrane desalination module.

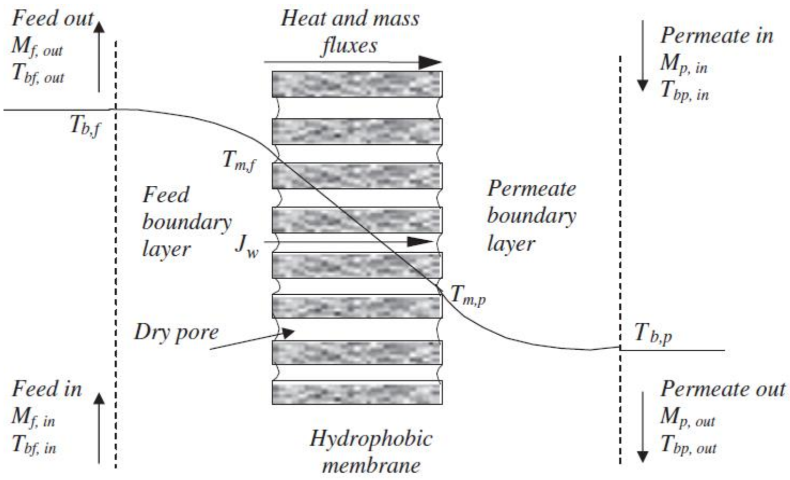

Figure 1.4. Heat and the mass transfer process of a DCMD module

Membrane-based desalination process has several significant advantages including low operating pressures and temperatures, low heat loss, less pre-treatment requirements, higher efficiently to remove ionic components from water, and ability to be coupled with solar and geothermal energy resources [5]. Also, the mass flux through the membranes is not affected by salt concentration when it is lower than 70 g/L [20].

1.4. Grey water

The generated domestic wastewater from showers, baths, washing machines, and kitchens is called greywater. Improving the quality of grey water provides the opportunity of reusing it for garden watering, lawn irrigation, toilet flushing, and laundry. According to the statistics published by the Government of Western Australia, a 3-occupant house consumes 825 L of water in one day that results in production of 120 L of greywater per person per day [21]. Taking into account the 2 million population of Perth, approximately 240 million litres of greywater is produced in Perth just in one day. Treating and reusing this significant amount of grey water instead of using potable water not only decreases the demand for the latter, but also decreases the volume of discharged wastewater to the environment.

1.5. Literature review

The first publication in the field of solar driven membrane desalination systems returns to 1991 in Australia where Hogan et al. [22] connected a 3 m^2 flat plate solar collector to a hollow fibre membrane module. They developed a mathematical model to evaluate the performance of the proposed system and analysed the effects of the design parameters, such as heat exchanger effective area, on fresh water productivity. They modelled the system based on mass and energy equilibrium by using Fortran and Trnsys. The theoretical results showed the optimum membrane area of 1.8 m^2 to be connected to the 3 m^2 flat plate solar collector. This combination resulted in production of 17 Kg/day fresh water per square meter of the solar collector.

In two similar studies, Banat et al. [23, 24] compared the fresh water production cost of a flat-plate solar membrane-based distillation system in small and large scale applications. While the temperature of the feed water was kept between 60 °C to 80 °C, their results estimated production costs of 15 USD and 18 USD per 1 m^3 fresh water for small and large scale applications, respectively. They reported the fresh water production rate of 2.5 L/h per square meter of the membrane surface area which showed the necessity of further improvements in the system. With the aim of solving water shortage challenges of Chines people in remote areas, Wang et al. [25] proposed a hollow-fibre vacuum membrane distillation system. The main energy source of the system was an 8m^2 flat plate solar collector and underground water was used as brackish water. The experimental data indicated that the proposed system was able to produce 32.19 L/h.m^2 of the membrane. They also developed a mathematical model and investigated the effect of some important parameters, such as feed flow rate, on the membrane

flux. In a similar study, Raluy et al. [26] installed the same system in Spain and continuously recorded its performance for five years. The minimum and maximum recorded fresh water production per day was 5 and 120 L, respectively, suggesting an overall satisfactory performance of the system. Similar theoretical and experimental investigations to analyse the solar driven membrane desalination systems have also been carried out during the last decade [27-33].

To date, several researchers have tried to propose innovative designs for combination of solar energy and membranes. However, none of them were able to achieve satisfactory fresh water production which is the most important parameter in development of such systems. Banat et al. [34] investigated the technical feasibility of connecting membranes to solar stills. In their proposed system, the solar still was responsible for both saline water heating (to feed the membrane) and potable water production. The experiments were divided into two categories: (i) indoor experiments, and (ii) outdoor experiments. They found from the experiments that the effect of the operational parameters such as feed and the permeate temperature and flow rate, climatic conditions, and salt concentration was significantly greater on the membrane module compared with the solar still. After analysing the results, the reported value of the water production rate did not exceed 3 L/m^2h that was very low.

In a novel design, Zwijnenberg et al. [35] experimentally evaluated the efficiency of a solar membrane-based system with pervaporation process by using a tubular polyetheramide membranes with 40 μm thickness in a closed transparent area to act as a greenhouse that reduced heat losses. In the proposed system, solar radiation passed through the transparent foils, stroke the membrane tubes and consequently warmed the water inside. The results showed that the mass flux through the membrane did not change until the concentration of the saline water reached 100 g/L. Also, the fresh water flux of the system was reported to be 5 L/m^2d. Chen and Ho [36] proposed a new configuration by attaching the absorber of the solar collector to the membrane module and investigated it both theoretically and experimentally. The saline water, which flowed underneath the absorber plate, reached up to 50 °C in their system. Also, a good agreement was observed between the data obtained from the experiments and the two-dimensional mathematical energy model. According to the obtained results, the fresh water production rate of the proposed system had the unsatisfactory value of 4.1 kg/m^2 h.

Another configuration which has attracted several researchers in recent years is the combination of membranes and solar ponds. In a theoretical research, Suarez et al. [37] investigated the application of the direct contact membranes at terminal lakes. They developed a computer program that was the combination of the salt-gradient solar ponds thermal modelling with the membrane heat and mass transfer modelling. Although using free energy of sun and low maintenance cost were the main advantages of the proposed system, its performance was not satisfactory mainly due to the low production rate (1.6 L/d per m^2 of solar pond). In another study comparing the performance of the vacuum membranes combined with solar ponds and solar collectors, Mericq et al. [38] developed a theoretical model for four different configurations: (i) solar collector's absorber placed on the membrane surface; (ii) the membrane connected to the solar collector; (iii) the membrane submerged in the solar pond; (v) the membrane connected to the solar pond. The results revealed that the membrane modules connected to the solar collectors were the best configuration producing 140 L/m^2h of fresh water. A recent study in solar pond integration also proposed a new configuration to reach a zero liquid discharge system [5]. They used one polyetrafluoroethylene (PTFE) membrane module with 0.1 m^2 membrane area and tested its performance under water salinity of 16 g/L. Theoretical and experimental results showed that the fresh water production capacity of the proposed system was 52 L/m^2 of fresh water.

Another type of solar collectors that is widely used in solar systems is evacuated tube collector which are made of parallel evacuated glass pipes and have significant advantages compared to the flat plate collectors [39]. Elzahaby et al. [40] evaluated the combination of the evacuated tube solar collectors with the direct contact membrane modules both theoretically and experimentally by using a 100 L solar storage tank and a 1 m^2 tubular micro type membrane module. They studied the effect of some operational parameters such as hot and cold channel temperature and flow rate, water salinity, along with some geometrical parameters (e.g. membrane dimensions) on the productivity of the proposed system. In their experiments, the feed water temperature was kept on 70 ˚C, the hot water flow rate was varied from 15 to 20 L/min, and at the same time, the salinity was systematically increased from 0 to 40 g/L. They finally reported that the maximum achieved fresh water was 40.587 L/m^2 per day. In a similar experimental study, Kabeel et al. [20] installed a pilot system and studied the solar membrane desalination system with vacuum tubes. They used an evacuated tube solar collector with a 250 L storage tank and a direct contact membrane module with 1 m^2 membrane area made of Poly Propylene (PP) with 0.2 µm pore size. The experiments were performed at 10 and 15 L/min

water flow rates and the results showed that the proposed system was able to produce 33.55 L/m^2d fresh water. The main disadvantage of this type of desalination systems is that the saline water flows inside the solar collector, hence, issues such as scale formation and tubes breaking due to corrosion can significantly influence the performance of the system.

Burrieza et al. [41] presented the results of a comparison between two configurations of the air gap membrane modules. The membranes were coupled with a solar system and tested for 1-35 g/L saline water for two years. The first configuration was a simple module, while the second one was divided into three sections connected in series. The effects of operational parameters on the thermal efficiency of the proposed system were discussed in details in their report. They found that increasing the feed water temperature had a positive effect on productivity of both configurations. Also, increasing the feed mass flow rate increased the mass flux through the membrane in the first configuration but decreased it in the second one. Kim et al. [42] also proposed a novel large scale and continuous operating solar-assisted membrane distillation system to store extra solar energy during peak hours and to reuse it when the system needed. They developed a theoretical model and investigated the overall performance of the system along with the effect of some important parameters such as water salinity and inlet flow rate. It was found that their proposed system was still energy intensive with no economic feasibility suggesting more design modifications and efforts are needed for achieving better performance.

Arsenic contamination of water resources has endangered many people and is now considered as a research priority within the World Health Organization [43]. Some researchers have tried to make arsenic removal systems more feasible by combining them with solar systems [43-45]. For instance, Manna et al. [43] proposed and experimentally analysed a solar membrane-based system to remove arsenic from the groundwater resources of India. They used a flat sheet hydrophobic membrane module made of polyvinylidenefruoride (PVDF) with 0.0162 m^2 area and 0.13 µm pore size. The membrane was placed in a solar loop and was connected to an evacuated tube collector with a 100 L storage tank. The proposed system was tested under various operational conditions and arsenic concentrations. Their results indicated that the system was able to produce 74 L/m^2h fresh water when the feed water temperature was around 40 ˚C. Simple design and membrane availability were mentioned as the most significant advantages of the system. In a similar study and with the same system, Pal and Manna [45] compared three hydrophobic membranes, one made of pure PP and the other two made of composites with PTFE active layer. The experiments indicated that with 40-48 L/m^2h arsenic-free water production, the PTFE-based membranes had a better performance compared with

the PP membrane. Pal and Mana [44] also studied a solar-driven flash-vaporization membrane distillation system for arsenic removal from contaminated resources. They investigated the effect of different parameters such as hot channel temperature and flow rate, operating hours, mass flux through the membrane, and arsenic rejection percentage. Their experimental results indicated that the proposed system was able to achieve fresh water production rate of 52.94 L/m^2 h with 99% arsenic rejection at feed water temperature of 70 ˚C.

To provide a reliable reference for choosing desalination technology, some researchers have published helpful review papers. Sharon and Reddy [46] published a comprehensive review paper on various membrane types integrated with solar systems. The performance of the previous proposed systems, their problems and restrictions, proposed novel methods, and economic issues have also been covered in their paper. Qtaishat and Banat [2] also published a comprehensive review paper about solar powered membrane desalination systems. They discussed heat and mass process of the membrane modules completely and stated their advantages and disadvantages. They reviewed all types of previously studied solar combinations, including solar photovoltaic, solar thermal, and solar ponds, as well as solar collectors, including flat plate collectors, parabolic through collectors, and solar stills. At the end of the paper, they presented the availability and cost analysis and concluding that the main requirement and the main cost of these systems are thermal energy and initial investment.

