A Feasibility Study for the Development of Sustainable Theoretical Framework for Smart Water-Energy Bathroom Unit

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Abstract

One of the major issues facing the world in the 21st century is climate change. However, sustainability has become a crucial concept to combat extreme consumption and utilization of environmental resources leading to climate change. The bathroom has been estimated to be the principal user of environmental resources in households in the consumption of water, electricity and gas. Therefore, the challenge that how a combined water and energy saving unit in the bathroom will contribute to the sustainability of the houses remain unresolved. This study challenges and extends existing knowledge on sustainability related to the smart bathroom systems from social, environmental, and economic standpoints to achieve a highly efficient water and energy consumption in the bathroom. This is with regards to the potential which the renewable-based options, advanced smart control techniques and profitability measures of bathroom reinforces the three pillars of sustainability.

This study reveals that a range of technological challenges are based on the individual components and technologies in the bathroom and concludes that a holistic approach is required for an effective modelling in the bathroom. This allows the examination of energy and water flows in the complex systems, shaped by various social, economic and environmental forces. The method this thesis presented adopts a conceptual modelling approach that is based on holistic modelling to design and implement a bathroom unit that is sustainable and smart. The system components assume three flat plate solar collectors, a solar heat exchanger, a pre-heating storage tank, main hot storage tank with auxiliary boiler system, mixing devices and two circulators to collectively improve the overall system efficiency. Parametric analysis was also conducted to know how change in variable parameters like location, load and switch-on temperatures will affect the performance of the system designed. Furthermore, a smart control for the bathroom system is designed to use the fuzzy logic controller, it was used because of its easy adaptability to the bathroom users' pattern.

While the result shows that solar total annual energy supplied to the bathroom system is 4,878 kWh and the total annual energy consumed by the system is 8,675 kWh with average annual system performance of 0.95. The solar thermal systems are still able to save between 50% and 60% of the energy that would have been required annually to heat up the hot water using conventional energy sources. After optimizing the system, the bathroom system completely provided an overall annual CO_2 savings of

1,398 kg. This study has shown the contribution of renewable energy source and smart control technologies in the bathroom and the significant contribution it makes to the water-energy nexus, levels of energy consumption and carbon emissions. The outcome of the fuzzy logic control design shows that the controller stabilizes and shows transient at the user desired temperature (20^oC and 25^oC) and flowrate (0.5 l/sec and 0.9 l/sec). The control has little overshoot, steady state error and stabilises quickly to the precise user desired flowrate and temperature hereby enhancing the efficiency of the reference system.

This study has established a strong quantitative and qualitative links between three dimensions of sustainability. This has made a major contribution to the design of sustainable development and infrastructure by developing a sustainable bathroom framework that have been presented in this study.

Publications

a) Oye, T. K., Goh, K., Gupta, N., & Oye, T. T., "A Smart and Sustainable Concept for Achieving a Highly Efficient Residential Bathroom: A Literature Review", *International Journal of Innovative Science and Research Technology,* Volume 5, Issue 3, pp. 1402-1407*,* ISSN 2456-2165, March 2020.

b) Oye, T. K., N. Gupta, K. Goh and T. T. Oye, "Design of a Smart and Intelligent Energy Efficient Controller for a Bathroom System," 2020 *9th International Conference on Renewable Energy Research and Application* (ICRERA), IEEE Xplore, Glasgow, United Kingdom. pp. 170-174, doi: 10.1109/ICRERA49962.2020.9242819. November 2020.

c) Oye, T. K., Gupta, N., Goh, K., & Oye, T. T., "Development of a Sustainable Theoretical Framework for a Renewable Based Bathroom Unit", *Journal of Environmental Management and Sustainable Development*, Volume 10, No. 3, pp. 10-35, ISSN 2164-7682, doi:10.5296/emsd.v10i3.18537, May 2021.

d) Oye, T. K., Gupta, N., Goh, K., & Oye, T. T., "Holistic Modelling and Parametric Study of Bathroom Solar Hot Water Heating System", *Journal of Environmental Management and Sustainable Development*, Volume 10, No. 3, pp. 36-61, ISSN 2164-7682, doi:10.5296/emsd.v10i3.18519, May 2021.

Dedication

God Almighty, I dedicated this piece to you for the strength and divine inspiration you gave me throughout the period of writing this thesis. To my entire family and my supervisor, thank you very much for your support.

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Declaration

To the best of my knowledge, this thesis contains no copy or paraphrase of work published by another person, except where duly acknowledged in the text. This thesis contains no material which has been previously presented for a degree at Napier University or any other university.

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List of Abbreviations

CO_{2e}	Carbon Emission Equivalent
COP	Coefficient of Performance
DEFRA	Department for Environment, Food and Rural Affairs
EA	Environmental Agency
EF	Energy Factor
EFW	Energy for Water
ETC	Evacuated Tube Collector
EU	European Union
FIS	Fuzzy Inference System
FLC	Fuzzy Logic Control
FPC	Flat Plate Collector
GHG	Green House Gas
IAQ	Indoor Air Quality
ICT	Information and Communication Technology
IEA	International Energy Agency
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
kJ	kilo Joules
MF	Membership Functions
MIMO	Multiple Input Multiple Output
NN	Neural Network
NTU	Number of Transfer Units
OECD	Organisation for Economic Co-operation and Development
Ofwat	Office of Water Services
PID	Proportional Integral Derivative
PVT	Photovoltaic thermal
RHI	Renewable Heat Incentive
SD	Sustainable Development
SHWS	Solar Hot Water System
SISO	Single Input Single Output

TRNSYS	Transient Systems Simulation Program
TUBs	Temporary Use Bans
UK	United Kingdom
UN	United Nations
UNCED	United Nations Conference on Environment and Development
UNCSD	United Nations Conference on Sustainable Development
UNEP	United Nations Environment Programme
UNSD	United Nations Statistics Division
WFE	Water for Energy
WHO	World Health Organization
WSSD	World Summit on Sustainable Development
WWHR	Waste Water Heat Recovery

List of Symbols

A_c	Solar collector absorber surface area, m^2
A_i	Surface area of inlet pipe between heat exchanger and solar panel, m^2
A_o	Surface area of outlet pipe between heat exchanger and solar panel, m^2
b_0	Incidence angle modifier coefficient
C	Drain water heat recovery unit NTU correlation equation's parameter
C_P	Specific heat capacity, J/kg.K
D_i	Diameter of pipe between heat exchanger and solar panel, m
D_o	Outer diameter of pipe including insulation, m
EF	Water heater's energy factor
F_{c-g}	View factor from solar collector surface to surrounding ground
F_{c-s}	View factor from solar collector surface to sky
F_R'	Modified solar collector heat removal factor
F_R	Solar collector heat removal factor
F_S	Daily solar fraction
G_{sc}	Solar constant, 1367 W/m^2
G_T	Global incident solar radiation on tilted surface, W/m^2
I	Hourly global irradiation on horizontal surface, w/m^2
I_b	Hourly beam solar irradiation on horizontal surface, w/m^2
kWh q_{SC}	Instantaneous heat flows collected by solar collector, kW
$MtCO_2e$	Metric tons of carbon dioxide equivalent
n	i^{th} day of year
Q_{DELVD}	Daily delivered energy, kWh
Q_{DW}	Daily recovered energy from drain water heat recovery unit, kWh
Q_{HP}	Daily heating energy generated by heat pump water heater, kWh
Q_{LOSS}	Daily storage tank thermal loss, kWh
$Q_{RESIDUAL}$	Daily residual energy, kWh
Q_{SC}	Daily collected solar energy, kWh
$Q_{SC.DELVD}$	Daily delivered solar heating energy, kWh
Q_{TDHE}	Total heating energy generated during one day, kWh
Q_{unmet}	Total daily system unmet load, kWh
Q_{WH}	Daily heating energy generated by main hot water storage tank,
R_b	The ratio of beam radiation on tilted surface to that on horizontal surface

RSI	SI equivalent value of tank insulation
SEF	Ratio of system's delivered energy to conventional energy consumed
T_a	Outdoor ambient air temperature, ℃
T_c	Cold make-up water temperature, ℃
T_D	Demand hot water temperature, ℃
T_{DW}	Shower drain water temperature, ℃
T_i	Inlet temperature of Heat transfer fluid to the collector, ℃
T_{PHT}	Temperature of delivered domestic hot water from pre-heating tank, ℃
T_s	Storage tank water temperature, ℃
$T_{S.max}$	Delivered hot water peak demand time
UA	Overall heat transfer coefficient-area product
U_F	Ratio of Unmet load to the total demand hot water consumed
U_L	Overall heat loss coefficient of the solar collector, W/m^2℃
$U_{L'}$	Modified heat loss coefficient of the solar collector, W/m^2℃
U_p	The heat loss coefficient between heat exchanger and solar panel
V_d	Demand hot water consumption, m^3/day
v_i	Instantaneous volume flow rate of delivered hot water m^3/s
V_S	Daily delivered domestic hot water, m^3/day
V_S.max	Delivered hot water peak demand, L/min
W_e	Daily consumed conventional energy, kWh
W_{HP}	Daily conventional energy consumed by heat pump water heater, kWh
W_{WH}	Daily conventional energy consumed by hot water storage tank, kWh
θ	Incidence angle of solar radiation,
ρ_g	Ground reflectance
C^*	Dimensionless capacitance rate of heat exchanger
$(V)_{shower}$	Volume flow rate of show drain water, L/min
$(\tau\alpha)_n$	Transmittance- absorptance for a solar collector
k	Insulation conductivity, $w/m^2.{}^\circ C$
δ	Angular position of the sun at solar noon, º
k_T	Hourly clearness index
I_d	Hourly diffuse solar irradiation on horizontal surface, w/m^2
I_0	Hourly extra-terrestrial radiation on a horizontal surface, w/m^2

I_T	Hourly global irradiation on a tilted surface, J/min.m^2
$\dot{m}$	Mass flow rate of delivered domestic hot water, kg/s
m	Total mass of the domestic hot water storage tank, kg
ε	Heat exchanger effectiveness
$\dot{m}_c$	Mass flow rate of heat transfer fluid volume flow rate, L/min
$K_{\tau\alpha}$	Incidence angle modifier
Φ	Latitude, º
β	Angle between the sloped collector and the ground,
I_{CO2}	CO2 intensity of a conventional energy source, kgCO2/kWh
L_{pipe}	Length of pipe between heat exchanger and solar panel, m
$(\dot{m}C_p)_s$	Domestic hot water heat capacitance, W/K.s
$(\dot{m}C_p)$	Heat transfer fluid heat capacitance, W/K.s
$\dot{m}_{PHT}$	Mass flow rate of delivered hot water from pre-heating tank, kg/s
$(mC_p)_{PHT}$	Domestic hot water heat capacitance, W/K
$(mC_p)_{DW}$	Shower drain water heat capacitance, W/K
$(\dot{m}C_p)_{min}$	The smaller value of $(\dot{m}C_p)_s$and $(\dot{m}C_p)_c$, W/K.s
˚ γ	Surface azimuth angle, ˚
º ρ	Density of water, (assumed to be 998 kg/m^3)
º ω	Hour angle,

Chapter One

1.0 Introduction and Background of the Study

Climate change and its effects are and will probably continue to be one of the major concerns that professionals need to deal with throughout the world in this century. The main features of climate change are global warming, sea level rises, precipitation changes and ice cap melting. For example, by the end of 21st century, average UK summer temperature is likely to rise by 3° C to 4°C, average summer rainfall across the UK may decrease by 11% to 27%, while winter is quite the inverse and the UK should expect significantly wetter winters. Sea levels are expected to rise, and extreme weather events are likely to become more common (IPCC, 2020). Therefore, it is obvious that climate change has significant potential to impact on urban environments and water infrastructure performance.

A recent report by CEPA (2021) emphasized that as a result of growing population, and changes in the way people use water in the UK, more than half of the current public water supply is for residential use. As a result, controlling domestic water demand is a priority in the UK. Whilst working on improved 'water supply' side forecasting is well established, limited attempts to effectively address uncertainties related to climate change and water demand management measures in demand forecasting models for longer term resource planning purposes have been reported. In the UK, the total range of forecasts found in Water Resource Management Plans of UK water providers is almost 50%, demonstrating the uncertainty and the high geographic variance of water demand Ritchie et al. (2021). As a result, there are few tools that can enable stakeholders to assess the likely costs and benefits of particular conservation and/or intervention measures (Marszal et al., 2021). There is a general consensus that the UK will probably experience warmer conditions and lower summer rainfall (Water UK, 2016, Ratajczak et al., 2021). Repeated occurrences of dry winters, prolonged lack of rainfall and lack of ground water recharge due to urban flooding, can lead to drought conditions which in turn increase the risk of water resources not meeting quality standards (Environment Agency UK, 2018). In Southeast England, a region already suffering water stress, summer precipitation is projected to decrease by 9% by the 2050s (Water Wise, 2021). Droughts have severe impacts on societies, economies, and agriculture and forward planning is critical for managing the potential impacts of drought. Continued lack of rainfall can lead to temporary water restrictions imposed by water providers on non-essential uses such as garden watering and car washing. A few studies show that temporary use bans (TUBs) can decrease consumption by over 30%, especially for high water users (Harald et al., 2021). In parallel, UK water providers have been launching domestic water efficiency initiatives over the past ten years and recent research has shown that there is scope for substantial water savings if the programs are focused on certain groups such as smaller and financially stretched households (Manouseli et al., 2017). However, little is still known about householders' response to drought or water efficiency measures in the UK and there are few if any studies which incorporate this evidence into models of demand forecasting in support of operational decisions about the most likely cost-effective drought management measures.

The water industry collects, treats and supplies more than 16 billion litres of water every day for domestic and commercial customers in the UK. Of this, about 6 billion tonnes are put into the public water supply. Electricity generation uses 9 billion tonnes, industry 2.1 billion, farming 0.2 billion, and other uses, such as fish farming, account for the rest (Waterwise, 2021). According to Future UK climate projections, annual average precipitation across the UK may decrease slightly, by between 0 and 15% by the 2080s CEPA (2021). This is quite alarming to know that the UK has less available water per person than most other European countries (Eurostat Water Statistics - Planned article, 2015). This is even more stressful in the Southeast of England as the most water stressed region (Environment Agency, 2018). Waterwise (2021) reported that nearly 52% of all public water supply is used at the household level. Household water and energy demands have been increasing since the 1950s, due to population growth and changes, household formation and development and lifestyles leading to increased pressure on water supply and resources system. Household water use, the single largest component of mains water use, is the focus of many water efficiency initiatives, particularly in the more densely populated and water-stressed areas of the UK. In the UK, the average person consumes approximately 150 lit/day of potable water for personal uses.UK government has a target of reducing water consumption by 20% per person by 2040 Water UK (2021). Energy Saving Trust (2020) has discussed this vision through cost effective measures, and reduced consumption to an average of 130 litres per person per day by 2040, or possibly even 120 litres per person per day depending on new technological developments and innovation.

Total energy consumption in the UK is already six times what it was in 1950 and is projected to grow by as much as 55% by 2040 as the combined effect of population growth and the improvement of living standards (Energy Saving Trust, 2020). The energy used in homes accounts for more than a quarter of energy use and carbon dioxide emissions in the United Kingdom and heating energy is by far the biggest slice of UK household energy use (Department for Business, Energy & Industrial Strategy, 2021). Studies by Dongwoo et al. (2021) has highlighted the directive set by EU in 2019 to reduce primary energy consumption by 20% by 2040 against business as usual projections through building renovation, Combined Heat and Power Plant and National Energy Efficiency Action Plan. In line with this, Department for Business, Energy & Industrial Strategy (2021) has set the target of 196 tWh energy saving in 2040, equivalent to 22 power stations, through socially cost-effective investment. That is around 11% lower than the business as a usual baseline (i.e.1990). It could also reduce carbon emissions by 41 $MtCO_2e$, contributing to achieving the carbon budgets.

Water and energy tariffs and price and affordability consumers have always been discussed. In 2020-21, the average combined bills for water companies ranged from £652 (Severn Trent Water, 2021) to £949 (Southwest Water) (Ofwat, 2021). According to Ofwat (2021) - Department for Work and Pension's Family Resources Survey (2018-19), has found that 33% of households in England and Wales spend more than 3% of their income on water and sewerage bills and 18% spend more than 5% on their energy bill. Also, the average annual electricity bill for all households monitored in the English Housing Survey Energy report (2019-20) was around £841 (at 2019 prices). This was 16% higher than the UK national average, costing on average an extra £120. Considering the fact that over 62% of water usage and over 60% of the energy used to heat water in domestic sector takes place in the bathroom area. Consequently, water saving is important not only due to water scarcity, the decline in recourses, and increase in demand, but also due to the fact that embedded energy in everyone litre of the water supplied in the household is 3.186 kJ and equivalent to 0.4 g of CO_2 emissions (Energy saving trust, 2021).

Water utilities face the challenge of becoming more energy efficient. Energy is the highest operating cost item for most water and wastewater companies. High energy consumption is inextricably linked to climate change. Climate change confronts the water sector with the need to optimise energy use and limit greenhouse gas emissions from their operations (Marszal et al., 2021). Energy efficiency can be achieved by saving energy but also by the recovery of energy from wastewater (Ritchie et al., 2021). It is also expected that climate change will cause scarcity of water in many countries, due to the forecast reduction in rainfall or the alteration of its regime. Population growth, increased consumption and urbanisation will also place increased pressure on water management. Nowadays, cities are highly dependent on external resources, while overlooking local possibilities of self-producing resources by cascading, recycling and recovering. For instance, rain and wastewater are seen as a nuisance and as such is removed from cities instead of valuing its potential as a local resource to optimise the urban water cycle. For reasons of sustainability, new concepts are under development to reuse or recycle grey water or to use rainwater. Extensive environmental benefits will also result from a reduced demand on water resources and, where grey water is used, reduced volumes of wastewater going to the sewer (Gelazanskas and Gamage, 2015; Kalantari, 2020).

At the bathroom level sustainability can refer to saving of water, materials and energy in the supply of water to a bathroom, to reuse or recycling of wastewater and rainwater and to recovery of heat and resources from wastewater. To study these concepts of sustainability, understanding the cold and hot water demand of a building on the fixture level or in the characteristics of the drainage loads is required. This knowledge is used for a design of installation and heater capacity based on realistic water demands to have sustainable and energy-efficient designs. Moreover, the information on the fixture level is needed to calculate the desired quantity of grey water for a building (for example to flush the toilets and for irrigation) and the amount of grey water leaving the building (from sinks, dishwasher, bath, and shower). The quantity and quality of the drainage loads, as temperature and concentration of nutrients, are required to study the recovery of heat and resources from water leaving the building through the sewage system.

There are far more interactions between water and energy than it might appear at first glance, water and energy are intrinsically linked. Energy is required for water and wastewater distribution, usage and treatment. Water and wastewater contains energy and water that is directly and indirectly necessary for energy conversion (Kalantari, 2020).

Nevertheless, bathroom water and energy management system can result in high consumption of significant quantities of water and energy (Gelazanskas and Gamage, 2015). This arises because of the linear approach that has been and generally used today especially in the bathroom and there is no significant effort to convert them into a recovery and recycle system which makes optimum use of water and energy in the bathroom to meet evolving needs as this can significantly reduce the quantity of water, be energy neutral and recycle great quantities of nutrient from the system (Kalantari, 2020). The result will be improved public health through reduced water abstraction, environmental discharges, reduced energy consumption and an easier system to upgrade and expand as technologies exist to accomplish this goal.

1.1 Solar Thermal Systems

For an average dwelling in the UK, solar thermal systems can possibly offer up to 70% hot water for domestic needs as well as space heating and consequently make a substantial difference in domestic energy usage (Benjamin and Adisa, 2014; Gelazanskas and Gamage, 2015). Subsequently, Zarei (2020), and Fayiah et al., (2020) considered the nexus between space heating demand and water heating requirement in highly insulated homes and indicates that a decrease in the demand for space heating increases the significance of water heating necessities and are comparatively constant which hinge on the behaviour of occupant. Likewise, water heating in the household usually requires a range of temperature between 50ºC to 60ºC compared to space heating demand which ranges between 20ºC and 22ºC. Study from Water Wise (2021) over a year period demonstrated that solar heating technology provided 57% of energy input to the heated water chamber and saves a considerable 1,850 kWh/year in fuel in comparison high efficiency gas condensing heater.

Research studies by Kalogirou (2004), Aisa and Iqbal (2016) have given some specific metrics and frameworks in determination of environmental sustainability for solar water heating systems, and this was demonstrated by comparing primary energy consumption, greenhouse gas (GHG) emissions, energy and emission payback times with conventional water heating systems. Albeit, the author also examined other environmental impact for solar thermal systems that has not been studied in-depth. As part of the objective of this study, it will demonstrate the capability of solar water heating in the UK to reduce energy usage, cut down GHG emissions, and subsequently, reduce the total dependence on non-renewable energy sources. The utmost environmental advantages are seen when solar substitutes a badly environmental performing heating supply alternatives, for example, oil and electric heating systems and these systems are mostly commonly used and encouraged by government (Marco et al., 2020).

1.2 Problem Statement

Increased energy consumption and demand, maintenance and upgrade costs and ageing infrastructure, drive the need to improve energy management in order to build up energy efficiency and resilience. Additionally, increased demand for fresh water, increased cost of treating water and aging water infrastructure drive the need to more efficient management of water resources. According to report from Eurostat (2021), total energy consumption is projected to grow by as much as 55% by 2040 as the combined effect of population growth and the improvement of living standards. The combined effect in a business as usual scenario might have outstanding effects over the environment and will put at risk maintaining the economic and social. Therefore, saving water can reduce the water bill, the energy use and bills, reduce the impact on local environment, and reduce carbon dioxide emissions by using less energy to pump, heat and treat the water. Within cities, households (groups of people living together) deserve particular attention because households are a major building block of cities. Several studies have demonstrated that the heating of water within households dominates energy use of the residential water cycle (Energy Saving Trust, 2021; Gelazanskas and Gamage, 2015; Menneer et al., 2021).

In the UK, a great many households are already making savings and making a difference – engaging in water saving behaviour, cutting their bills and conserving resources. But since the average home uses nearly 360 litres of water every day, there is still astonishing potential to save water, energy and utility bills through further change. According to Water UK (2021), showers, lavatories, baths and bathroom sinks consume more than two-thirds (68%) of household water. On average, 60% of a household's energy bill relates to heating water for showers, baths and hot water taps. This is on average about £940 a year. As a result, heated water contributes a lot to energy bills, while bathroom uses the hottest water in the home, and so it is the responsible for the most water-related carbon emissions. The energy used to heat water for devices and appliances emits an average of 875kg of CO_2 per household per year.

However, the energy consumption of water heating systems has not achieved concurrent efficiency improvements. Hence, water heating now makes up almost one-third of the energy consumption in high-performance homes. Many conventional water heating systems waste energy and water and are plagued by insufficient capacity and long wait times for hot water. Homeowners often compensate for these inefficiencies by raising tank temperature, increasing tank size, or lowering expectations of system performance. Although some advances in the efficiency of water heating equipment and distribution systems have been made, a systematic approach to high performance water heating design remains to be established. A high performance water heating system is one that is energy efficient, has sufficient capacity to meet household needs, delivers hot water quickly to the point of use, and wastes little water. Although many studies have examined the components of water heating systems, little has been done on integrated system design and holistic performance optimization. An integrated systems approach to water heating design examines all aspects of the design including preheating the cold water supply, heating water efficiently, delivering hot water to fixtures quickly, providing sufficient capacity of hot water, and reducing the amount of wasted energy and water.

Therefore, the challenge that how a combined water and energy saving unit in the bathroom will contribute in sustainability of the houses remain unresolved.