1.6. Research gaps

Despite many studies and efforts that have been conducted to date, solar driven membrane-based systems have still many undiscussed aspects. Integrating solar energy and membrane technology is not yet a straightforward matter and has many opportunities for technical and economic improvements. For instance, technical and economic feasibility of these integrated systems can be improved by using updated technologies, introducing new combinations, and improving efficiency of the components. Utilizing new solar technologies such as heat pipe solar collectors, their combination with thermal-driven membrane modules, and trying to improve thermal and overall efficiency of this integration can be the bedrock of novel researches.

Moreover, almost all the conventional solar systems have been operated with constant solar working fluid mass flow rates. However, during a significant time of the day, the solar radiation reaches its high values which provides a great potential for harvesting the thermal energy. Therefore, by taking the dynamic behavior of solar radiation into account, regulating the solar working fluid mass flow rate with the changes in solar radiation throughout the day is likely to play an important role in achieving the optimum performance of these systems.

In addition, it has been proven that nanofluids are a promising technology which have the potential of replacing the conventional fluids in heat pipe solar systems. However, these studies have not considered two major issues which are concentration optimization and reliability of nanofluids in terms of characteristics consistency. Instead of investigating the stability of the applied nanofluids and consistency of their thermo-physical characteristics, they have relied either on random concentrations of nanoparticles or on the data provided by former studies.

Regarding the theoretical modelling of HPSCs, the literature review reveals that even though the data-based methods have been proven to be promising and more accurate, all the efforts in the field of HPSCs have been focused on conventional methods. In other words, a study considering various data-based techniques to simulate the performance of HPSCs has not been reported in the literature. In addition, while accurate equations relating the output parameters of a solar collector to the operational and climatic conditions in a solar water heating system are well-studied and established for FPSCs and ETSCs, such equations are completely under-researched for HPSCs.

Regarding the membrane-based desalination system, the literature review reveals that most of the previous studies have not considered the changing nature of the operational parameters (e.g., salinity, temperature, and mass flow rate) along the membrane’s length. Ignoring the changing trend of these parameters along the membrane’s length may lead to little errors at the bench-scale research experiments, however, it is likely to result in noticeable errors in long membranes and large-scale applications. On the other hand, another group of proposed models are too complex imposing excessive economic costs and increase computational processing times. In addition, most of the previous investigations have mainly focused on flat-sheet membrane modules, have not taken the experimental and theoretical observations beyond common trends, and also have not considered the effects of concentration and temperature polarizations.

Furthermore, most of the previous studies and research activities have been focused on desalination systems while the proposed systems have been either inefficient or energy intensive. Therefore, the fresh water production efficiency of the solar membrane-based desalination systems should be increased significantly to achieve economic feasibility. At the same time, the significant amount of domestic grey water that is produced every day is another great source for producing fresh water [21]. While it has a great research potential, solar membrane-based grey water treatment systems still remain inattentive.

1.7. Research questions

Q1. How efficient can a heat pipe evacuated tube solar water heater operate under climatic conditions of Perth in Western Australia?

Q1.1. What are the effects of replacing solar working fluid with an optimised nanofluid on the performance of the system?

Q1.2. Does regulating the solar working fluid mass flow rate with solar radiation intensity improve the performance of the solar system?

Q1.3. How accurate are other modelling techniques than conventional methods in predicting the performance of heat pipe solar systems?

Q2. How efficient will be the integration of heat pipe evacuated tube solar collectors with direct contact membrane modules for improving water quality?

Q2.1. How is the performance of the proposed integrated system to improve the quality of residential gray water?

Q2.2. Can this integrated system be effectively used for desalination?

Q3. What are the key parameters to improve the thermal and the overall efficiency of the proposed solar membrane-based system?

Q3.1. Can increasing the temperature difference between the feed and the permeate channels improve the overall performance of the system?

Q3.2. Can inclusion of a cooling unit improve the overall efficiency of the system?

1.8. Research methodologies

The above research questions are addressed in this thesis by applying both experimental and theoretical methodologies. Theoretical study of the HPSC, DCMD unit, and the integrated system include analysis of solar collector, heat pipe, manifold, and DCMD module. The analysis is performed by using appropriate energy and exergy equations solved in Matlab software considering heat and mass transfer equations along with energy and mass balance equations.

The developed mathematical model was used to obtain the optimum characteristics of both solar and desalination systems. Based on the obtained data, an experimental rig was designed, manufactured, and tested under different climatic and operational conditions (Fig. 1.5). The system was controlled using a central control unit including a control unit, a National Instrument Data Acquisition (NI-DAQ) system, and a power unit. An application program interface (API) was programmed in the LabVIEW 2014 software to record the data at 10-second intervals. Climatic data including solar radiation, ambient temperature, and wind velocity were collected from the weather station located at Edith Cowan University, Joondalup Campus which is located 23 km north of Perth business district.

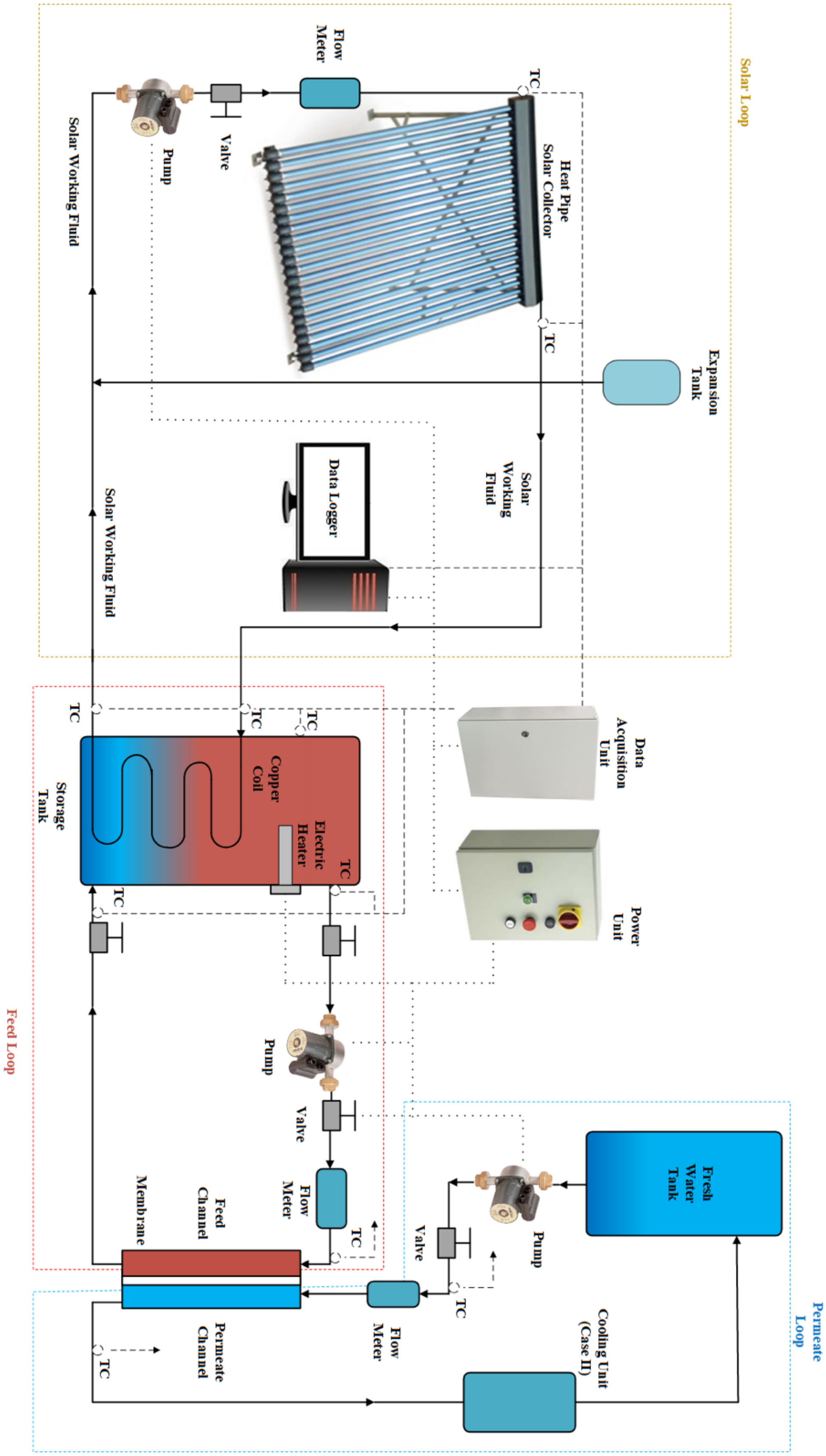

Figure 1. 5. Schematic of the heat pipe solar membrane-based water purification system

1.9. Thesis structure

This thesis is written based on “Thesis with publication″ format[1]; and is organised in 7 chapters as follows:

Chapter 1 presents the general overview of the project topic, literature review, and research gaps in the field of solar membrane-based desalination. This is followed by project motivations, objectives of the thesis and methodology used in this research.

Chapter 2 provides information about the thermal performance of an evacuated tube heat pipe solar water heating system in meeting the hot water demand of Perth residents in cold seasons.

Chapter 3 studies the implementation a novel variable mass flow rate technique which regulates the solar working fluid mass flow rate of the system with the solar radiation intensity. In addition, the effects of replacing the solar working fluid with an optimised nanofluid on the performance of the system are discussed.

Chapter 4 compares the modelling performance of various data-based and energy balance-based methods, based on different accuracy criteria, in theoretical analysis of HPSCs. In addition, the optimum equations relating the outlet temperature of HPSCs to the operational conditions of the solar water heating systems as well as the climatic conditions are discussed.

Chapter 5 discusses the performance of a thermal-driven tubular direct contact membrane distillation (DCMD) system theoretically and experimentally using a novel multi-step numerical model.

Chapter 6 presents a novel integrated solar membrane-based desalination system including vacuum glass tubes to increase absorbed solar energy and to decrease heat loss, heat pipes to transfer the absorbed energy efficiently, and a tubular direct contact membrane distillation module to use the absorbed energy more effectively. In addition, the effect of adding a cooling unit to the permeate loop of the desalination unit for improving the freshwater production rate and overall efficiency of the proposed system is discussed in this chapter.

[1] “Thesis with Publication” is an acceptable format of thesis for postgraduate research at ECU policy. The current thesis has been written based on the guideline provided at http://www.ecu.edu.au/GPPS/policies_db/policies_view.php?rec_id=0000000434. In this format, the submitted thesis can consist of publications that have already been published, are in the process of being published, or a combination of these.

Chapter 7 provides information about an integrated solar wastewater treatment system by taking advantage of technologies such as heat pipes, vacuum glass tubes, and tubular direct contact membrane distillation modules. The proposed system aims to overcome the drawbacks of previous wastewater treatment systems especially high energy demand.

Chapter 8 provides a general discussion of the results presented in each chapter and addresses the research questions of the project.

Chapter 9 integrates the findings of all chapters and also outlines directions for future research.