The three bottom line principles of sustainability namely, economic, environment and social is significant in considering the sustainability of bathroom systems; however, the real issue confronting bathroom user with respect to the three bottom line principles of sustainability is whether human action is sustainable. For this study, the bathroom system is regarded as sustainable if:

- The system considers the three pillars of sustainability namely; environment, economic and social. Whilst this study will focus on the three arms of sustainability, it will however concentrate majorly upon the strong sustainability aspect of the system and, or

- The most efficient means for re-establishing the system to sustainability may necessitate change in the system. In other words, combining both the renewable and smart/ intelligent system as a unique system for the sustainability of the system which in turn improves the human adaptation of the wellbeing of the users.

1.3 Aim

This study aims to challenge and extend existing knowledge on sustainability by developing/introducing a theoretical sustainability framework for a smart bathroom unit by combining energy and water saving technologies.

1.4 Objectives

- To conduct comprehensive literature review of sustainable-based smart energy-water saving bathroom unit with holistic approach.
- To develop a holistic modelling for a sustainable-based smart bathroom unit.
- To use computer model to investigate the performance of the solar based bathroom hot water heating systems.
- To assess the economic impact of the renewable-based system.
- To develop and validate the theoretical framework resulting into overall sustainability of the bathroom system.

1.5 Research Questions?

- How does the application of renewable energy technology in smart bathroom unit improve the energy consumption and carbon emission?
- How does the application of fuzzy logic control improve the performance of the model developed by saving more water, energy and providing thermal comfort?
- Can bathroom performance achieve overall sustainability (environment, social and economic) by implementation of smart energy and water saving technologies?

1.6 Hypothesis

A smart and sustainable bathroom performance can be achieved with the implementation of appropriate smart alternative technologies and control systems in the bathroom.

1.7 Research Sustainable Theoretical Framework

The research sustainable theoretical framework designed for this study to efficiently solve the research problems is revealed in Figure 1. 1

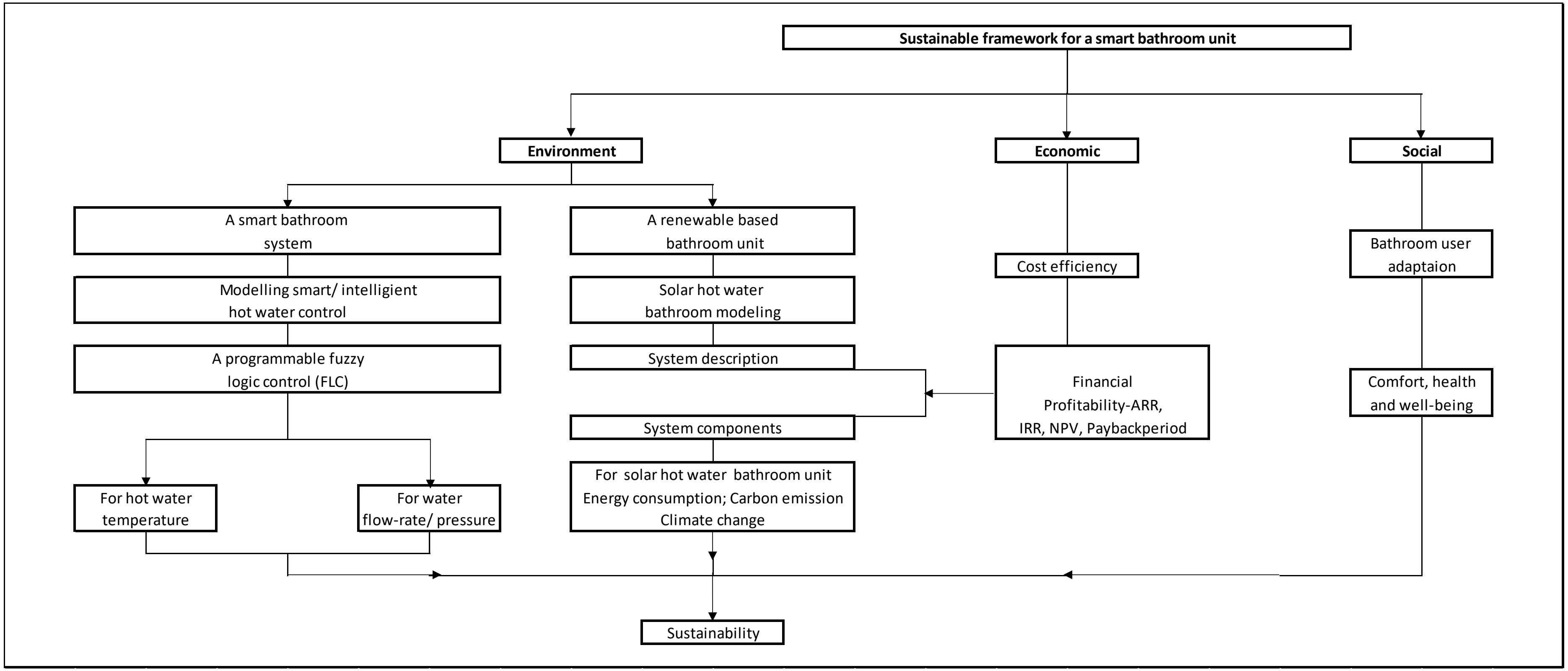


Figure 1. 1: Research theoretical framework for sustainable smart bathroom unit

Figure 1.1 provides a schematic representation of the proposed conceptual framework for sustainable smart bathroom unit. The aim of the framework is to demonstrate the linkages between the key elements that are proposed as important for improved smart sustainability assessment practices. These are renewable development, smart sustainable development, and dynamic systems approach. Pairing these elements improves the understanding of their interaction. On the other hand, integrating the three elements provides the foundation for sustainable smart bathroom unit in this study.

Correspondingly, the proposed framework is subsequently enhanced by the three pillars of sustainability i.e., environment, social and economic which in turn describes the basis of sustainable smart bathroom considered in this study. Here, the theoretical framework of the proposed system is thoroughly designed by way of the adaptation strategy of the three bottom line principles of sustainability as emphasized by Bell and Morse, (1999); Moir and Carter (2012); Dreby and Lumb (2012) - where the environment is technically influenced by both the social and economic sustainability. Therefore, moving from top-to-bottom, this in turn indicates sustainable environment for sustainable-based smart bathroom.

1.8 Thesis Structure

The thesis report is structured as follows:

Chapter One: This chapter includes a clear introduction to the background of the study, the logic behind the proposed research and the purpose of the study, the hypothesis of the research, the aims of the research, the objectives of the research, the research methodological sustainable theoretical framework and the structure of the research.

Chapter Two: This chapter consist of a critical appraisal of previous research and publications carried out on sustainability and bathroom unit. It focused on water and energy nexus in the bathroom; how water and energy depend in each other, water and energy efficiency, sustainability, and sustainable development. This chapter also revealed existing issues in the bathroom and the system sustainability strategy by way of revealing the three bottom line principles of sustainability namely, environment, social and economic that is connected with the bathroom sustainability. The system sustainability study strategy revealed action strategy for achieving the overall sustainability of the bathroom system. A further study is suggested on requirement for renewable-based bathroom and smart/intelligent computational control technologies for bathroom unit.

Chapter Three: The chapter focused upon on different technologies have been used to reduce the required energy for bathroom operation. Individual components like a solar collector, heat pump, and heat exchanger, tanks that are instrumental in achieving the efficient energy savings and carbon emission in the bathroom. This chapter also emphasized on different previous studies on solar water heating and how each of this author came about improving solar collector performance, storage tank thermal performance, heat pump and how to manage the hot water usage pattern in reducing energy and carbon emission. Furthermore, a smart control for the bathroom system is designed to use the fuzzy logic controller, it was used because of it is easy adaptability to the bathroom users' pattern. Studies was done on how control execution is mostly founded on accurate determination of fuzzy. Discrepancies in gaps and options in the study area are scrutinised and are employed as the source for the research thesis modelling approach.

Chapter Four: This chapter focused on the adoption conceptual approach and how it can design and implement a bathroom unit that is environmentally sustainable and smart. The conceptual modelling of the bathroom unit is meticulously studied and each component of the system which is in accordance with the manufacturer's specifications were presented. The chapter also focused on the actual system components that were examined and applied as a basis for the system's description in this study. The holistic designed system assumes three flat plate solar collectors, a solar heat exchanger, a pre-heating water storage tank, a main hot water storage tank with natural gas fired water heater, mixing devices and two circulators to collectively improve the overall system efficiency with necessary optimization while achieving substantial energy savings and carbon reductions and tackling global warming climate change were also presented. Parametric analysis was also conducted to know how change in variable parameters, location, load and switch-on temperatures will affect the performance of the system designed.

Chapter Five: The simulations are systematically carried out on the platform of Polysun and MATLAB Simulink respectively, which is theoretically grounded upon the conceptual modelling of the smart bathroom unit. The developed model in Polysun software was assessed based on energy and environmental performance indices (solar fraction, energy supply or yield, total energy consumption of the system, primary energy savings, system performance and efficiency, reduction of carbon emissions) in order to depict the fundamental ideology of sustainability. Parametric study was conducted, and the results shows effects of locations arise because of the differences in solar radiation. Three different climatic locations were analysed, locations with much radiation was found to have better performance over the reference system. The switched-on temperatures of the auxiliary heating system and the volume of hot water use were also a function of the performance of the system. The result obtained in chapter three was also validated internally.

Chapter Six: This chapter reveals the economic assessment of the proposed system by means of calculating the accounting rate of return, net present value, payback period and the internal rate of return – the financial profitability of the system. The advantages and drawbacks of each financial assessment indicators are subsequently considered for proper assessment of the system. The financial profitability of the system is analysed and discussed while considering the economic sustainability and profit of the system. For this chapter demonstrates how significant savings can perhaps be achieved through utilising economically sustainable and renewable means of technology - the solar bathroom system.

Chapter Seven: This chapter offers the discussion and framework validation of the study. It systematically begins with the conceptual issues of sustainability that informed the studies, followed by the sustainable framework assessment and application of sustainability that fundamentally adds to the knowledge base of the system through the theoretically developed framework. This chapter also presents some insightful suggestions proposed by researchers and addresses some deficiencies in previous studies. It also examines the implication of the environment, economic and social sustainability which forms the sustainable framework principles of the study. The penultimate section of this chapter presents the outcome of the semi-structured interviews with the system experts, used to externally validate the proposed framework.

Chapter Eight: This chapter presents the overall conclusion of the study. It systematically summarizes the entire study and reviews the stated research objectives. This chapter also details the main findings from the study and discuss their implications on sustainable theoretical framework. It also presents the contribution to knowledge of the study and recommendation for future studies.

Chapter Two

2.0 Literature Review

2.1 The Water Energy Nexus

Water and energy are two of the most important elements of modern society. The interrelationship between water and energy lies on facts that energy generation requires abundant water input and the water supply also necessitates non-trivial energy input. The water-energy nexus has received gradual attention since the 1990s. Gleick (1994) reviewed the myriad connections between our demand for and use of energy and water. As he describes, ‘energy and freshwater resources are intricately connected: we use energy to help us clean and transport the fresh water we need, and we use water to help us produce the energy we need’ (Gleick, 1994). Following this concept, we can dissect this nexus into two aspects: energy for water (EFW) and water for energy (WFE). Water and energy systems are both essential to modern life, and inextricably linked (Norouzi and Kalantari, 2020). If a city’s energy system fails, for example, the reliability of water services quickly plummets, posing a threat to public health and safety (California Energy Commission 2005). Energy used to deliver water around the world uses an estimated 7% of the world’s energy (James et al. 2002), which highlights the importance and impact of water consumption on energy use. From the energy perspective, water is integral to electricity generation in the industrialised world. In Australia, water-based thermal processes form a significant proportion of the energy mix and water scarcity is increasingly leading generators to turn to recycled water as an alternative reliable source (Orchison, 2008 and Zarei, 2020).

Current concerns about population driven increases in demand for water and energy and the associated environmental impacts of excessive water withdrawals, wastewater discharges and greenhouse gas emissions are catalysing research towards better integration for water and energy services (Zarei, 2020, Norouzi and Kalantari, 2020). Improved integration of water and energy systems will enable these concerns to be addressed in more cost-effective ways with more sustainable outcomes (Fayiah et al., 2020). Understanding the connections between water and energy services is a necessary first step to better integration in planning. While some studies adopt a systems perspective to explore the interactions of all urban infrastructure services, others adopt particular sector perspectives which can lead to increased integration within current institutional structures.

On-going discussions on the water-energy nexus have identified interconnectedness in four dimensions, physical, environmental, economic and social (see Table 2.0).

Table 2.0: Four Dimensions of the Water-Energy Nexus (Zarei, 2020)

Water-Energy Nexus	
Physical	• Water input for fossil fuel production and electric generation • Energy input for water supply, treatment and distribution.
Environmental	• Energy production often affects water quality • Environmental burdens on production areas
Economic	• Dynamic relationship between cost and demand • A strong motivation for change
Social	• Water, energy and food security • Social and environmental justice within and across regions

Physical Dimension

The physical interconnectedness of water and energy is the fundamental element of the nexus. Most of the previous studies focused on exploring the detailed linkages and quantifying the physical connections. In the energy-for-water (EFW) aspect, energy, in the form of electricity, is an essential input for the entire life cycle of water supply. Electricity is needed to abstract water from ground and surface sources, and move or lift water for distribution and allocation, eventually carry it to the end users. Also, energy is required to process the raw water to meet the drinking water standard. It is worth noting that desalination, a process that removes salt from water, is the most energy-intensive and expensive option for treating water (IEA, 2012). In the water-for-energy (WFE) aspect, water is required for practically every step of energy production.

Generally, water input for energy takes place in two stages. The first one is water for fuel production. For fossil fuels, water is used in resource extraction, mining, fuel refining and processing, and transport (World Energy Council, 2012). The second process is electricity generation, where water serves for cooling and other process-related needs at power plants. It is estimated that electric power plants account for approximately half of the industrial water withdrawal globally (Davies, et al., 2013). Thus, the energy sector can be highly vulnerable to changes in water resources. In water-scarcity regions, the lack of water for cooling and chemical processes may constrain local energy production.

Environmental Dimension

The second dimension of this nexus involves with environmental concerns. Energy production process can affect the quality of water used. Water quality may be degraded at every step of the fuel cycle, from mining, extraction, refining, to combustion. Not only fossil fuels themselves are significant water contaminants, the chemicals used to process and refine these fuels also pose huge threats to water quality (ADB, 2013). Wastewater from mining operations, boilers, and cooling systems may be contaminated with heavy metals, acids, organic materials, and suspended solids (Gleick, 1994). Even the discharge of waste hot water from power plants' cooling systems can adversely interrupt aquatic ecosystems by increasing the temperature of rivers and lakes (U.S. Department of Energy, 2006). Some studies have pointed out the intensive use of pesticides and fertilizers to support the expansion of bioenergy will have negative impacts on water quality, as well (Gheewala, et al., 2011). The emergence of shale gas has also added extra concerns on aquifer contamination by chemicals added during the hydraulic fracturing process, such as benzene. This process affects the underground water quality. (Asian Development Bank, 2013). However, while many studies have recognized such water-quality impacts (Bartos et al., 2014), few of them have expanded their analyses into detailed water contamination measurement or control.

Economic Dimension

The economic interrelationship between water and energy is now emerging as another critical component of the water-energy nexus. The physical linkages of the two lead to interplay at the economic dimension, i.e., the dynamic relationship between cost and demand. The price of energy has a direct influence on the cost of water production, hence the water price; and vice versa. Such influence is extremely crucial for water production since the cost of energy usually constitutes the largest share of the total cost of water supply. Lofman et al. (2002) describe how price reflects the amount of energy required to move water from the source to the consumer. Studies found that unit pricing of electricity can affect the groundwater use efficiency and productivity positively (Kumar, 2005). More importantly, economic pressure often acts as a stronger motivator for change when facing environmental issues (Bazilian, et al., 2011). Acknowledging this point, an increasing number of studies started to explore the economic linkages of water-energy and draw policy implications.

Social Dimension

Since water and energy are fundamental resources for a society, the links between the two inevitably interact with various social segments. First, the recognition of the nexus offers a comprehensive approach to reassess water, energy, and food security, and contribute to the well-being of the poorest and vulnerable population (Bazilian, et al., 2011; Bizikova, et al., 2013). Furthermore, the issues of the water-energy nexus become more urgent under the context of climate change. The impacts of global warming on freshwater availability, food production, energy generation and ecosystem pressure us to reconsider the invisible and long-ignored interconnectedness of water and energy (Chandel, et al., 2011; Scott, 2013). In addition, the social element of the water-energy nexus involves social and environmental justice issues associated with resource allocation. The trade-offs between different users need to be addressed at and across the local, national and transnational scale (Middleton, et al., 2015). Overall, it is significantly important to develop a holist approach to manage these two essential resources in a broader social context. Increasing the social recognition and public acceptances towards conservation, energy efficiency, and alternative water or energy solutions can prepare us for future challenges (Hamiche et al., 2016).

Nexus-Oriented Strategy

This section will link the discussion of sustainability with the emerging concept of water-energy nexus and explore the implication of the water-energy nexus in achieving regional sustainability. As mentioned earlier, strong sustainability calls for a self-sufficient system featured with qualitative improvement, decentralization, and local empowerment, etc. When it comes to water and energy resource management, these features imply an alternative strategy that challenges our current conventional system (Middleton, et al., 2015). Targeting at all the limitations with the current system, this thesis promotes a shift from a conventional approach towards the water-energy nexus-oriented strategy. The latter can be more effective in promoting sustainable resource stewardship and long-term stability and reliability of water and energy system. Figure 2.0 highlights the key features of such a shift.

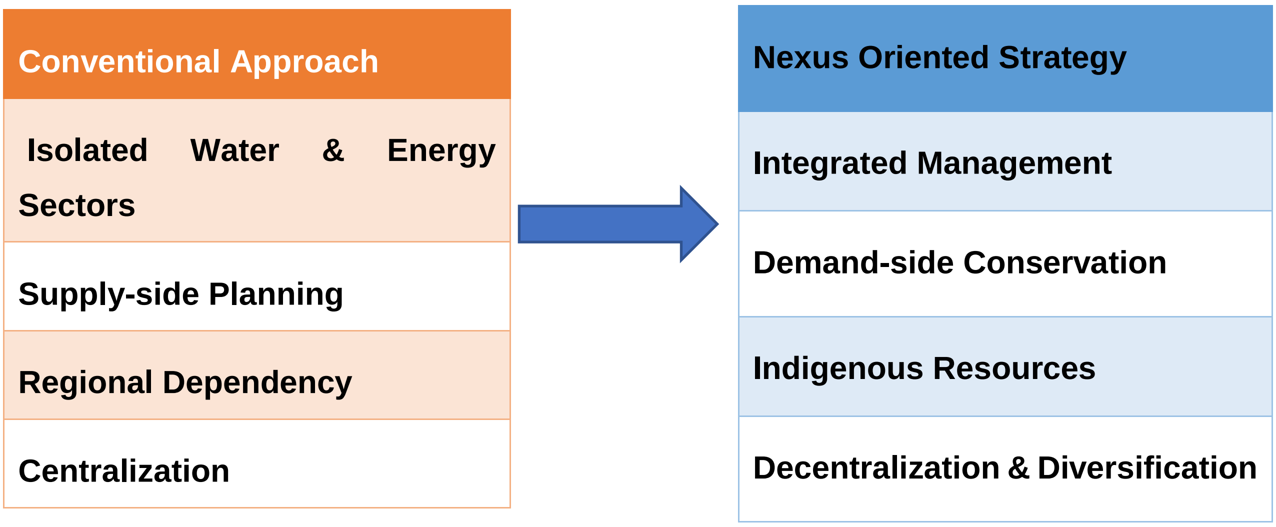


Figure 2.0: Nexus-Oriented Resource Management (Middleton et al., 2015)

First and foremost, the water-energy nexus calls for integrated management of the two. In most countries and regions, water and energy are currently managed totally separately. Each sector has its own administration agencies, with no or little (if any) overlaps. The limitation of such isolation is evident. As water and energy are essentially connected, overlooking each other can cause various problems. A recent study of Ceres (2020) found that 57% of the wells for hydraulic fracturing in the U.S. were located in water stress regions, including Texas, Colorado, Oklahoma and California. It is important to avoid such short-sighted decision-making by bridging the two sectors from administration level and technical level. Integrated management can provide insightful guidance on future energy and water planning. Making water-smart choices on energy options, such as switching water-efficient technologies, like PV, solar collector and wind power, could help avoid or minimize energy-water collision in the future and render a stronger power system (Fthenakis & Kim, 2010; Rogers, et al., 2013). Similarly, when putting forward water strategies, it is important to consider any foreseeable energy constraint. For instance, applying seawater desalination at a large scale in countries with limited energy supplies would trigger water-related energy challenges (Siddiqi et al., 2013). Such nexus-oriented thinking is of particular importance when water or energy is partially or seriously limited in quantity or quality, as choices about both energy and water supplies will be far more difficult (Gleick, 1994).

The second implication of the water-energy nexus is the need to go beyond the supply-side planning and to adopt demand side conservation as the priority. Current water and energy sectors are mostly supply-oriented; if there is demand, supply will be made available. It is only legitimate when it comes to serve basic human needs. However, in our modern world, incremental demand often comes from overconsumption. It is impossible to satisfy our endless appetite with the limited water and energy resources. Thus, the new alternative system urges to combine the traditional supply-side planning with demand-side management to develop integrated resource planning (IRP). Demand-side management is no news to water or energy policy makers. Through demand-side programs, the energy utility can improve their grid reliability during peak hours and avoid the need to build additional power plants. Furthermore, the synergic effect of water-energy nexus-saving water to save energy and saving energy through saving water--introduces more incentives to do so. Studies provide strong evidence that significant opportunities for energy savings exist through water efficiency and conservation, and vice versa (Wang et al., 2015). For example, Wang et al. (2015) estimated that, through the implementation of Energy Efficiency Resource Standards

(EERS), three Mid-Atlantic States in the U.S. could save 20% of its in-state water consumption by 2035. More importantly, this enormous synergic effect has been underexploited in many countries. It is also widely noted that conservation programs require much less time to plan and deploy than building infrastructure works, making the savings through water-energy conservation the 'low-hanging fruit' (Pitzer, 2009).

Another feature of the nexus-oriented system highlights the key role of indigenous resources. Resource transfer has become a popular solution to deal with regional resource shortage. In the energy field, a mature international market has been created to move fossil fuels around the world, along with countless regional and subnational transportation networks. In the water field, the water transfer has emerged to be a new type of water source. Although water resource by its nature often stays within its local system, engineering projects were put into place to overcome the natural boundary of water area. The water-energy nexus addresses such cross-boundary exchange of resources by adopting the concept of virtual water and embodied energy. It offers a different perspective to assess energy trading or water transfer in terms of water-energy security and environmental equity (Wang et al., 2015). To be specific, the virtual water transfer, associated with inter-regional energy trade, shifts the available freshwater away from energy exporters and place the environmental burdens on energy-producing communities. Such 'indebtedness' not only leads to additional environmental cost and environmental degradation in exporting communities but would also affect the local resiliency in resource importing areas. Thus, nexus-oriented strategy encourages the use of localized sources and the reduction of regional interdependence. As a matter of fact, many populated cities in different countries, such as Berlin, Orange County, Singapore, Seoul, Tokyo, have already started to embrace the idea of water self-sufficiency by adopting water planning, water recycling and rainwater management, and desalination (Rygaardm et al., 2011). Areas, like California, are leading the transformation towards energy self-sufficiency by promoting conservation and renewable energy.