1.10. Chapter references

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Chapter 2

Thermal performance of a heat pipe solar water heating system in cold season

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Abstract

This study evaluates the performance of a heat pipe solar water heating system to meet a real residential hot water consumption pattern theoretically and experimentally under non-ideal climatic conditions during a cold day in Perth, Western Australia. A mathematical model was developed and used to calculate the optimum number of glass tubes of the heat pipe solar collector. Based on the obtained data, an experimental rig with 25 glass tubes was designed, built, and tested as the temperature changes after 25 tubes reached the insignificant value of 0.6%. The results showed that hot water extraction had significant impact on the thermal performance of solar water heating system by increasing the amount of the absorbed energy and overall efficiency and decreasing exergy destruction. This indicates the importance of considering hot water consumption pattern in design and analysis of these systems. Auxiliary heating element was a necessary component of the system and played an important role mainly at the beginning of the operation in early morning (operation time of 19 minutes) and partly during the cloudy and overcast periods (operation time of 8 minutes). Two empirical equations relating the thermal and exergetic efficiencies of the heat pipe solar collector to the operational and environmental parameters were proposed. Comparison of the theoretical and experimental outlet temperature of the collector showed very good agreement with the maximum absolute and standard errors being 5.6% and 1.77%, respectively.

Keywords: Heat pipe collector, Solar water heating, Consumption pattern, Thermal efficiency, Exergy efficiency.

Chapter 2

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Chapter 3

Enhancing heat pipe solar water heating systems performance using a novel variable mass flow rate technique and different solar working fluids

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Abstract

This paper aims to improve the overall efficiency of heat pipe solar water heating (HPSWH) systems by implementing a novel variable mass flow rate technique which regulates the solar working fluid mass flow rate of the system with the solar radiation intensity. To analyze the system under real operational conditions, the residential hot water consumption pattern of Perth residents in Western Australia was used in the experiments. In addition, a nanofluid (Al_2O_3/DI) was fabricated and its performance as the solar working fluid was investigated to find the optimum concentration and to confirm its stability and thermo-physical properties consistency. The HPSWH system was operated during three days having similar climatic conditions using distilled water at a constant mass flow rate (Case I), the optimized nanofluid at a constant mass flow rate (Case II), and the optimized nanofluid at a variable mass flow rate (Case III). The results revealed that 0.1 wt.% Sodium Dodecyl BenzeneSulfonate (SDBS) was the optimum concentration of SDBS for 0.05 wt.% Al_2O_3/DI water nanofluid at which it exhibited the highest thermal conductivity enhancement and stability. Moreover, the transferred energy to the solar working fluid in Cases II and III were respectively 8.9% and 22.7% higher than Case I. The system had respectively 12.46% and 19.34% higher thermal efficiencies in Cases II and III compared with Case I. The exergy efficiency improvement of Cases II and III were respectively 1.58% and 2.66% compared with Case I. Overall, the results proved the significant effectiveness of the variable mass flow rate technique to improve the thermal performance of HPSWH systems.

Keywords: Solar collector; Efficiency; Heat pipe; Water heating; Nanofluid

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Chapter 4

Comparative and performative investigation of various data-based and conventional theoretical methods for modelling heat pipe solar collectors

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Abstract

Solar collector, as the key component of any solar system, has always been the focal point of research in the field of solar energy. Based on the literature, data-based methods, which have been proven to be promising in accurate modelling of solar collectors, have not been used for modelling heat pipe solar collectors (HPSCs). At the same time, accurate equations relating the thermal efficiency of solar collectors to the operational and climatic conditions have not been obtained for HPSCs. Therefore, in this study, various data-based and energy balance-based modelling methods were proposed, and based on different accuracy criteria, their precisions were compared in predicting the performance of HPSCs. First, an experimental rig was manufactured and the operational data of the system was recorded throughout a year. The recorded experimental data was used to train and validate various modelling approaches. Then, the accuracies of the proposed models were analysed and assessed. The evaluated models included Artificial Neural Network (ANN), Thermal Resistance Network (TRN), Artificial Neuro Fuzzy Inference System (ANFIS), and Fuzzy methods. Among different modelling approaches, ANN had the best performance which was followed by the ANFIS and TRN methods. The Fuzzy method was not recommended due to its poor accuracy. In addition, the optimum equations relating the outlet temperature of HPSCs to the operational conditions of the solar water heating systems as well as the climatic conditions were obtained and verified.

Keywords: Solar water heating; Data-based modelling; Heat pipe solar collector; Energy balance modelling

Chapter 4

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Chapter 5

Performance of a thermal-driven direct contact membrane distillation system

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Abstract

This paper examines the performance of a thermal-driven tubular direct contact membrane distillation (DCMD) system theoretically and experimentally. A multi-step mathematical model was developed to predict the freshwater productivity of the tubular DCMD module applicable for both small and large-scale applications by considering the changes in the operational variables along the membrane's length. The proposed model was verified by building an experimental rig which was tested under different operational conditions. The results showed that keeping the mass flow rates in the hot and cold channels either near the end or beyond the transition range of the flows results in higher water production. In addition, heating up the feed stream is more efficient for enhancing the water productivity than using the same amount of energy to cool the permeate stream down. Finally, the effects of operational and physical factors on the freshwater productivity of were identified and discussed.

Keywords: Desalination; Membrane; Fresh water productivity; Heat and mass transfer

Chapter 5

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Chapter 6

A novel solar-driven direct contact membrane-based water desalination system

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Abstract

This study proposes a novel integrated solar membrane-based desalination system. The system includes vacuum glass tubes to increase absorbed solar energy and to decrease heat loss, heat pipes to transfer the absorbed energy efficiently, and a tubular direct contact membrane distillation module to use the absorbed energy more effectively. To improve the freshwater production rate and overall efficiency of the proposed system, a cooling unit was also added to the permeate loop of the desalination unit. The performance of the system was experimentally investigated without (Case I) and with (Case II) the cooling unit in summer and without the cooling unit in winter (Case III) under climatic conditions of Perth, Western Australia. The experimental results indicated that except a few minutes in the morning, the heat pipe solar system was able to provide all the required thermal energy for the desalination system. The maximum thermal efficiency of the solar system in summer reached ~78% and its exergy efficiency fluctuated between 4-5% for a noticeable amount of time from 10:30 AM to 3 PM. Moreover, the maximum freshwater production rates were 2.78, 3.81, and 2.1 L/m^2h in Cases I, II, and III, respectively. The overall efficiency of the system improved from 46.6% in Case I to 61.8% in Case II showing the technical effectiveness of implementing the cooling unit in the permeate flow loop of the system. In addition, the daily averaged specific energy consumption in Cases I, II, and III were 407, 377, and 450 kWh/m^3, respectively.

Keywords: Solar desalination; Direct contact membrane distillation; Freshwater production; Heat pipe

Chapter 6

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Chapter 7

A novel solar membrane-based wastewater treatment system for high-quality water production[1]

Abstract

This study proposes a novel solar wastewater treatment system comprising efficient solar energy absorption and contaminant separation processes. The proposed system aims to overcome the drawbacks of previous membrane-based systems especially high energy demand and lack of a complex wastewater consideration. Synthetic wastewater was prepared and the solar system was experimentally analysed under climatic conditions of Perth, Western Australia in summer and winter. The findings revealed that the solar thermal efficiency of the system fluctuated mainly around 63% in summer and 52% in winter. The system reached its maximum exergy efficiency in the afternoon with 5.54% and 4.82% for summer and winter, respectively. Moreover, the highest rate of treated water in summer and winter were 4.21 and 2.85 L/m^{2}h, respectively. The results also indicated that the removal percentages of Fe, Mn, Cu, Na, K, and Ca were 96, 89, 96, 100, 100, and 94%, respectively. In addition, almost 100 % of organics and nutrients were removed. The highest recorded gained output ratio and overall efficiency were 0.71 and 49.6% in summer, while these parameters were 0.58 and 46.6% in winter. Overall, the proposed solar-driven membrane-based system is a feasible and efficient option in the separation of contaminants from wastewater.

Keywords: Solar thermal system; Wastewater treatment; Energy efficiency; Contaminants removal efficiency

[1] This chapter has been prepared based on an under-review manuscript which has been submitted to Energy.

Chapter 7

The fulltext of Chapter 7 is unavailable in this version of the thesis.

Chapter 8

General discussion

The main aim of this chapter is to integrate the research outcomes to help build a better overall picture in this area. In this way, this chapter will not only establish connections among the chapters, but will also address the research questions presented in Chapter 1.

8.1. Heat pipe solar water heating system

The first research question of this study was mainly about the performance of a heat pipe solar water heating system under climatic conditions of Perth, Australia (Fig. 2.4). The developed mathematical model (Fig. 2.2) showed that the optimum number of glass tubes in a heat pipe solar collector is 25 for climatic conditions of Perth, Australia (Fig. 2.6). The experimental results showed the importance of considering hot water consumption pattern while analysing the performance of solar heating systems (Fig. 2.7). In addition, the outlet temperature of the solar collector relied heavily on the solar radiation while the inlet temperature depended mainly on the temperature of the water in the storage tank and hot water consumption pattern (Fig. 2.7). The results also suggested that to reach the optimum performance of heat pipe solar water heaters, the amount of hot water extraction should be aligned with the variations of the solar radiation. Hence, a prudent selection of water extraction pattern provides the opportunity to attain higher proportions of available solar energy reflecting greater thermal efficiency (Fig. 2.9). Based on the obtained optimum correlation, which describes the efficiency of the heat pipe solar collector as a function of operational and environmental parameters, it was concluded that decreasing the temperature difference between the inlet working fluid and the environment has a positive effect on the system's thermal efficiency. In addition, higher solar radiation leads to higher efficiency if the inlet temperature of the collector is lowered (Fig. 2.10a). Increasing the number of heat pipes, increased the temperature of the solar working fluid but with the cost of efficiency reduction (Fig. 2.10b). The results of the exergy analysis revealed that any strategy which can increase the collector inlet and outlet temperature difference has a positive effect on the exergy efficiency (Fig. 2.11a). It was also concluded that regulating the solar working fluid mass flow rate with solar radiation improves the performance of the system significantly (Fig. 2.13).

The first part of research question 1 was regarding the effects of replacing solar working fluid with an optimised nanofluid on the performance of the solar system. Similarly, the second part of this research question focused on regulating the solar working fluid mass flow rate with the solar radiation and studied its effect on the performance improvement of the solar system. In order to evaluate the effectiveness of the proposed techniques, three different cases having different solar working fluids and mass flow rates were considered (Table 3.2 and Fig. 3.5) and experiments were conducted throughout three different days with similar climatic conditions (Fig. 3.6). An Al_2O_3/DI water nanofluid was fabricated and its performance was investigated to find the optimum concentration and to confirm its stability and thermo-physical properties consistency. Sodium Dodecyl BenzeneSulfonate (SDBS) at 0.1 wt.% was the optimum concentration of SDBS for 0.05 wt.% Al_2O_3/DI water nanofluid exhibiting the highest stability and thermal conductivity enhancement (Fig. 3.7 and 3.8). The results also showed that the highest thermal efficiency improvement of the system (i.e., 19.34%) occurred when nanofluid with variable mass flow rate was used, followed by the use of distilled water with variable mass flow rate (i.e. 12.46%) (Fig. 3.10). Overall, the application of both techniques (i.e., nanofluid and variable mass flow rate) significantly improved the overall performance of the solar system (Fig. 3.9, 3.10, and 3.11).

The last part of research question 1 focused on comparing the performance of various data-based and energy balance-based methods in theoretical analysis of HPSCs based on different accuracy criteria. The experimental data collected throughout a year was used to train, validate, and test different methods. The results of various accuracy criteria, proved that the best method to predict the performance of HPSCs was ANN. The results also showed that ANN method was followed by ANFIS and TRN methods in terms of accuracy while Fuzzy method had the worst performance in simulation of HPSCs' processes (Table 4.1). In addition, the optimum equations relating the outlet temperature of HPSCs to the operational conditions of the solar water heating systems as well as the climatic conditions were obtained (Table 4.1).

8.2. Direct Contact Membrane Distillation

The first part of the third research question was regarding the performance of the DCMD module, its sensitivity to operational and physical parameters, and its optimum characteristics. A novel multi-step mathematical model was developed to predict the fresh water productivity of the tubular DCMD module applicable for both small and large-scale applications by considering the changes in the operational variables along the membrane's length (Fig. 5.3). A

good agreement was observed between the theoretical and experimental results attesting the reliability of the developed multi-step theoretical model to predict the performance of the tubular DCMD modules under different conditions (Fig. 5.5, 5.6, 5.9, and 5.10). The results recommended to keep both the feed and permeate flow rate either near the end or beyond the transition range (Fig. 5.5). Another key finding was that the permeate water productivity of the tubular DCMD module was independent of the feed water salinity (Fig. 5.7). As expected, higher feed temperatures as well as lower permeate temperatures resulted in higher water productivity (Fig. 5.7). It was also revealed that heating up the feed stream was more efficient for enhancing the water productivity than using the same amount of energy to cool the permeate stream down (Fig. 5.8, 5.9). It was indicated that at a constant feed temperature, increasing the feed mass flow rate has a positive effect on the GOR value (Fig. 5.11). The results also showed that at all feed temperatures, the mass flux through the membrane decreased exponentially as the membrane's length increases (Fig. 5.12)

8.3. Solar membrane-based desalination system

The second parts of research questions 2 and 3 were respectively regarding the integration of heat pipe evacuated tube solar collectors with direct contact membrane modules for seawater desalination and improving the overall efficiency of the system using a cooling unit. The performance of the system was experimentally investigated without (Case I) and with (Case II) the cooling unit in summer and without the cooling unit in winter (Case III) under climatic conditions of Perth, Western Australia. The experimental results indicated that except a few minutes in the morning, the heat pipe solar system was able to provide all the required thermal energy for the desalination system (Fig. 6.6). The maximum thermal efficiency of the solar system in summer reached ~78% (Fig. 6.6) and its exergy efficiency fluctuated between 4-5% for a noticeable amount of time (Fig. 6.8). Moreover, the maximum freshwater production rates were 2.78, 3.81, and 2.1 L/m^2h in Cases I, II, and III, respectively (Fig. 6.10). The overall efficiency of the system improved from 46.6% in Case I to 61.8% in Case II showing the technical effectiveness of implementing the cooling unit in the permeate flow loop of the system (Fig. 6.12). In addition, the daily averaged specific energy consumption in Cases I, II, and III were 407, 377, and 450 kWh/m^3, respectively (Fig. 6.13).

8.4. Solar membrane-based wastewater treatment system

The first part of the research question 2 was regarding the performance of the proposed integrated system in wastewater treatment. Synthetic wastewater was prepared by dissolving different metal salts in deionized water and the performance of the solar system was experimentally studied under summer and winter climatic conditions of Perth, Western Australia. The results indicated that the solar thermal efficiency of the system fluctuated mainly around 63% in summer and 52% in winter (Fig. 7.8). The system reached its maximum exergy efficiency in the afternoon with 5.54 and 4.82% for summer and winter, respectively (Fig. 7.9). Moreover, the highest rate of treated water in summer and winter were 4.21 and 2.85 L/m^2h, respectively (Fig. 7.10b). The results also indicated that the removal percentages of Fe, Mn, Cu, Na, K, and Ca were 96, 89, 96, 100, 100, and 94%, respectively, which well confirmed the effectiveness of the proposed system for separation processes (Fig. 7.11). In addition, the maximum gain output ratio and overall efficiency of the system were 0.71 and 49.6% in summer while these parameters were 0.58 and 46.6% in winter (Fig. 7.12, 7.13). Overall and based on the results, the proposed solar-driven membrane-based system can be considered as a feasible and efficient option in the separation of hazardous metals from wastewater

Chapter 9

Conclusion and Future Work Recommendations

This chapter integrates the findings of all chapters and offers suggestions for possible future works.

9.1. Conclusions

This thesis largely focused on a novel heat pipe solar membrane-based desalination and water treatment system. Both experimental and numerical techniques were utilised to address the research questions stated in Chapter 1. The following conclusions were derived from the analysis of the obtained results:

- The hot water consumption pattern significantly influences the temperature distribution of the heat pipe solar collector and the storage tank. Hence, considering hot water consumption pattern plays a crucial role in optimum design of solar water heating systems.
- Hot water extraction has a positive effect on the thermal efficiency of the solar system while low solar radiation significantly reduces the system efficiency. In addition, the highest exergy destruction occurs at the beginning of the day.
- Sodium Dodecyl BenzeneSulfonate (SDBS) at 0.1 wt.% was the optimum concentration of SDBS for 0.05 wt.% Al_2O_3/DI water nanofluid exhibiting the highest stability and thermal conductivity enhancement. The application of this nanofluid as the solar working fluid improves the overall heat transfer and efficiency of the solar system.
- Implementation of a variable solar working fluid mass flow rate and regulating it with solar radiation significantly improves the overall performance of the HPSWH system.
- The best modelling method to predict the performance of HPSCs is ANN, which is followed by ANFIS and TRN methods in terms of accuracy. The Fuzzy method has the worst performance in simulation of HPSCs' processes.

- The proposed multi-step model has the capability of predicting the performance of tubular DCMD modules accurately even in large-scale applications in an economic manner.
- The freshwater productivity of the tubular DCMD module is independent of the feed water salinity and increasing the mass flow rates has a positive effect on TPC and freshwater productivity of the tubular DCMD module to some extent. Based on the results, it is highly recommended to keep both the feed and permeate flow rates of the DCMD module near or in the turbulent range of the flows.
- Heating up the feed stream in a DCMD module is more efficient for enhancing the water productivity than using the same amount of energy to cool the permeate stream down.
- The maximum thermal efficiency of the solar system in summer reaches ~78% while its exergy efficiency fluctuates between 4% and 5% for a noticeable amount of time. The exergy efficiency in winter days has an ascending trend reaching its maximum value of ~5% at the end of the day. Any strategy which can increase the collector inlet and outlet temperature difference has a positive effect on the exergy efficiency of the solar system.
- The overall efficiency of the solar membrane-based desalination system improves by approximately 15% upon the application of a cooling unit in the permeate flow loop of the system indicating the effectiveness of the proposed configuration.
- The maximum freshwater production rate in summer reaches 3.81 L/m^{2}h, while the freshwater production rate in winter has a parabolic trend throughout a day having the maximum value of 2.1 L/m^{2}h.
- The effectiveness of the proposed solar-driven membrane-based system for removing hazardous metals from the fabricated wastewater (i.e. $NaHCO_3$ (200 mg/L), NH_4Cl (190 mg/L), $CuSO_4$ (30 mg/L), $NaNO_3$ (30 mg/L), $CaCO_3$ (10 mg/L), $FeCl_2$ (10 mg/L), K_2SO_4 (10 mg/L), and $MnSO_4$ (10 mg/L)) is proved. The proposed system effectively removes the contaminating metals in the wastewater by showing the removal percentage of 96, 89, 96, 100, 100, and 94% for Fe, Mn, Cu, Na, K, and Ca, respectively. The system can be considered as a feasible and efficient option for industrial applications and use in remote areas where access to clean water is an issue.

9.2. Future research directions

Recommendations for future research directions include:

- There are limited research on the economic analysis of HPSCs and it is highly recommended that the economic feasibility of previous and future proposed systems should be evaluated for all different applications and configurations. In addition, modelling-based analysis or estimation of the proposed solar membrane-based desalination and wastewater treatment system's annual output and economic viability have a significant research potential.
- Improving the performance of heat pipe solar collectors as the most important components of the solar system is also very important. Therefore, the application of novel working fluids (e.g., various nanofluids), investigating the effect of design parameters (e.g., pipe diameters and materials), and studying the effect of some operational parameters (e.g., working fluid mass flow rate, and climatic conditions), are recommended.
- Optimization of solar working fluid mass flow rate and regulating it with the climatic conditions to achieve the optimum performance of the system is highly recommended for further research.
- Although increasing the mass flow rates in a DCMD module increases the turbulence level, it decreases the residence time. Therefore, studying the effect of residence time on water productivity of the tubular DCMD system can be the future research direction in this field.
- Although the application of the cooling unit in the permeate flow loop of the system improved the freshwater productivity significantly, the economic feasibility of implementing it needs further investigations.
- Application of multiple DCMD modules in different configurations and investigating their effect on the performance of the system is another possible research topic.
- Improving the overall efficiency of the system by using energy recovery systems is highly recommended as a future research direction.
- Phase change materials are becoming more popular in energy systems and their application in solar membrane-based systems has significant research potentials.

Appendix A

A review of latest developments, progress, and applications of heat pipe solar collectors

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Abstract

Among all the available solutions to the current high energy demand and consequent economic and environmental problems, solar energy, without any doubt, is one of the most promising and widespread solutions. However, conventional solar systems face some intractable challenges affecting their technical performance and economic feasibility. To overcome these challenges, increasing attention has been drawn towards the utilization of heat pipes, as an efficient heat transfer technology, in conventional solar systems. To the authors' knowledge, despite many valuable studies on heat pipe solar collectors (mainly during the last decade), a comprehensive review which surveys and summarizes those studies and identifies the research gaps in this field has not been published to date. This review paper provides an overview of the recent studies on heat pipe solar collectors (HPSCs), their utilization in different domestic, industrial, and innovative applications, challenges, and future research potentials. The concept and principles of HPSCs are first introduced and a review of the previous studies to improve both energy efficiency and cost effectiveness of these collectors is presented. Moreover, a concise section is dedicated to mathematical modeling to demonstrate suitable methods for simulating the performance of HPSCs. Also, the latest applications of HPSCs in water heating, desalination, space heating, and electricity generation systems are reviewed, and finally, some recommendations for future research directions, regarding both development and new applications, are made.

Keywords: Solar collector; Heat pipe; Efficiency; Applications; Progress.

Appendix A

The fulltext of Appendix A is unavailable in this version of the thesis.

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Appendix B

Strategies to improve the thermal performance of heat pipe solar collectors in solar systems: A review

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Abstract

Invention of evacuated tube heat pipe solar collectors (HPSCs) was a huge step forward towards resolving the challenges of conventional solar systems due to their unique features and advantages. This has led to their utilization in a wide range of solar applications surpassing other conventional collectors. However, relatively low thermal efficiency of heat pipe solar (HPS) systems is still the major challenge of solar industry evidenced by numerous studies conducted mainly during the last decade to improve their efficiency. To date, several review papers have been published summarizing studies relevant to utilization of HPSCs in various thermal applications. However, to the authors' knowledge, a comprehensive review which surveys and provides an overview of the studies undertaken to improve the thermal performance of HPS systems (mainly during the last decade) by implementing different strategies has not been published to date. This review paper summarizes all the proposed strategies to improve the thermal efficiency of different industrial, domestic, and innovative HPS systems. First, the concept, structure, and operational principles of HPSCs are introduced concisely. Then, novel structures and designs of HPSCs aiming to increase the thermal efficiency of the collector as the most important component of the solar system is reviewed. This is followed by a comprehensive review of various methods to store solar energy more efficiently, increase solar system's operation time, increase overall efficiency by turning the solar system into a multi-purpose system, enhance heat transmission in the solar system, and implement new solar loop and heat pipe working fluids with better heat transfer characteristics.