The fourth key element of nexus-oriented strategy is to promote decentralization and diversification. Current water and energy systems are dominated by centralized supply, following the conventional wisdom of 'bigger is better'. It is believed that larger projects can lower the unit cost of supply because of economies of scale. Although such theory attributed to the success of large fossil fuel power plants in past decades, the revolutionary progress of renewable energy opened up a new era of ‘thinking small’. Nexus-oriented thinking suggests that a more decentralized and diversified system works better than this centralization model. A decentralized system can be tailored to satisfy the unique local need while utilizing local resources. For instance, instead of relying on outside power production, small-scale renewable power plants can be sited next to the users, cutting off the transmission loss and need for transmission capacity. Furthermore, introducing a diversified supply profile can improve the system reliability. Adding a variety of renewable sources into energy mix, instead of relying solely on a few types of fossil fuels, can increase the energy reliability and reduce the associated water need. This applies to the water sector, as well. Exploring the potentials of alternative water sources, such as direct utilization of seawater, rainwater harvest or water recycle, and water conservation as a new source, can offer some insights to increase system flexibility and decouple it from high energy input. As noted by Lovins (1977), the ‘hard path’ has caused so much environmental disruption and resource waste, it is time to focus more on a ‘soft approach’ that is more harmony with nature. Meanwhile, the decentralization process requires the support of a democratic political system, which empowers the local stakeholders, increases public participation, enables equal decision-making, and hence improves the policy adaptability (Engle and Lemos, 2010). Encouraging the transition towards a participatory governance is of particular importance to countries with a centralized command-and-control system, such as India and China (Lele et al., 2014).

2.2 Perspectives on the Water Energy Nexus

There are different perspectives from which the water energy nexus is considered, which illuminate different opportunities for increasing efficiency and reducing environmental impacts (Wang et al., 2015). The relationship can be viewed through the following key perspectives or ‘lenses’:

- The energy use of water infrastructure – focus on water service provision
- The water use of energy infrastructure – focus on power generation

- Energy and water as part of an urban system – analysis of overall system impacts or changes to energy or water consumption and provision.

The relationship can also be viewed from the perspective of scale, as some studies focus on the water and energy use of a specific technology or end use, while others have estimated the water and energy use across a whole state or country.

The perspectives outlined here consider the links between direct energy and water consumption (Energy saving trust, 2013). They do not include the energy and water embodied in material infrastructures which are considered in lifecycle analyses, as these are already covered extensively in literature (Middleton et al., 2015).

2.2.1 Micro Level Water and Energy Nexus

Studies on the water energy nexus at a micro scale are focused on the energy (and other environmental) impacts associated with a specific treatment technology or specific water end use, so that energy use is disaggregated. Life cycle analysis has been used to determine the energy and greenhouse impact of a number of water cycle elements including hot water heating, rainwater tanks and small-scale treatment facilities. The following review summarises the findings from a selection of these studies.

2.2.2 Energy Use of Household End Uses

Domestic Hot Water Systems Heating water accounts for approximately 16% of total residential energy consumption (Koomey 2011). Consequently, the conservation of hot water has a direct impact on energy use. In a U.S. study carried out by Koomey et al., (1994) the expected impact of water efficiency standards on water use and water-heating energy use were projected for the year 2010. The study was designed to determine the impact of water efficiency standards introduced in 1994. Data on end uses was based on the existing stock of toilets, taps, showerheads and dishwashers. For example, the average shower flow rate prior to the introduction of standards was

12.9 L/min. Standards introduced in 1994 meant that new showerhead flow rates were 9.5 L/min.

Estimates of the energy used by hot water heaters were carried out based on the energy content of the hot water used as well as the energy lost during hot water storage (standby losses). Energy saved due to water heater standards and water efficiency with hot water end uses such as taps, baths, showers, clothes washers and dishwashers were determined for the United States as a whole.

Studies has shown that hot water use in the United States in 2010 is approximately 9 billion m3/year (9,000 GL) and that the efficiency standards would be likely to save 1.2 billion m3 of this total (1,200 GL). The energy saved from electrical water heating was approximately 470 x 1015 J/year, while an additional 400 x 1015 J/year was saved from gas and oil water heaters (Koomey, 2011).

While in the UK, energy and water consumptions (and consequently carbon dioxide emissions) are two main pillars of the Code for Sustainable Homes which became temporary mandatory in the UK in 2008 however, currently it is implemented voluntary, partly due to lack of realistic technologies to achieve required sustainability levels. The code has six levels, level 6 representing a zero-carbon home and has played a significant role in improved sustainability of new-built houses in past few years. However, the property developers' focus for commercial reasons has been on achieving highest level with minimum cost and minimum negative experience by the end users. These included vastly in using efficient bulbs, appliances, fittings, taps, and high efficient heat insulations.

According to Communities and Local Government (2009), for water saving, the requirement for water consumption for various levels are as in Table 2.1.

Table 2.1: Maximum water consumption for various codes for sustainable homes

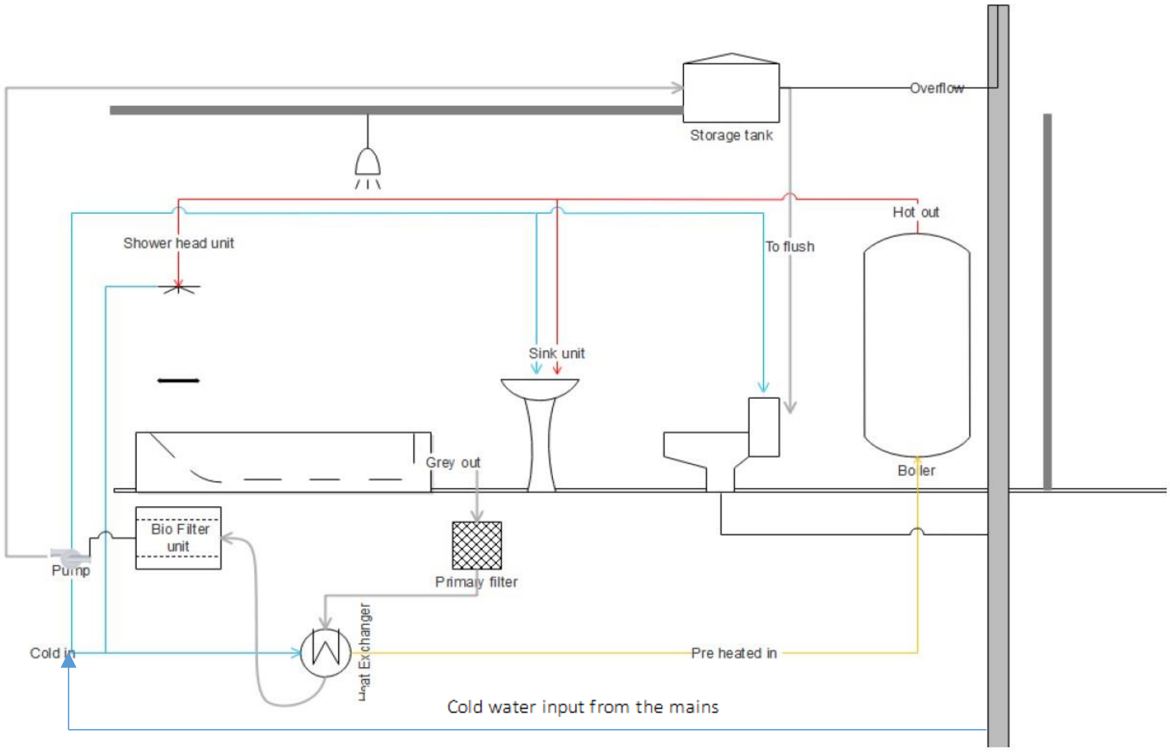
Code Level	**Maximum indoor water consumption in litres per person per day**
Level 1 (one star)	120
Level 2 (two stars)	120
Level 3 (three stars)	105
Level 4 (four stars)	105
Level 5 (five stars)	80
Level 6 (six stars)	80

Waterwise (2009) indicates that achieving level 1-2 is possible without extra cost for new developments by using a combination of standard and efficient fittings and appliances however although level 3-4 can still be achieved by using efficient water using fittings however this could add (for level 3) up to £240 to the cost of the new fittings. The same reference also mentions that achieving levels 5 and 6 will require some kind of integrated technological solution and could add up to £4500 to the cost of new homes. The report also indicates that greywater recycling has to be used for toilet flushing for the typical achievement of level 6 sustainable home. Waterwise (2009) also indicates that users are more acceptable of use of greywater recycling for toilet flushing than cloths washing however quality water saving products is important to ensure the performance of the system is acceptable to the end user.

2.3 The Bathroom System

A bathroom can be defined as an environment where sanitary and bathing process takes place and its operation requires hot water and cold-water supply. A standard bathroom consists of a room that has a sink/basin, toilet, and a shower regardless of whether a bathtub is present or not in the room. In reference to Energy saving trust in 2013, both shower and bathroom consumes the highest percentage of water i.e. 33% in a single domestic dwelling with, 22%, and 7% of water are consumed for flushing toilet, hot tap demand respectively, whilst a unit total of 62% of water is consumed in the bathroom

Also, a bathroom can be a room for individual user, or it might be a shared bathroom for use by more than one Individual. For instance, bathroom can also be considered as a room that have more than one sinks, toilet and urinals for use of more than a person. Although, despite the term bath is taken to incorporate different types of baths, including a shower bath, Steam bath, Sauna bath, or Swimming bath, this study will only consider the term shower bath. Therefore, a room containing just one showers will at present can be viewed as a bathroom regardless of whether there is no bathtub or other type of bowl in this room. In like manner, the expression "bath environment" alludes to the space around at least one-bathroom installations, For example, toilet, bathtubs, sinks, hot tubs, or just as the Space inside or around other bathing Spaces.



Colour codes: Blue – cold water input, yellow – preheated water, red – hot water

Figure 2.1: A schematic of a standard bathroom unit

The Figure 2.1 above shows a representation of bathroom unit appliances with their integrated operational connections. Potable/clean water in the bathroom are used for different purposes i.e., it is used in different types of showers (e.g. combi, electric, gravity feed, and the likes). The potable water is mixed with incoming hot water to regulate the water to the desired user temperature usually between 40-45 ^{o} C (Waterwise, 2009).

Basin is one of the outlets in the bathroom that is a regular user of water and consumes more of portable water, in past years in the UK, basin usually have separated hot and cold-water taps although mix taps have now since been introduced into the UK homes. This mixes hot water with cold water in the tap and the resulting outflow is regulated to the user-preferred temperature.

The toilet also is a major consumer of water in the bathroom and it consumes water in various volumes for flushing purposes. At present, there are different range of unit products (bath, basin, shower and toilet) that are obtainable in marketplace. They have various design, specification and prices also, they come with diverse level of operational efficiencies.

For a conventional bathroom unit in the United Kingdom, hot water is utilized for bathing, basin tap uses and showering. The hot water is usually heat up by boilers by heating up the inflow of potable water and the heated hot water for domestic and bathroom uses in separate tank, and this is retained in a big thank and distributed where and when needed (Waterwise 2014). There are numerous problems with boilers, for example, its excessive maintenance, weight, corrosion, size, fouling and energy consumption.

The amount of energy consumed in the bathroom is associated with the amount of hot water used (aside from lighting) for shower, basin. Electricity is often utilised to heat the cold water to the desired high temperature set by the user (40^{o}C – 45^{o}C). The Figure 2.2 below illustrates the input and its resulting output of a bathroom activity or operations, where the input are energy and cold water and output are blackwater (from toilet), greywater from bathtub, bath, sink and shower resulting to indirect GHG emission from energy and water consumption.

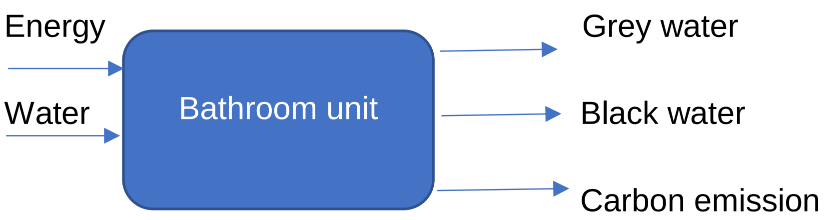


Figure 2. 3: Schematic of a bathroom unit inputs and outputs.

According to (Bathroom laboratory, 2018), there have been different argument and opinion about the operation and efficiency of bathroom appliances, although at present more energy and water efficient technologies and product have been introduced to the market to minimize water and energy consumption, grey/blackwater and GHG emission production.