Keywords: Heat pipe, Solar system, Thermal performance, Efficiency improvement

Appendix B

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Appendix C

Theoretical modelling approaches of heat pipe solar collectors in solar systems: A comprehensive review

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https://doi.org/10.1016/j.solener.2019.09.036

Abstract

The invention of heat pipe solar collectors (HPSCs) is considered as an immense step forward towards solving the challenges of conventional solar thermal systems. Their unique qualities have acted as a great motivation for researchers to focus their studies on HPSCs and their applications. A considerable share of these studies has been allocated to theoretical studies due to several technical and economic reasons. However, to the authors' knowledge and despite many valuable efforts in this field, there is no review paper available to summarize the relevant proposed and developed theoretical models to date and identifies the research gaps in this field. Therefore, in this review paper, the latest theoretical studies in the field of HPSCs along with their advantages, disadvantages, and contribution have been categorized, reviewed, and discussed. First, the operational principles and structure of HPSCs have been explained to create a background for readers. This is followed by a short section dedicated to the simulation of solar radiation as the most important input for all solar mathematical models. In addition, various mathematical approaches including steady state models (i.e. one-dimensional energy balance and thermal resistance network methods), dynamic models, and models for novel configurations and applications of HPSCs have been reviewed. Moreover, mathematical models to determine the exergy efficiency of HPSCs, which is an effective tool to evaluate the solar systems from a thermodynamic point of view, have been presented. Finally, the challenges, research gaps, and recommendations for future research directions have been provided.

Keywords: Solar collector; Mathematical model; Heat pipe; Theoretical study

Appendix C

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Appendix D

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

Published in Case Studies in Thermal Engineering, 21 (2020) 100662

https://doi.org/10.1016/j.csite.2020.100662

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.

Keyword: Heat pipe; Thermal performance; Energy evaluation; Solar water heating

D.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 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]. 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 [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.

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].

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.

D.2. Materials and Methods

D.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. D.1). 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].

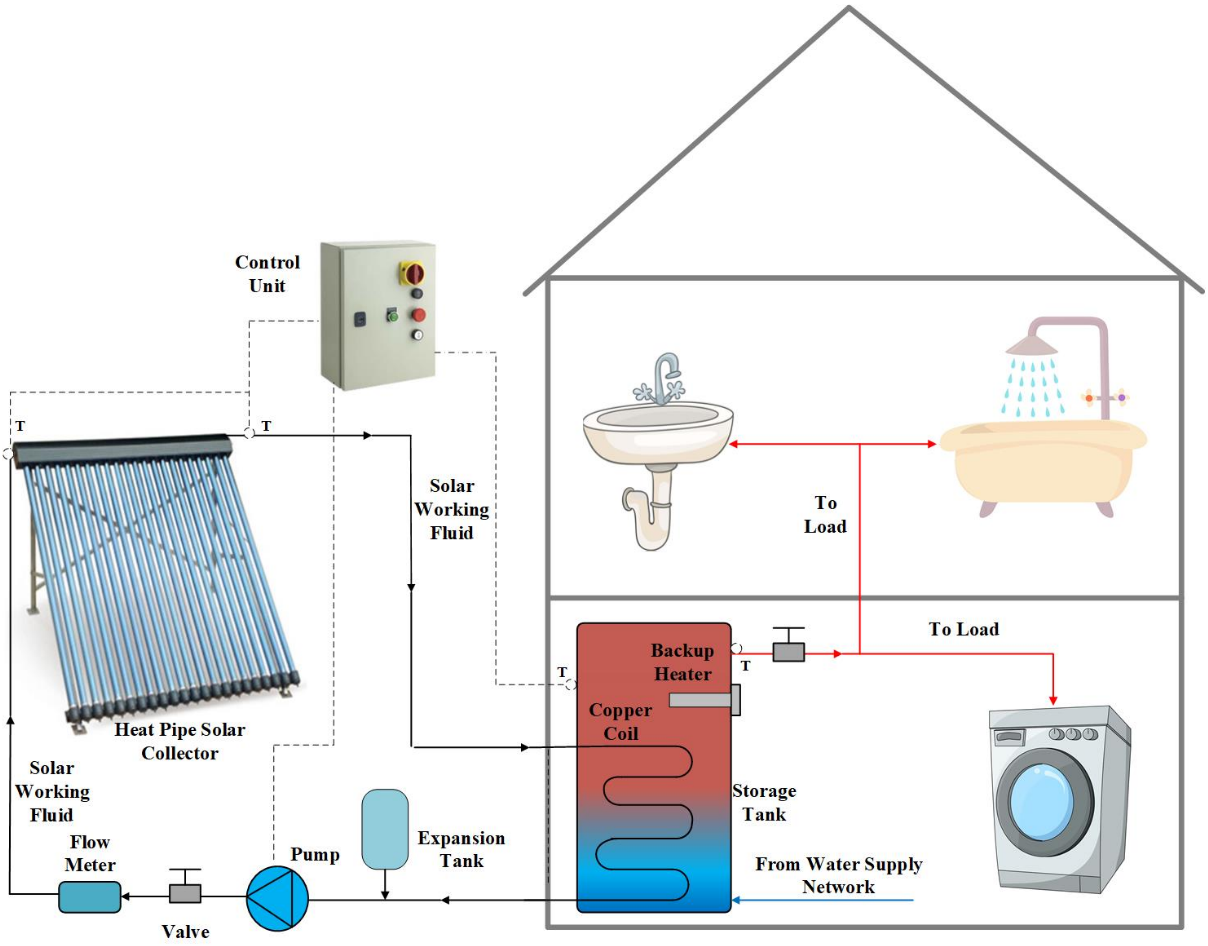
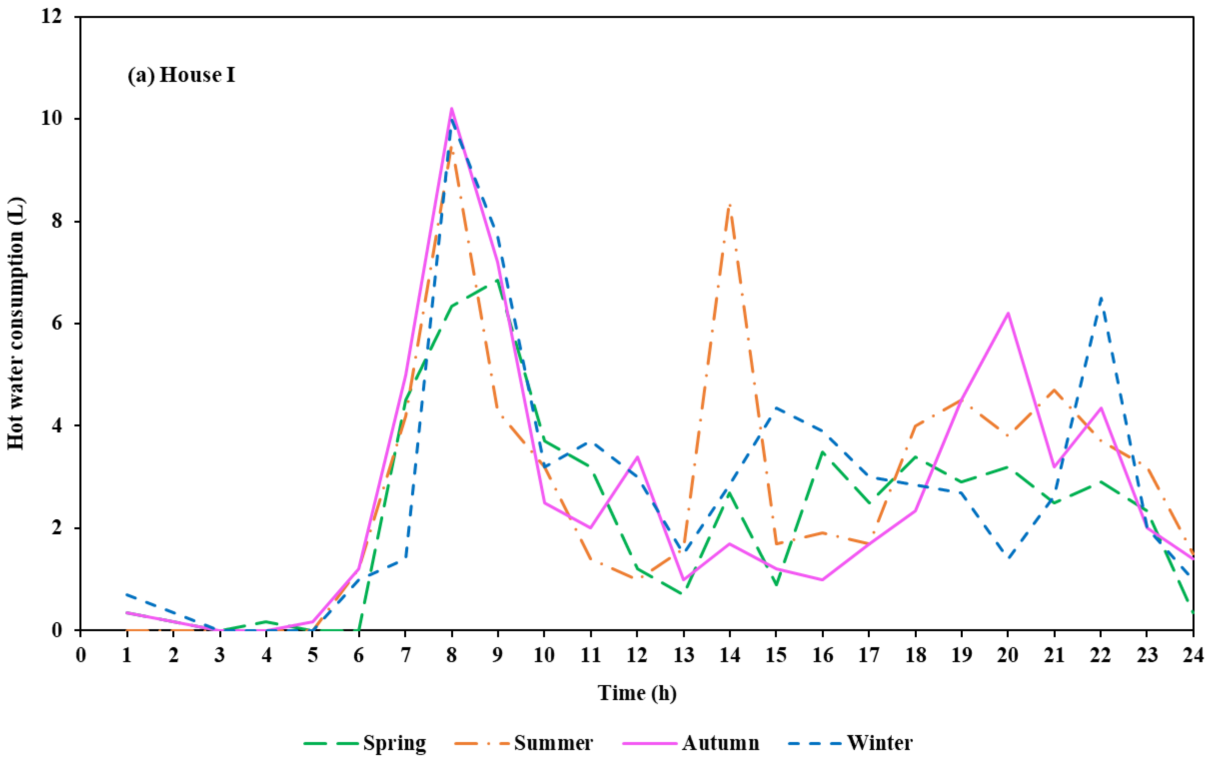
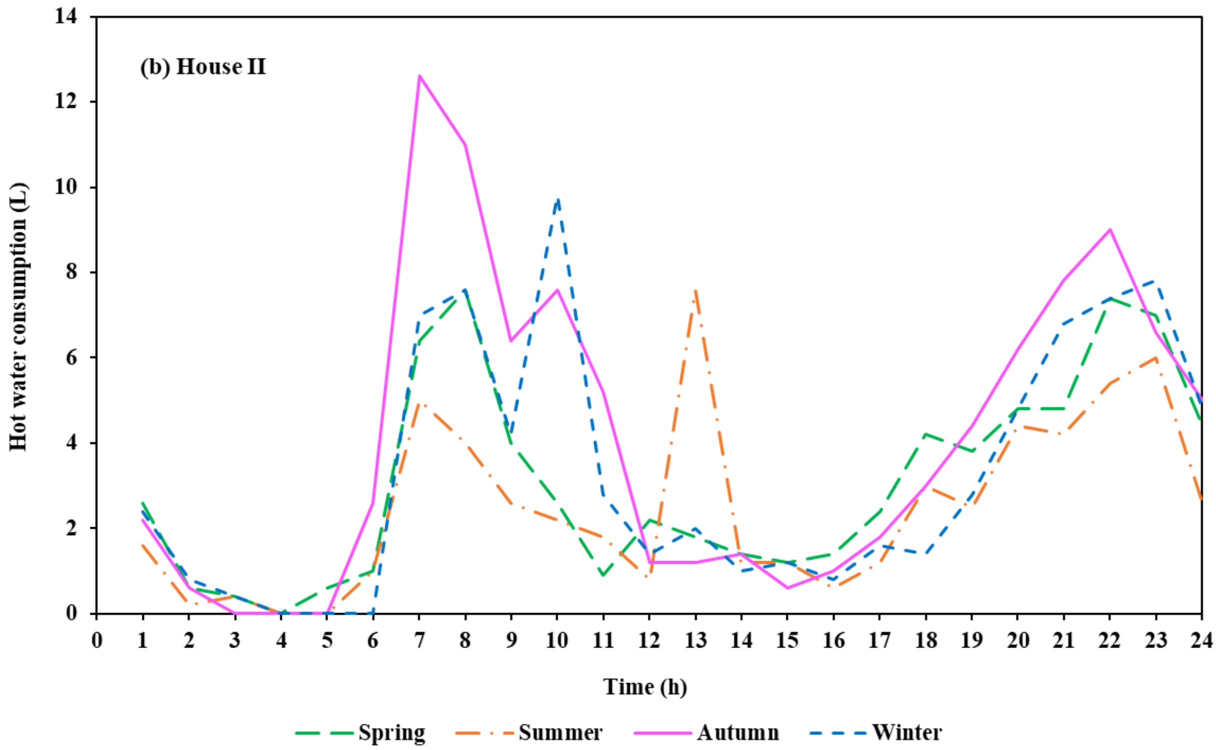


Figure D.1 Schematic of the HPSWH system

D.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 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. D.2) [35].