2.4 Environmental Efficiencies in the Bathroom

This implies accomplishing more with less. It is a state wherein the need set to achieve environmental sustainability can be met without affecting its ability to enable all individuals to live well, presently for future generation (Evers, 2018). It is the process where renewable resources are been managed and harvested, non-renewable resources are being discontinued indefinitely in the bathroom, if they cannot be proceeded indefinitely, at that point they are not sustainable. The idea has turned into a main issue in discussions about sustainable development. Halliday (2008) realises that specific natural resources are depleted and are becoming rare, Haliday also emphasized and called for replacement of uncommon material with less uncommon or inexhaustible materials. Strong clarifications about the requirement for radical upgrades in the utilization of energy resources and materials have accomplished acknowledgment in policy circles. The contention is that efficiency improvement is important to limit impacts on capacity of natural systems to assimilate energy and waste material.

2.4.1 Energy Efficiency in the Bathroom

Early study from Ahmad, 2017 gave significant attention to the extremely growing demand for hot water in the bathroom and the associated cost of producing the heat to heat-up the potable water. The author also identified possible ways of decreasing the energy usage involved and the associated cost to produced energy, by recovering the energy from waste grey/black water that is released from the drain each day in the bathroom. This is subject to the amount of hot water that is diluted by the introduction of cold-water to give a user preferred temperature, the grey water is mostly channelled down the drain from temperature ranging from 35 ^{o}C − 55^{o}C. Taking into account that supply of hot water is mostly heated from 10^{o}C − 70^{o}C by the water heater, it is evident that roughly 70-80% of all hot water vividly truly goes down the drain (Watercycles, 2007). In response to this discourse, Eslam-nejad and Bernier (2009), Pomianowski et al. (2020) have considered the economic potential for waste heat recovery in terms of the availability of the waste heat and if the amount can meet the supplies of the heating loads. To recuperate heat from wastewater in the bathroom unit is difficult to accomplish in quality due to its low temperature range.

Heat recovery process aims to improve energy efficiency by collection and re-using of heat arising from any process that would otherwise be lost. Products and technologies are currently available that are used in a bathroom unit to capture the heat from greywater (from showering and basin uses). In heat recovery process, the incoming cold water flows first through a heat exchanger where it is pre-warmed by heat from greywater flowing down from showering or washing in the basin.

Although, according to Lana et al. (2020), highlighted that if the waste heat recovery system can recover more than 26-30% of heat from the wastewater into the potable water supply it could reduce related cost-rate to a sustainable minimum considering the extent of energy utilized during the heating operation. Attempts to reuse this waste heat could bring about substantial energy savings. Energy efficiency is the main purpose of heat recycling process that would one way or another be lost to the surroundings. Presently, there are numerous technological inventions and products that are obtainable in the marketplace for capturing energy from wastewater i.e., from basin and showering usage in the bathroom. Studies from Słyś and Kordana (2013) for instance said the appropriate user desired temperature for human body during showring process is normally at 40ºC and during the shower or basin usage process, about 5-10ºC is lost to the surroundings in the bathroom. Although in addition, heat recycling process will make the bathroom system more energy efficient and in-turn save energy bills, it will also contribute to the reduction of carbon footprint.

However, study from Markham (2014) have also projected that around 80 to 90% hot water used for daily activities usually goes to the drain as a final output. In the thermodynamics of heating and cooling, the cost needed to heat up potable water is perhaps one of the major expenses in the household, especially in the bathroom, greater part of this energy is being squandered by streaming heat down the drain to the outside surroundings. Collecting or recuperating energy from basins and showers are one of the possible ways to improve energy efficiency in the bathroom and save associated cost. Domestic drain heat exchanger and wastewater heat recovery are not new ideas or concept, though, due to installation and design limitation, it has not been really employed on a small scale and are mostly implemented on large industrial applications. According to Energy saving trust (2013), households emit an average of 875kg of carbon every year from energy used in heating cold water for appliances and devices in each dwelling. This emitted carbon gas is worth to be proportional to the emission produced by traveling in excess of 1,700 miles in a regular family vehicle. The bathroom has been estimated to be the principal user of hot water for domestic dwellings and it is accountable for the major water-energy associated emission of approximately 539kg.

2.4.2 Water Use Efficiency in the Bathroom

Study from Waterwise (2012) defined water use efficiency as the process of limiting the volume of water wasted daily and not impacting the consumer’s satisfaction based on its usage. The idea of saving water can be categorised in to indirect and direct water savings. Indirect water saving refers to the volume of water used from grey water recycling process whereas direct water savings aims to save water using technological process before its usage. Notwithstanding, both ideas have the similar purpose of decreasing fresh consumption of water in a bathroom unit.

Recent report from Waterwise (2017) highlighted different direct method, guidelines and technological appliances for water saving in the bathroom level. The guidelines and method emphasised by the author includes dual toilet flushing, stopping drips, shower fitters and so on. Although, these method/strategies do have their own restrictions and limits and may request changes to customer's way of life.

There are several smart technologies available in the market for toilet flushing. Essential parameters for the assessment of the smart technologies will incorporate – amount of water used per flush, cost, drainage system and pan clearance. For instance, the double push button in a twin flush toilet system enables the toilet user to choose and determine the amount of water to be utilized. Double flush toilets ordinarily use 4-6 litters of water for every flush when contrasted with 10-13 litres old conventional toilet system. A double flush can be introduced with siphon component or push-catch flush valve device. Envirowise (2009) have further made a comparison among push button flush valve device, siphon system, variable flush, interruptible flush, twin flush (push button flush valve system) and twin flush (siphon mechanism) based on its merit and demerit and have concluded that a siphon system is less expensive to retrofit, more efficient and have low probability of leakages. The push button system has a shortcoming of being not vigorous as the siphon system and have high possibility of valve leakages then leads to higher maintenance. Based on the conclusion from the author in terms of water savings for toilet systems, an interruptible flush siphon system and a double flush siphon system with a twin flush volume are the best obtainable to save water.

Literature reviews from Waterwise (2008) have uncovers various approaches to decrease the volume of water used in a domestic lifecycle. This approaches in general include:

1) A grey water mechanism that recuperates non-potable water or rainwater for irrigation purpose or dual plumbing designing to reuse or recycle water for flushing toilet. Grey water is an outcome of activities such as showering, bathing, hand washing and is not to be treated intensively as black/swage water as this can be reused or recycled in the bathroom for toilet flushing or for site irrigation.

2) Using efficient water plumbing fixture, i.e., low-flow showerheads, ultra-low flow urinals and toilet, water-efficient dishwashers, low-flow and sensored valve sinks to decrease the amount of wastewater output.
3) Harvesting rainwater utilizing grey water and rainwater storage for both toilet flushing and irrigation use can significantly limit the utilization of treated water. In actual fact, individuals in several districts of the world have severally depended on harvested rainwater for their water supply though this might not be the case in many advanced countries depending on household water harvesting policy.

2.5 Sustainable Development and Sustainability

Sustainable development has become the slogan in development discourse, having been associated with different definitions, meanings and interpretations. Taken literally, sustainable development is a “development that can be continued either indefinitely or for the given time period (Stoddart, 2011). Structurally, the concept can be seen as a phrase consisting of two words, “sustainable” and “development.” Just as each of the two words that combine to form the concept of sustainable development, that is, “sustainable” and “development”, has been defined variously from various perspectives, the concept of sustainable development has also been looked at from various angles, leading to a surplus of definitions of the concept. Although definitions abound with respect to sustainable development, the most often cited definition of the concept is the one proposed by the Brundtland Commission Report (Schaefer & Crane, 2005). The Report defines sustainable development as development that meets the needs of the current generation without compromising the ability of future generations to meets their own needs.

According to definitions from Cerin (2006) as well as Abubakar (2017) argue that sustainable development is a core concept within global development policy and agenda. It provides a mechanism through which society can interact with the environment while not risking damaging the resource for the future. Thus, it is a development paradigm as well as concept that calls for improving living standards without jeopardising the earth’s ecosystems or causing environmental challenges such as deforestation and water and air pollution that can result in problems such as climate change and extinction of species (Benaim & Raftis, 2008; Browning and Rigolon, 2019).

Sustainable development can be termed as an approach to development which uses resources in a way that allows them (the resources) to continue to exist for others (Mohieldin, 2017). Evers (2017) further relates the concept to the organizing principle for meeting human development goals while at the same time sustaining the ability of natural systems to provide the natural resources and ecosystem services upon which the economy and society depend. Considered from this angle, sustainable development aims at achieving social progress, environmental equilibrium and economic growth (Zhai and Chang, 2019). Exploring the demands of sustainable development (SD), Ukaga et al., (2011) emphasised the need to move away from harmful socio-economic activities and rather engage in activities with positive environmental, economic and social impacts.

It is argued that the relevance of sustainable development deepens with the dawn of every day because the population keeps increasing but the natural resources available for the satisfaction of human needs and wants do not. Hák et al. (2016) maintain that conscious of this phenomenon, global concerns have always been expressed for judicious use of the available resources so that it will always be possible to satisfy the needs of the present generation without undermining the ability of future generations to satisfy theirs. It implies that sustainable development is an effort at guaranteeing a balance among economic growth, environmental integrity and social well-being. This reinforces the argument that, implicit in the concept of sustainable development is intergenerational equity, which recognises both short and the long-term implications of sustainability and sustainable development (Stoddart, 2011). According to Kolk (2016), this is achievable through the integration of economic, environmental, and social concerns in decision-making processes. However, it is common for people to treat sustainability and sustainable development as analogues and synonyms but the two concepts are distinguishable. According to Diesendorf (2000) sustainability is the goal or endpoint of a process called sustainable development. Gray (2010) reinforces the point by arguing that, while “sustainability” refers to a state, sustainable development refers to the process for achieving this state.

2.5.1 History of Sustainable Development

Although the concept of sustainable development has gained popularity and prominence in theory, what tends to be neglected and downplayed is the history or evolution of the concept. While the evolution might seem unimportant to some people, it nonetheless could help predict the future trends and flaws and, therefore, provide useful guide now and for the future (Elkington, 1999). According to Pigou (1920), historically, sustainable development as a concept, derives from economics as a discipline. The discussion regarding whether the capacity of the Earth's limited natural resources would be able to continually support the existence of the increasing human population gained prominence with the Malthusian population theory in the early 1800s (Dixon and Fallon, 1989; Coomer, 1979). As far back as 1789, Malthus postulated that human population tended to grow in a geometric progression, while subsistence could grow in only an arithmetic progression, and for that matter, population growth was likely to outstrip the capacity of the natural resources to support the needs of the increasing population (Rostow & Rostow, 1978). Therefore, if measures were not taken to check the rapid population growth rate, exhaustion or depletion of natural resources would occur, resulting in misery for humans. However, the import of this postulation tended to be ignored in the belief that technology could be developed to cancel such an occurrence. With time, global concerns heightened about the non-renewability of some natural resources which threaten production and long-term economic growth resulting from environmental degradation and pollution (Paxton, 1993). This re-awakened consciousness about the possibility of occurrence of Malthus' postulation and raised questions about whether the path being chattered regarding development was sustainable.

Similarly, examining whether the paradigm of global economic development was "sustainable", Meadows studied the Limits to Growth in 1972, using data on growth of population, industrial production and pollution (Rostow, 1978). Meadows concluded that "since the world is physically finite, exponential growth of these three key variables would eventually reach the limit" (Meadows, 1972). However, several academicians, researchers and development practitioners (Dernbach, 2003; Paxton, 1993) argue that the concept of sustainable development received its first major international recognition in 1972 at the UN Conference on the Human Environment held in

Stockholm. According to Daly (1992) and Basiago (1996), although the term was not referred to explicitly, the international community agreed to the notion—now fundamental to sustainable development—that both development and the environment hitherto addressed as separate issues, could be managed in a mutually beneficial way.

Following these developments, the World Commission on Environment and Development, chaired by Gro Harlem Brundtland of Norway, renewed the call for sustainable development, culminating in the development of the Brundtland Report entitled "Our Common Future" in 1987 (Goodland & Daly, 1996). As already mentioned, the report defined sustainable development as development that meets the needs of current generation without compromising the ability of future generation to meets their own needs. Central to the Brundtland Commission Report were two key issues: the concept of needs, in particular the essential needs of the world's poor (to which overriding priority should be given); and the idea of limitations imposed by the state of technology and social organisation on the environment's ability to meet present and future needs (Kates et al., 2001).

Jain and Islam (2015) intimate that the Brundtland report engendered the United Nations Conference on Environment and Development (UNCED), known as the Rio Earth Summit, in 1992. The recommendations of the report formed the primary topics of debate at the UNCED. The UNCED had several key outcomes for sustainable development articulated in the conference outcome document, namely Agenda 21 (Worster, 1993). It stated that sustainable development should become a priority item on the agenda of the international community" and proceeded to recommend that national strategies be designed and developed to address economic, social and environmental aspects of sustainable development (Allen et al., 2018). In 2002 the World Summit on Sustainable Development (WSSD), known as Rio+10, was held in Johannesburg to review progress in implementing the outcomes from the Rio Earth Summit. WSSD developed a plan of implementation for the actions set out in Agenda 21, known as the Johannesburg Plan, and also launched a number of multi-stakeholder partnerships for sustainable development (Mitcham, 1995).

In 2012, 20 years after the first Rio Earth Summit, the United Nations Conference on Sustainable Development (UNCSD) or Rio+ 20 was held. The conference focused on two themes in the context of sustainable development: green economy and an institutional framework (Allen et al., 2018). A reaffirmed commitment to sustainable development was key to the conference outcome document, '"The Future We Want" to such an extent that the phrase "sustainable development" appears 238 times within the 49 pages (UNSD, 2018a). Outcomes of Rio +20 included a process for developing new SDGs, to take effect from 2015 and to encourage focused action on sustainable development in all sectors of global development agenda (Weitz et al., 2017). Thus, in 2012, sustainable development was identified as one of the five key priorities by the United Nations (UN) Secretary-General Ban Ki-Moon in the UN action agenda, highlighting the key role sustainable development should play in international and national development policies, programmes and agenda. Recently, the Paris Agreement came into power by legally binding international treaty on climate change. It was adopted by 196 Parties at COP-21 in Paris, on 12 December 2015 and entered into force on 4 November 2016. Its goal is to limit global warming to well below 2, preferably to 1.5^{o}C, compared to pre-industrial levels (UN, 2016). To achieve this long-term temperature goal, countries aim to reach global peaking of GHG emissions as soon as possible to achieve a climate neutral world by mid-century. The Paris Agreement is a landmark in the multilateral climate change process because, for the first time, a binding agreement brings all nations into a common cause to undertake ambitious efforts to combat climate change and adapt to its effects (UN, 2015).

2.5.2 Defining Sustainability

Literally, sustainability means a capacity to maintain some entity, outcome or process over time (Basiago, 1999). However, in development literature, most academics, researchers and practitioners (Tjarve, & Zemīte, 2016; Mensah & Enu-Kwesi, 2018) apply the concept to connote improving and sustaining a healthy economic, ecological and social system for human development. Stoddart (2011) defines sustainability as the efficient and equitable distribution of resources intra-generationally and inter-generationally with the operation of socio-economic activities within the confines of a finite ecosystem. Ben-Eli (2015), on the other hand, sees sustainability as a dynamic equilibrium in the process of interaction between the population and the carrying capacity of its environment such that the population develops to express its full potential without producing irreversible adverse effects on the carrying capacity of the environment upon which it depends. From this standpoint (Thomas, 2015) continues that sustainability brings into focus human activities and their ability to satisfy human needs and wants without depleting or exhausting the productive resources at their disposal. This, therefore, provokes thoughts on the manner in which people should lead their economic and social lives drawing on the available ecological resources for human development.

Hák et al., (2016) have argued that transforming global society, environment and economy to a sustainable one is one of the most uphill tasks confronting man today since it is to be done within the context of the planet's carrying capacity. The World Bank (2017) continues that this calls for innovative approaches to managing realities. In furtherance of this argument, DESA-UN (2018) posits that the ultimate objective of the concept of sustainability, in essence, is to ensure appropriate alignment and equilibrium among society, economy and the environment in terms of the regenerative capacity of the planet's life-supporting ecosystems. In the view of Gossling-Goidsmiths (2018), it is this dynamic alignment and equilibrium that must be the focus of a meaningful definition of sustainability.

However, as argued by Mensah and Enu-Kwesi (2018), the definition must also emphasise the notion of cross-generational equity, which is clearly an important idea but poses difficulties, since future generations' needs are neither easy to define nor determine. Based on the foregoing, contemporary theories of sustainability seek to prioritize and integrate social, environmental and economic models in addressing human challenges in a manner that will continually be beneficial to human (UNSD, 2018). In this regard, economic models seek to accumulate and use natural and financial capital sustainably; environmental models basically dwell on biodiversity and ecological integrity while social models seek to improve political, cultural, religious, health and educational systems, among others, to continually ensure human dignity and wellbeing (Acemoglu & Robinson, 2012; Evers 2018), and for that matter, sustainable development.

In recent years, the term sustainability has several widespread of definitions and have become a popular phrase in expressing environmental strategy and utilization of environmental resources. This issue has led to significant number of implications on what to include and what no to. Although in recent times, an acceptable definition has been agreed by authors in literature according to each academic discipline. Prior to any further review in this thesis, it is significant to have a working definition to be adopted to evaluate what is sustainable or not sustainable. Table 2.2 below is the most widely recognised definition in literature.

Table 2. 2: Different sustainability definitions according to authors

Authors	Sustainability definitions
Council of Academies of Engineering and Technological Sciences	*"It means the balancing of economic, social, environmental and technological consideration, as well as the incorporation of a set of ethical values".*
A Contribution toward Its Realization, Earth Chapter, 1995.	*"The protection of the environment is essential for human well-being and the enjoyment of fundamental rights, and as such requires the exercise of corresponding fundamental duties".*
Jenkinson, C.S,1978	*"Then I say the Earth belongs to each generation during its course, fully and in its right no generation can contract debts greater than may be paid during the course of its existence".*
Anna, 2017	*'' Development which meets the needs of current generation without compromising the ability of future generations to meet their own need''*

World Commission on Environment and Development (Brundtl and Commission), 1992	*‘’Development that meets the needs of the present without compromising the ability of future generations to meet their own needs”.*
UNESCO, 2009	*‘’A sustainable development is defined as a development that meets the needs of present users while protecting and enhancing opportunity for the future’’.*
Science for Sustainable Development Agenda 21, Chapter 35, 1992.	*“Development requires taking long-term perspectives, integrating local and regional effects of global change into the development process, and using the best scientific and traditional knowledge available”.*

All the above definitions have stressed an essential part of sustainability and have emphasized that sustainability can lead to effective use of natural resources in a way that environment, social and economic necessities can be satisfied while sustaining the biological diversity and ecological processes of everyday life. Regardless of whether there is some uncertainty in these definitions, it all suggested that the future generations must be left with enough resources to meet there on needs and to survive as well. Although, there is no clarity on the amount of the resources to be used at present as this makes it difficult to foresee future situations.

The Idea of sustainable development includes environmental, economic and social viewpoints from environmental conservation to climate change. The World Commission on Environment and Development (Brundtl and Commission) in 1992 grounded the definition of sustainability on moral equity among and between generations. Consequently, besides meeting the essential needs for the present, sustainability idea also suggests maintaining the life-support system on earth while extending to all the chance to fulfil their goals for an improved life. Thus, according to

Hanjali´c et al., 2008. A more meaningful specific definition of sustainable development is defined as

“a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations”

The above definition includes a significant change and development of the environmental idea of sustainability to the economic and social aspect of development. Subsequently, defining sustainability cannot be expressed only from environmental perspective or based on demeanours. The major issue is trying to define sustainability from reliability and a functioning standpoint while incorporating environmental, and economic and social standpoint (Kates et al., 2001).

This sustainability concept has given rise to two vital problems that should be determined i.e. normative and positive perspective issues. The first problem has to do with aims and objectives of sustainability, i.e. answering the questions ‘’what must be sustained’’ and ‘’ what type of developments are to be favoured’’ These questions are normative and include decisions regarding the objectives of general public with reverence to environment, social and economic goals (NRC, 1999). The subsequent problem involves the positive part of the sustainable development and it answers the questions, the viability of the issue of ‘’ what can be sustained’’ and ‘’what type of strategy should be implemented’’. This entails a detailed knowledge of how this various system functions, integrate, interact, develop and how they could be overseen. This can be implemented in a dynamic model with equations and limits (NRC, 1999).

2.5.1 Measuring Sustainability

Sustainability measurement is a key problem in designing and determinations of sustainability development (Hammond, 2000). The enhancement of any device than can precisely determine sustainability is essential to identify systems that are not sustainable and to observe the effect on social environment. At present, tool and indicators are being advanced for sustainability measurement and this involve parameters associated with practicality, reliability, appropriateness and limitation of measurement (Binswangen, 2001). For the indicators to adjust to the difficulty of dealing with different systems, the indicators should be able to measure the whole system and also the interaction of the sus-systems. Therefore, indicators must be able to determine the strength of the interactions between the system component, sub-system and its environment. Hence, the chosen indicators must be associated with the interactive process of the system that enables the determination complex connection of each sub-system and its related environment (Waston, 1998).

2.5.2 Features of Effective Indicators

Indicators are suitable as representation or alternatives for determining conditions that are problematic to an extent that there is no straightforward measurement (Pemberton, 2001). For example, studies from Hanjali´c et al. (2008) stated the difficulty to measure the “quality of life in a specific district” on the grounds that there are vast varieties of things that comprises quality of life and individuals may have various views about what should take priority most. According Hanjali´c et al. (2008), these alternative indicators tries to view the district as a whole system for assessment i.e. determining the ‘’difference in the number of individuals moving In and out of a district’’.

Sustainability has always been displayed as a triangle-pyramid representation, where each point on the triangle-pyramid signifies one of the efficiencies in the evaluation or determination of any system (D’Angelo et al., 2001). The eco-efficiency line in the triangle refers to sustainability index value as shown in Figure 2.3 below. When an equilibrium is obtained in all the remaining three efficiencies with a forced constraint, the term sustainability index is said to be attained.

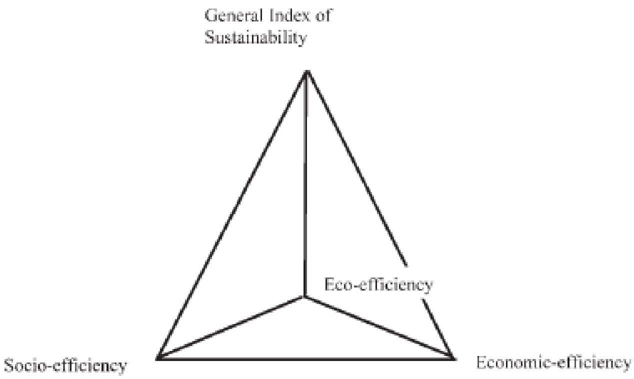


Figure 2. 3: Sustainability index

Figure above 2.3 also shows that sustainable development is underpinned on three important pillars i.e., the economic, environmental and social obligations according to Legend et al., (2014). Sustainable development is achieved only when these three fundamental pillars are in balance within the management of the direct user and the fundamental pillars. Also, from bottom angles point 1 to 3 shows the interaction and dynamism among the three underlined concepts for sustainable development and also signifies is non static nature of sustainability. It is of vital importance to examine the three concepts of sustainability as an ongoing process i.e. social learning and climate change process. In the evaluation any system, social, economic and ecological efficiencies are important (D'Angelo et al., 2001).

2.6 Smart and Sustainable

The idea of the terms smart and sustainability have long been in existence since the mid-late 90s, and at present, different business division, government and academics have studied its applicability and potentials. Authors in literature views this idea differently which creates an extensive but similar approach. Several expressions have been used in the literature to describe the terminologies such as green bathroom, intelligent bathroom, carbon-neutral bathroom, smart bathroom, green bathroom. Even though the ideas vary, they all try to associate sustainability with smart. Each ideas purposes to develop a smart, modern and sustainable bathroom with efficient system components that improve innovations and designs with sustainable and smart solutions.