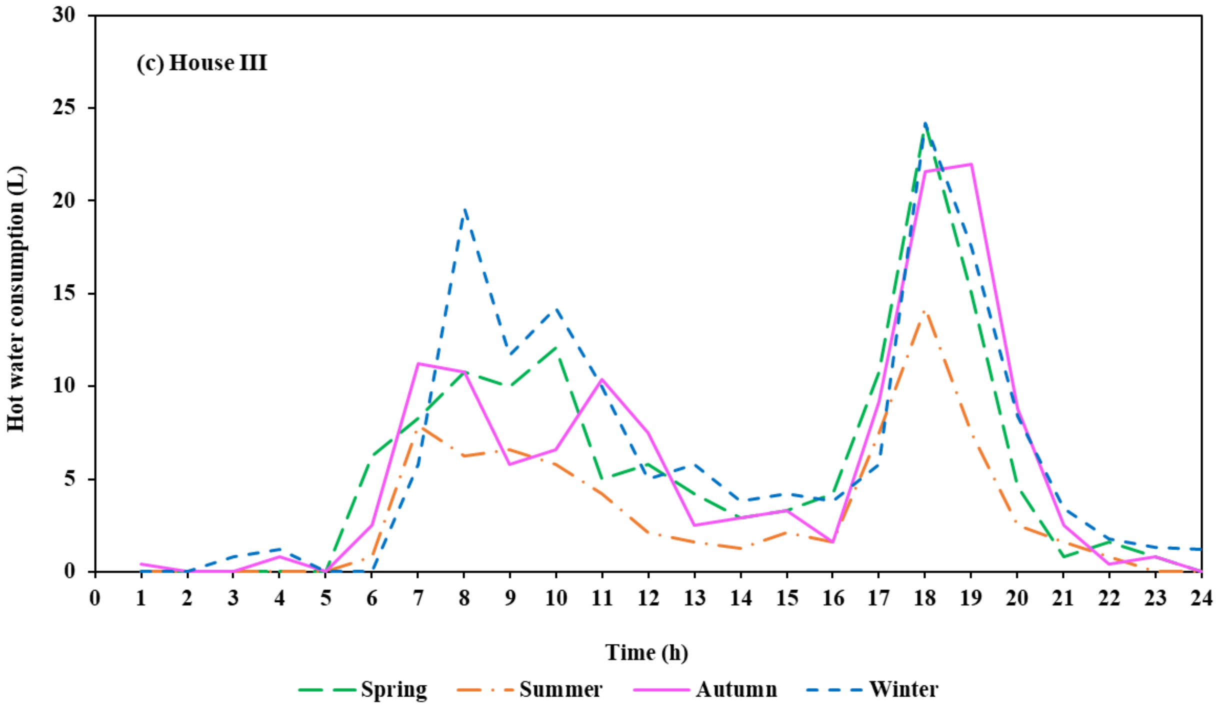


Figure D.2 Seasonal domestic hot water consumption patterns: (a) Houses I, (b) House II, and (c) House III

D.2.3. Climatic Data

The climatic data (i.e. solar radiation and ambient temperature) was continuously recorded in one-minute 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.

D.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 seconds. 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.

D.2.5. Mathematical modelling

D.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:

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

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.

D.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]:

$$Q_{ab} = Q_{en} - Q_{loss} \quad (2)$$

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 [37, 38]:

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

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

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 [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:

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

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 ($T_{w,network}$):

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

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

D.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.

D.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.

D.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.

D.2.5.5. 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 D.1 provides information regarding the input parameters as well as their values.

Table D.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

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 D.2, were considered in this study.

Table D.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

D.3. Results and discussions

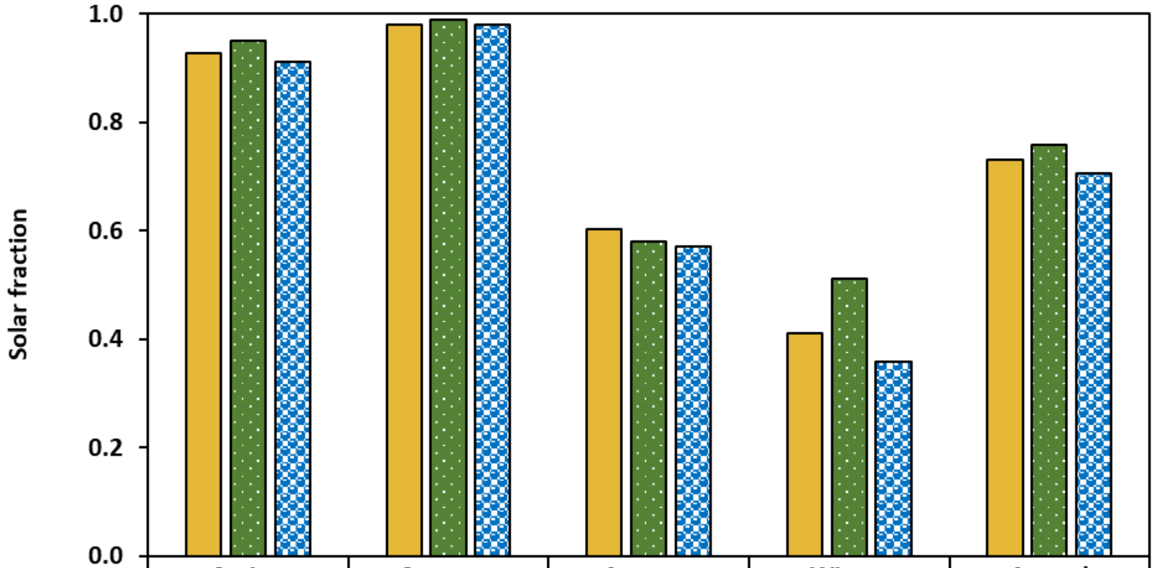
D.3.1. Energy analysis

D.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. Figure D.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.



	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

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

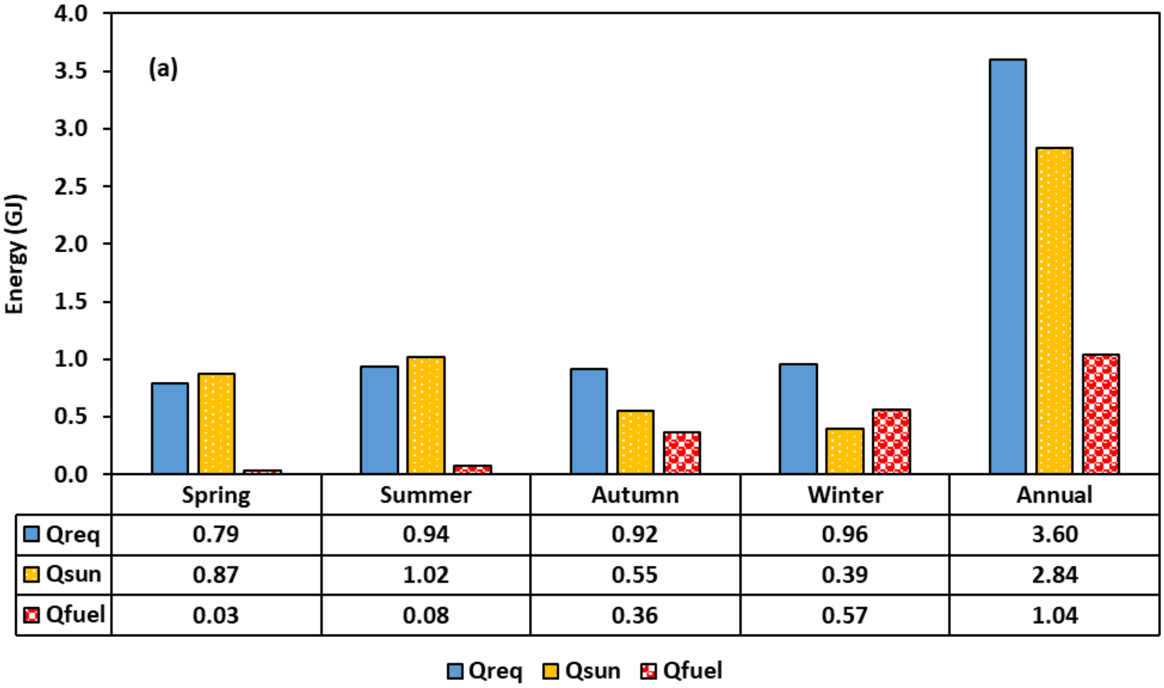
D.3.1.2. Required, absorbed, and backup energy

Figure D.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.

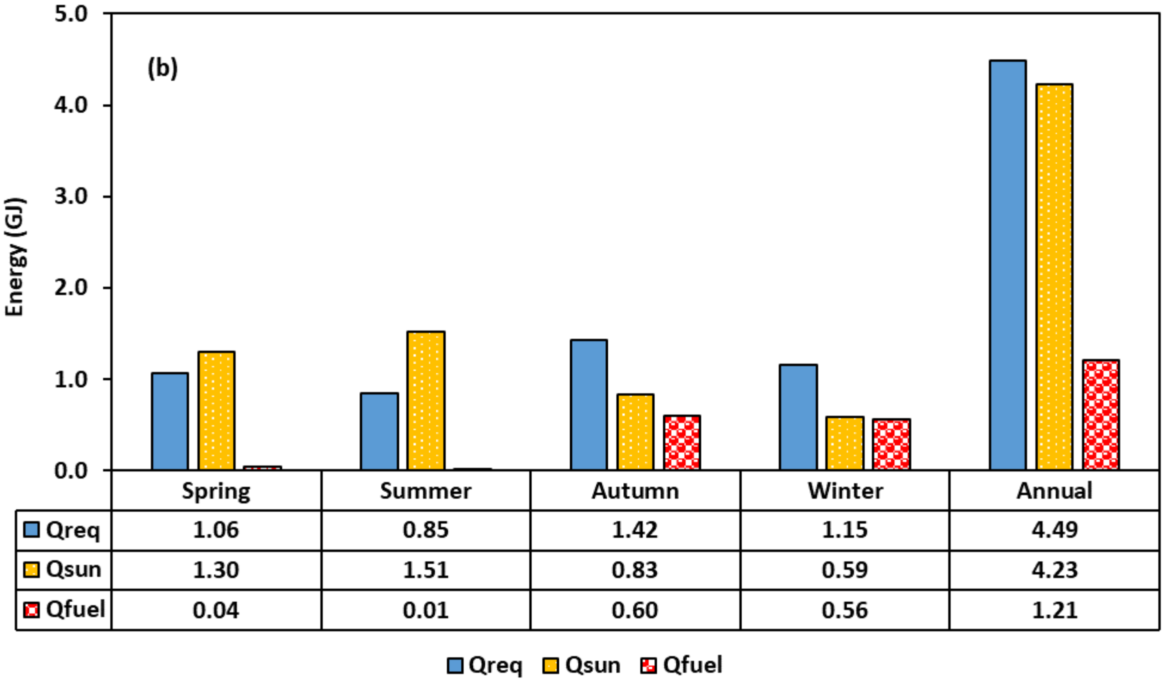
The amounts of annual absorbed solar energy are 2.84, 4.23, and 5.61 GJ for Houses I, II, and III, respectively. These values depend significantly on weather data and characteristics of the solar system. Around 1.04 GJ of the annual energy in House I should be supplied by external fuel sources while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



	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



	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

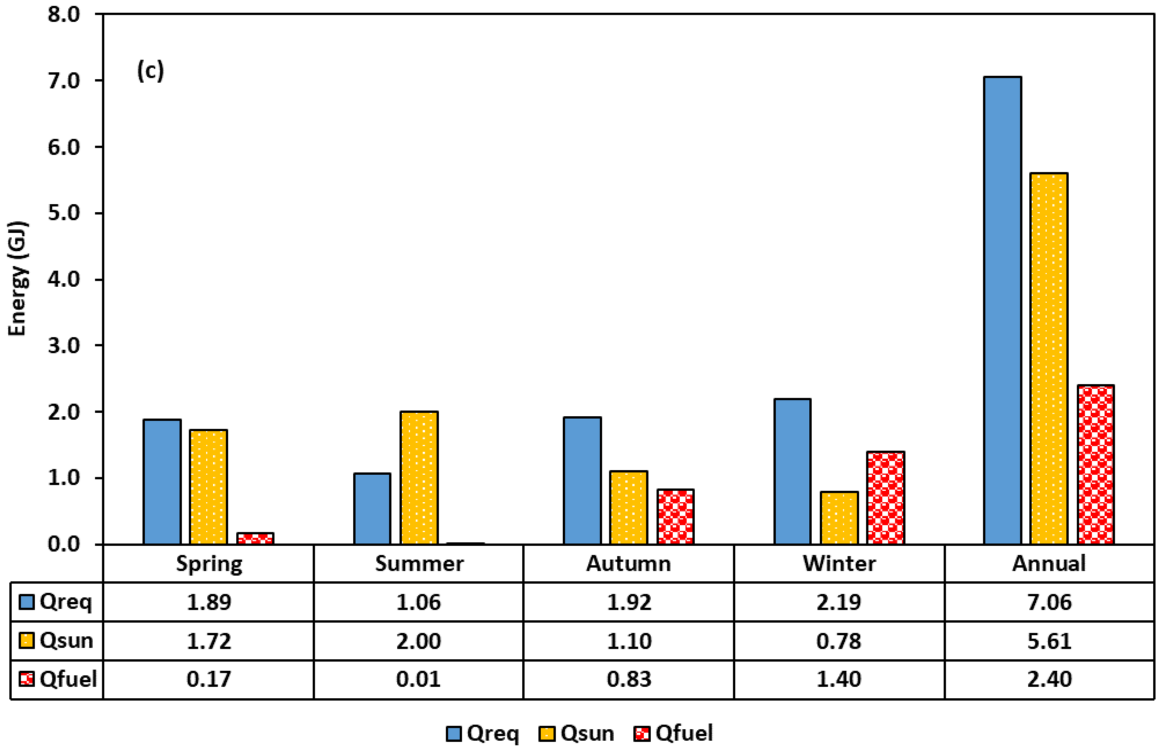


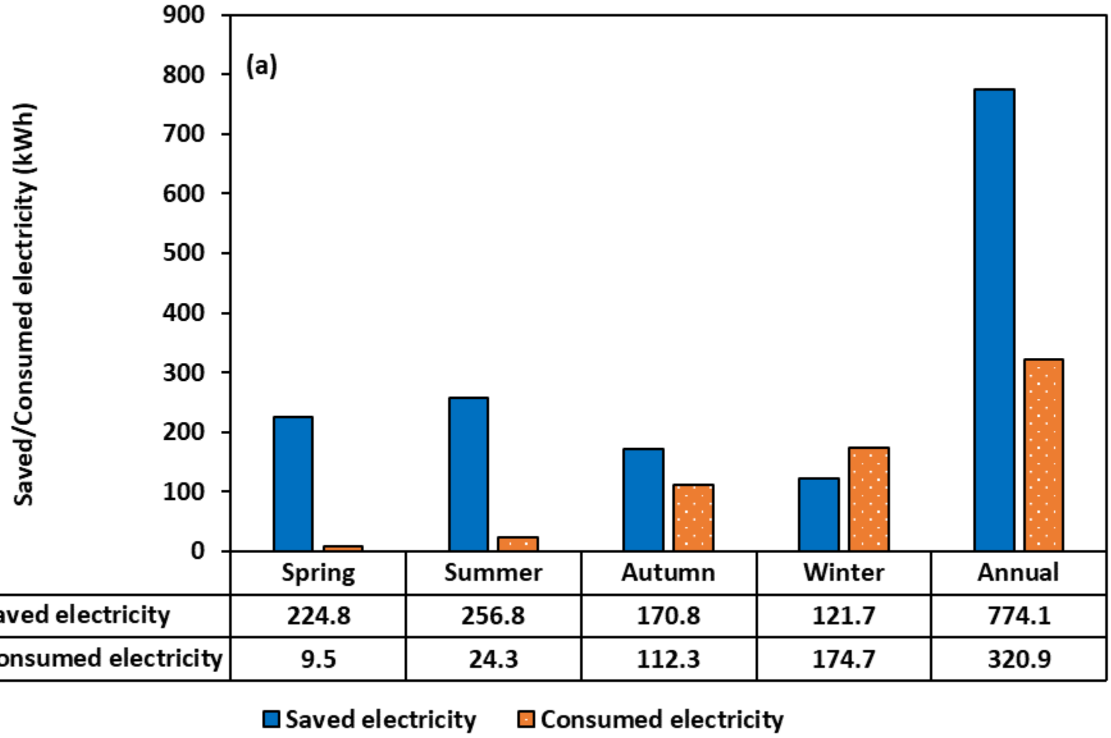
Figure D.4 Seasonal and annual energy required, supplied by the sun, and backup energy to meet the hot water demand of (a) House I, (b) House II, and (c) House III

D.3.2. Environmental analysis

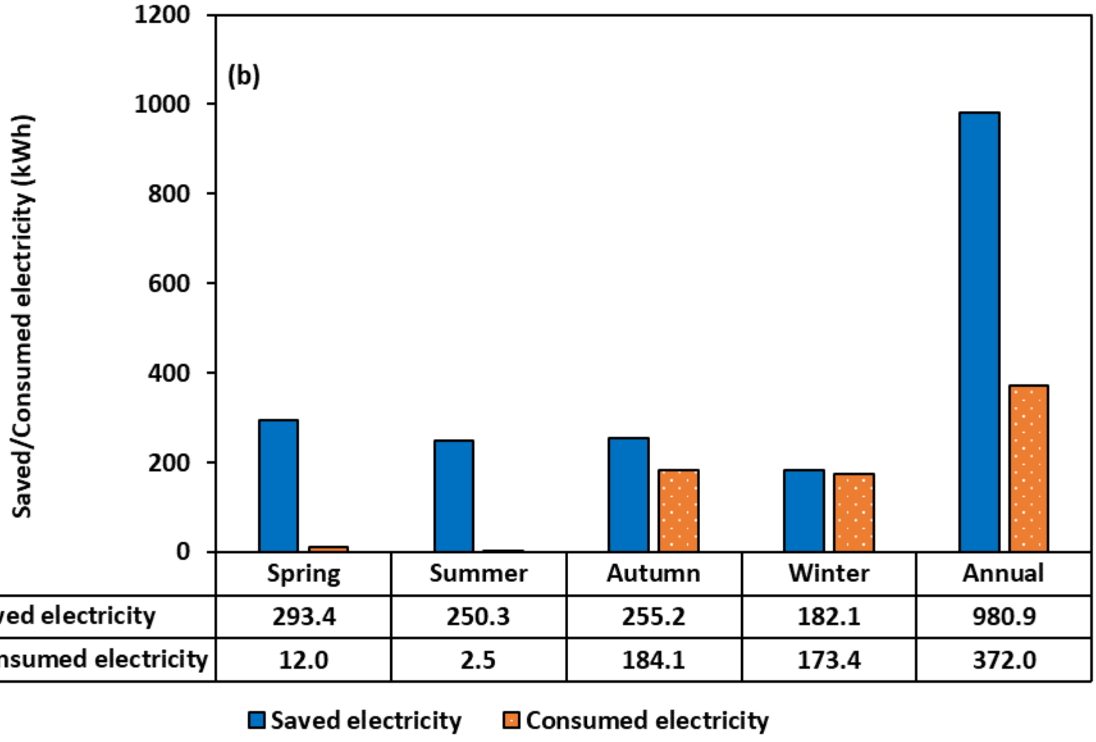
D.3.2.1. Saved Electricity

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. D.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 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.



	Spring	Summer	Autumn	Winter	Annual
Saved electricity	224.8	256.8	170.8	121.7	774.1
Consumed electricity	9.5	24.3	112.3	174.7	320.9



	Spring	Summer	Autumn	Winter	Annual
Saved electricity	293.4	250.3	255.2	182.1	980.9
Consumed electricity	12.0	2.5	184.1	173.4	372.0

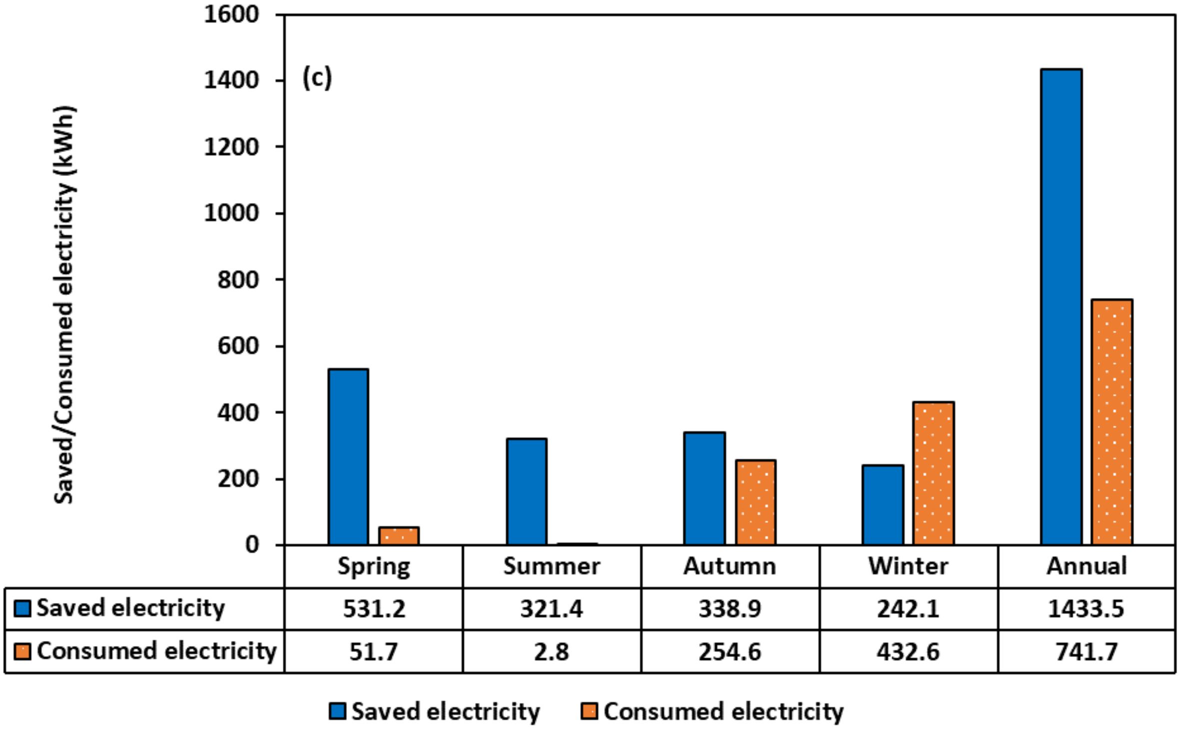
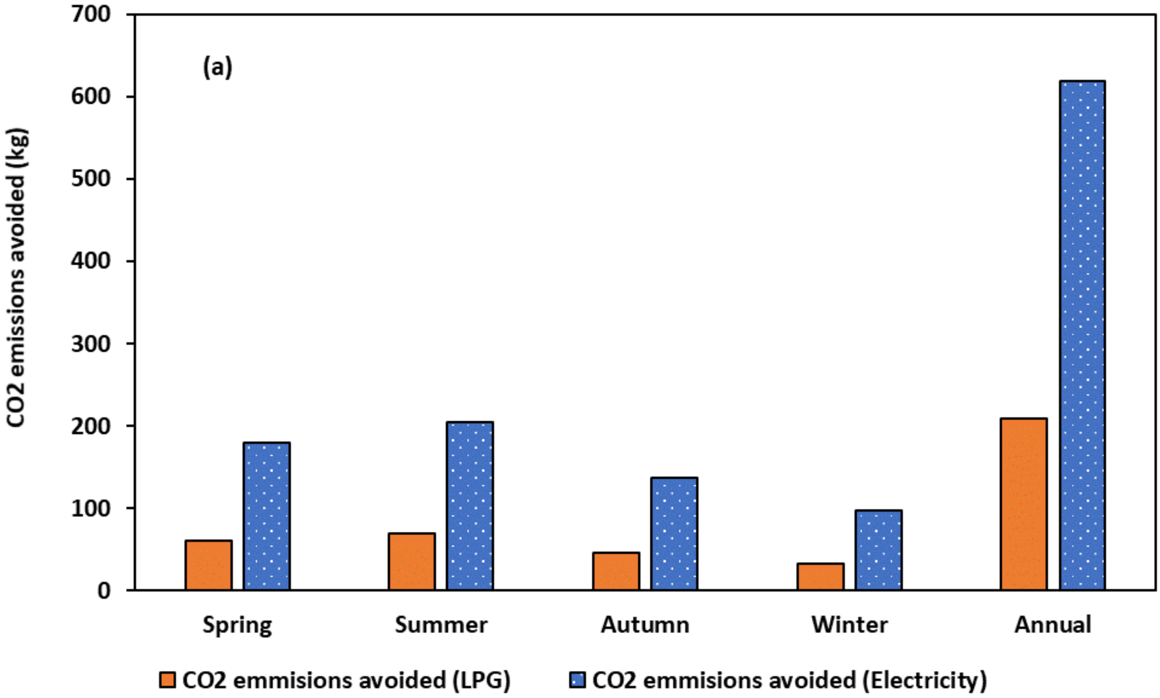


Figure D.5 The seasonal and annual saved electricity using the HPSWH system and the consumed electricity by the backup system in (a) House I, (b) House II, and (c) House III

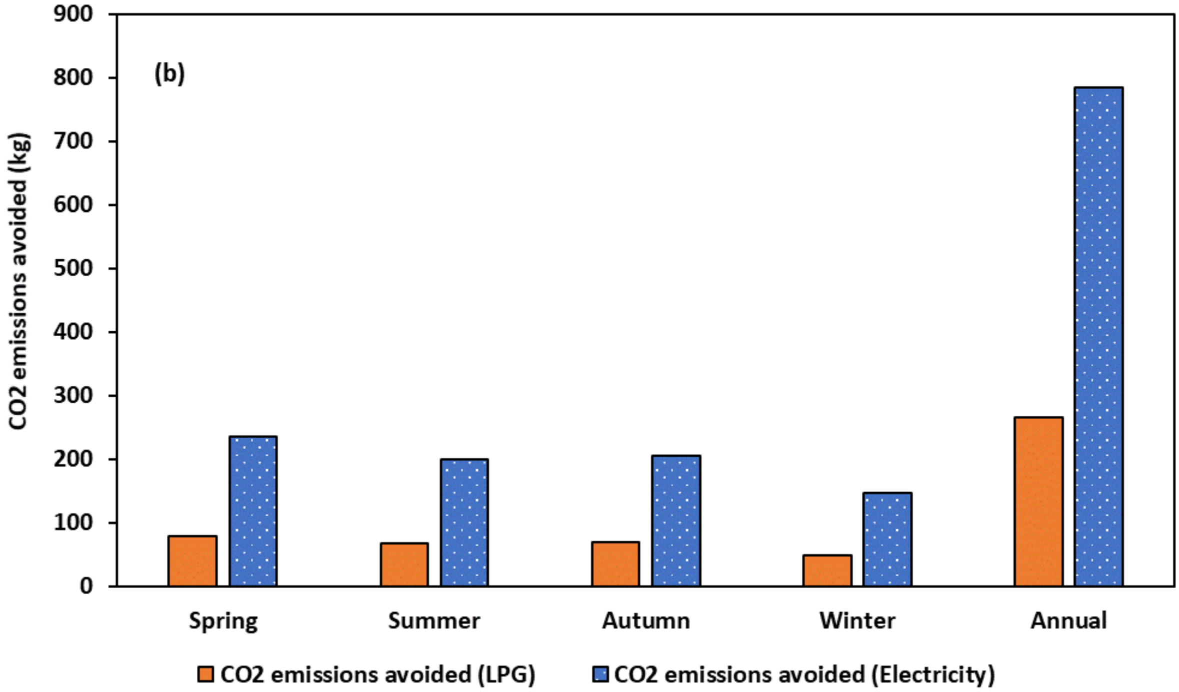
D.3.2.3. Avoided CO_2 emission

The distribution of the seasonal and annual CO_2 emissions which can be avoided by applying the HPSWH system is shown in Fig. D.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.



(a)
CO2 emissions avoided (kg)
700
600
500
400
300
200
100
0
Spring
Summer
Autumn
Winter
Annual
CO2 emmisions avoided (LPG)
CO2 emmisions avoided (Electricity)



(b)
CO2 emissions avoided (kg)
900
800
700
600
500
400
300
200
100
0
Spring
Summer
Autumn
Winter
Annual
CO2 emissions avoided (LPG)
CO2 emissions avoided (Electricity)

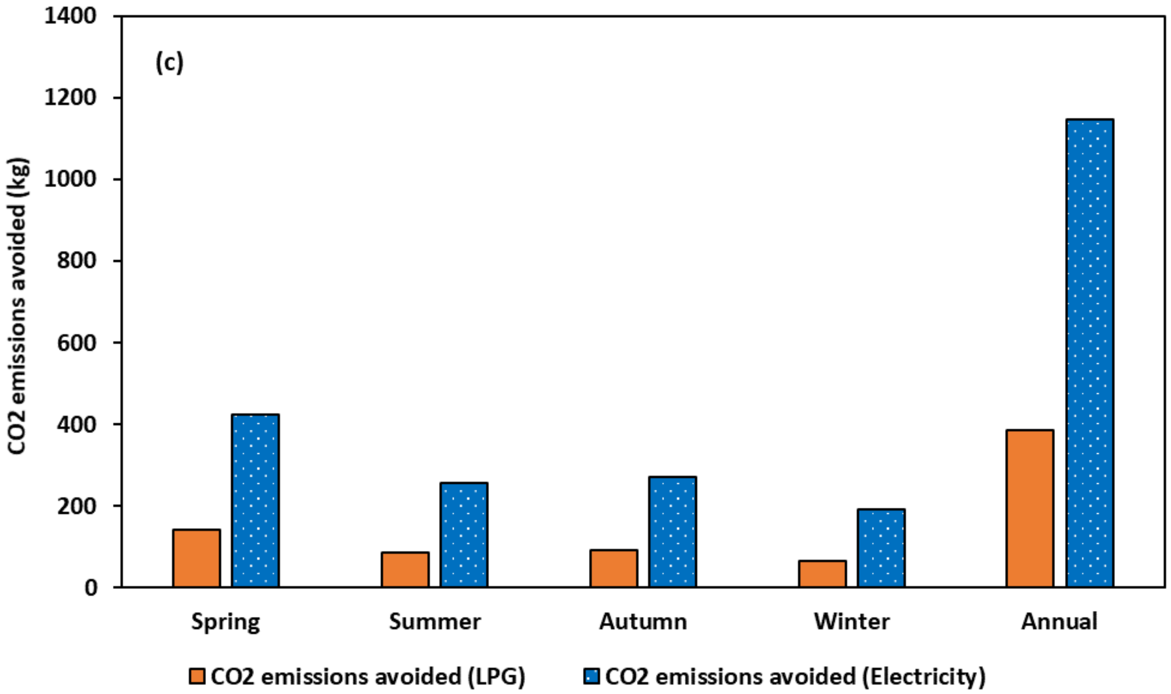


Figure D.6 The seasonal and annual CO_2 emissions avoided by using the HPSWH system in (a) House I, (b) House II, and (c) House III

D.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. Figure D.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.

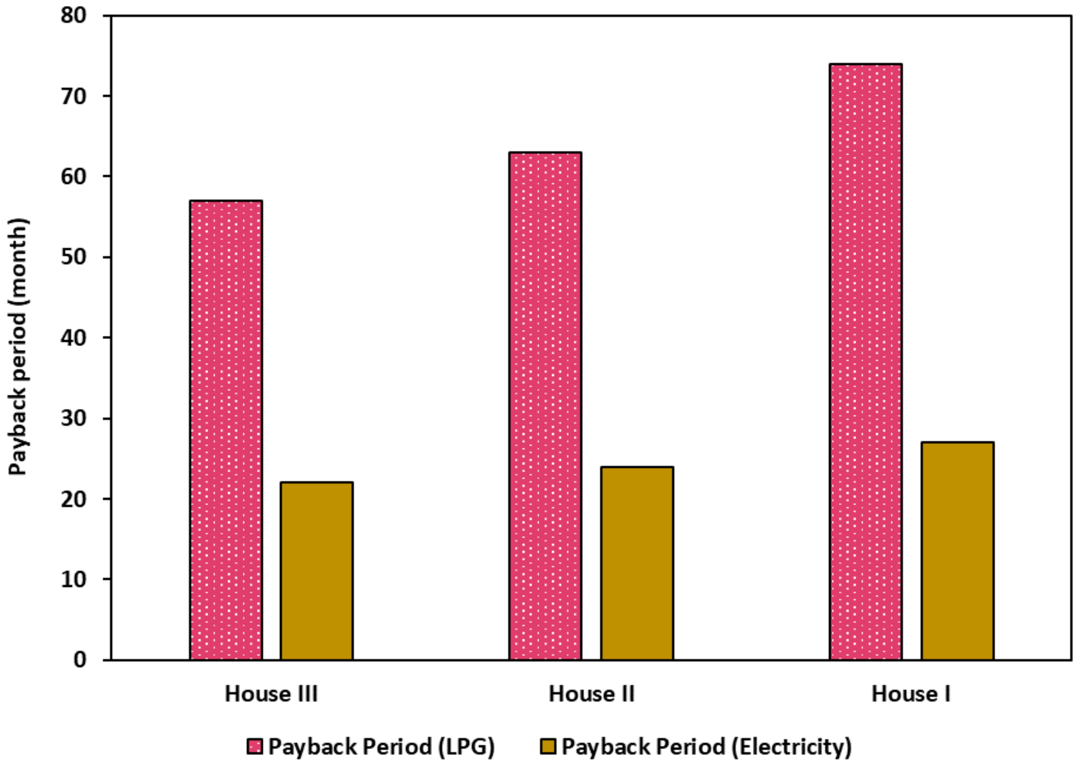


Figure D.7 The payback period of the HPSWH system in different Houses

D.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 D.3. It is worth noting that as the experimental rig was manufactured to meet the hot water requirements of House III (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.

Table D.3 Theoretical and experimental absorbed energy for House III

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

D.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.

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