The concept of smart and sustainable has been a common term used to describe the performance of a households and also bathroom inclusive i.e.'' making a bathroom sustainable'' or ''making a bathroom smart''. In simple terms, a ''sustainable bathroom'' means a bathroom that minimize and manage its resources in an efficient way that will not hamper the future generation while making a ''bathroom smart'' means to utilise ICT and automated technologies for daily activities in the bathroom. The terms smart and sustainable approaches as defined are diametrical to each other, and without any uncertainty, technology with intelligent solutions are major component to the Idea, although describing ''smartness'' does not imply to the usage of technology and intelligent system alone. Studies carried out by Nam and Pardo in 2012, defined intelligent/smart systems as a means of attaining the desired outcome and not the outcome itself. Authors like Marco, 2013, Anna, 2017 and Art et al., 2011, have tried to synergies the concept ''sustainability'' to the smart bathroom idea and thus taking the discussion to a whole new level.

Study carried out by Marco (2013) have assessed the two concepts ''smart'' and ''sustainable'' approaches leading to smart and sustainable bathroom and described these terms based on two different standpoints i.e.

- *"Making sustainable bathroom smart (by using smart bathroom technology to improve sustainability)?*
- *Making smart bathroom sustainable (by improving the sustainability of the technology itself)?''*

Whiles Anna in 2017 also examined the two concepts based on different standpoints. i.e.

- *'Normative, which treats "smartness" as a desirable outcome and not as a tool;*
- *Instrumental, in which "smartness" is a tool to reach a set target, be it "sustainability" or something else''.*

Based on the above-mentioned approaches, this study will adopt the viewpoints of Marco Blumendorf, 2013 and Anna 2017 to define smart and sustainable as an innovation that uses intelligent system to improve operational efficiency and management of resources while ensuring that the present and future needs are not impeded with respect to social, environmental and economic goals.

To summarize the above viewpoints to define bathroom, a smart and sustainable bathroom must:

- Satisfy and achieve the needs of its present generation without compromising the capacity of the future generations to achieve their needs.
- Accomplish the above using smart technological with renewable energy system and other means in a smart way.

Study from Art et al., (2011) have stressed the importance of integrating the three sustainable approaches to achieve a smart and sustainable bathroom as this will lead to a new planning approach.

The major important characteristics this study will consider for a sustainable and smart bathroom are technological efficiency, integration and functionality, intuitiveness and smartness of the system while its major operations includes:

- Automatic temperature and water pressure control,
- Control of water outflow,
- Use of artificial intelligence (automatically memorization of constant user behaviour),
- Adapting the work of the device to the individual needs of users,
- Automatic operation of the devices.

Smart bathroom integrates new and innovative fixtures, technologies and materials to create internet of things (IoT) bathroom and proposes a comfortable environment that is healthy, functional, user-friendly, accessible, and energy and resource efficient. A smart bathroom enhanced with sensors, actuators, and interactive displays to support innovative and useful features (Jaglarz and Charytonowicz 2015). User-friendly bathroom that supports the integration of new technology and enhances the daily routines experienced in the bathroom is focused on:

- Smart Living - an easy-to-use integrated interface allows multigenerational users to perform a multitude of bathroom operations, such as monitoring and controlling hot water, energy, and resources like toilet paper and soap.
- Smart Technology - integrated cutting-edge fixtures, adjustable furniture, smart accessories, and intelligent lighting provide a comfortable, user-friendly bathroom experience.

Constructing a bathroom from the inception provides the likelihood for a new sustainable and smart considerations, although, retrofitting a bathroom is apparently considered increasingly significant from a sustainable perspective/point of view and it is unsustainable to deconstruct a bathroom to build a smart and sustainable one (Bruce, 2013). A bathroom that is smart and sustainable is considered to be equipped to store and reuse (harvesting) energy and water it requires for the comfort and conducive environment for the occupant. Diverse technological systems like solar hot water, PVT, geothermal energy, wood burner has been used to provide hot water for bathroom. Potable water should be stored, reused, treated with continuous onsite recycling.

A sustainable bathroom should then ideally be capable of harvesting its water and energy it needs to provide a comfortable living environment for its users. Various technologies have been used to harvest the required energy for domestic application, also, the usage of low energy devices can help to reduce the energy needs. Different technologies like a wood burner, solar hot water, geothermal energy or heat from a compost pile can be combined to provide warm water. Water should be harvested and treated locally and ideally be continuously recycled on site. This must be supported by the utilization of natural and unharmful products for dishwashing, showering, laundry and cleaning. Studies by Marco, (2013) laid emphasis on how ICT can make the fundamental procedures increasingly effective by observing/monitoring the energy use, educating the consumer about it and developing different automated processes to utilize energy more effectively in another sub-system in the same bathroom area. This helps in checking and dealing with the supply of heated water, gives security measures and makes life comfortable through stimulation of the systems and sus-system in the bathroom. Although, ICT automated machines are vital in the efficiency of bathroom systems and it is instrumental in achieving the overall goal climate/carbon neutral in the bathroom and studies have shown that it uses more energy than it saves as its major task is as its name suggests (information and communication technology). The smartest piece for a smart and sustainable bathroom by all accounts is the user. The bathroom user purposefully picks his/her consumption pattern and activities and is in this manner are the major effect and the last instance for any choice whether ICT is used or not. ICT's key role is to notify the bathroom user about the impacts his actions will/have on environmental sustainability and thus making the user to have an informed choice in making efficient decisions to reduce water and energy consumption and making the environment to give off an impression of being the fields that ICT is best at. Although it makes a great difference in enabling and encouraging transition progressively to an increasingly sustainable way of life and managing natural resource for sustainable living acceptable yet considering its own system and process, it will have to confront its own innate unsustainability. While new methodologies are not too far off to discourse these problems, they are not yet adequately tended to and in this way ICT, at its present state, probably won't be fit for being the principle driver to make the environment sustainable in the foreseeable future.

2.7 Sustainable Issues with Bathroom

Extreme energy and water consumption in a domestic bathroom bring about various hidden sustainability consequences and most especially their combined nexus impact. The UN – Water and Energy sustainability in 2014 report underlined the need to improve sustainability in a business as usual scenario, which may effectively impact the environment and risking the sustenance of social and economic developments. Studies from Waterwise (2014) have also illustrated some major effects form extreme energy and water consumption that cause challenges with the social, economic and environmental sustainability, for example, degrading water surface because of contaminated surface overflow flushing into the water body, further water abstraction that causes degradation of the water body and high cost of maintenance with possible upgrade of water supply and treatment of waste-water mechanism. Although, for this study, the major purpose of saving water and energy is not only due to the decline in natural resources, water shortages, and rise in demand, but also due to the amount of

CO_2 that could be saved in every litre of potable/hot water in the bathroom activities i.e. for a typical bathroom, 3.186kJ which is equivalent to 0.4g of CO_2 emission can be saved (Energy saving trust 2013).

According to Families and Households (2015) report, the present pressure on the water supply corporation and water treatment coupled with the ongoing problem of water resources scarcity and depending on a newly manufactured systems will only bring out future imminent impact. Since UK population is roughly about 65million with an average of 2.4 individual per house-hold and there are almost 27 million houses (old and new) coupled with a goal of building at least 2million houses every year by the government, this will take the UK government over 100 years to implement a new water saving system in all bathroom/households units in the UK if the innovation executed in all newly houses are being adopted for the existing house, consequently, retrofitting a domestic bathroom is a significant factor in any novel system for sustainability.

To save water and energy for bathroom applications, the use of smart/intelligent control system is of great importance in any localised system. The smart controls system enables adaptation to the pattern of the end-user and further increases the efficiency of the system, this would be a substantial enhancement to an integrated system in any household dwellings to save both water and energy. Although in a domestic application, bathroom has the most potential to save water and energy, retrofitting a bathroom with an integrated water and energy saving technologies does not involve big makeovers in the bathroom building and will utmost result in being sustainable having maximum and timely influence. The adaptability of smart or intelligent systems in essential in retrofitting bathroom systems.

According to Energy Saving Trust report in 2009, about 50% of showers in United Kingdom are electric in most bathroom, electric showers are usually based on the principle of a smart flow control rather than the energy control system. The flow controls have two heating elements, the operator could decide by manually switch both or one of the heating elements on or could as well turn the device off. At the point when preheated water is provided from the flow controls, the flow rate is increased to attain the user desired temperature generally around at 40-43oC, this also increases the pressure and volume of water use, the resulting temperature output could rise to an unsafe degree. Consequently, due to the high risk of temperature, electric showers do not really save energy as it also increase the volume and pressure of water usage as the temperature increases. In the application of waste water heat recover (WWHR) system combined with an electric shower are capable of saving energy if they are well designed to allow preheated water. Preheated water is efficiently utilized in mix showers and boilers. The energy saved is derived from needing a reduced amount of energy to heat the potable water coming from the mains to a specific temperature once the water temperature feed is higher. For greywater recycling, fundamental difficulties are cost, quality of water treatment, system size, payback period and setup for water storage.

Improvement in taps and shower delivery are vital prospect for technological advancement in the bathroom. Albeit, presently several technological developments have occurred in decreasing flowrate during showering without impacting the comfort of the user, nevertheless if the same can be said for energy storage and recovery development and application, then preheated water for basin-taps, bath and shower could make significant difference to achieve high energy efficiency in the bathroom unit. This may occur basically by redirecting the preheated water to the cold water tap which affect the user in having cold water. The other arrangement could be creating blender taps with three input, hot, preheated and cold. The mixer will mix cold and preheated water for specific requests and whenever required will draw high temperature water from the boiler.

At present, the WWHR in the market are instantaneous in operations. The heat recovered from showering is immediately used back in heating cold water going to the shower system to reduce energy. Also, since the WWHR is instantaneous and mostly horizontal in design, this makes the efficiency of the system to be limited. Likely issues with the vertical design is that it could be expensive to retrofit as it needs alterations to the core vertical sewage pipe. Lastly, another disadvantage of these WWHR systems is that they do not reclaim any heat from utilizing basin/bath, consequently, integrating energy storage facility could increase the efficiency of the waste heat recovery system.

2.8 Sustainable Issues

The swift innovations in the technical and scientific knowledge during the past five decades have enabled civilization with the control to change the planetary system significantly. The new uncovered control collectively with the growing populace size has led to the extreme disproportionate exploitation of renewable natural resources i.e., forestry, fish and wildlife (Hill and Bowen, 1997). As a result, civilizations are beginning to acknowledge that, the damage inflicted on the planet cannot be a business as usual.

Several research studies uncovered that in spite of developing issues about sustainability, there is practically no accord on what it implies. However, the most generally utilized meaning of sustainability is the Brundtland report's meaning of sustainable development according to Mebratu (1998), meeting the needs of the present generation without compromising the ability of future generations to meet their own needs (World Commission on Environment and Development, 1987). For Giddings et al., (2002), it is contended that this definition is human-centric as it proposes that, but human rely upon the environment to address our issues, it is just our human needs that is of major importance (Hopwood et al., 2005). In any case, it assumes that, in any event as far as human lifetimes, a long-haul view should be established with the goal for sustainability to be accomplished.

Similarly, sustainable growth is frequently utilized interchangeably with sustainable development (Daly, 1996). In any case, as Goodland (1995) proposed, sustainable development and sustainability are not synonymous. Likewise, Goodland (1995) accept sustainable development to be advancement that is economically, socially and environmentally sustainable. Daly (1990) characterizes growth as quantitative increment in physical scale and development as subjective improvement. Therefore, issues of sustainable development are usually identified with the development of poor nations, while issues of sustainability are for all nations. However, research studies by Meyer (2000) contend that, despite the fact the poor nations need sustainable system, the rich nations need to contract, and that development ought not to be identified with only one part of sustainability but rather to the accomplishment of social, economic and environment approach of sustainability. On the other hand, Dreby and Lumb

(2012) suggested that the rich nations can change to “environmentally friendly” system.

While the poor nations develop by methods for such system. As expressed by Thomson (2013), the planet can support an environment without an economy, but it cannot continue an economy without an environment. In essence, the economy is a subset of the environment and the environment is a limited worldwide ecosystem (Daly, 1990). As the environment can grow, however cannot develop, exponential economic-based development is in this way not sustainable in the long haul (Daly, 1990).

Accordingly, Dark and Milne (2002) characterize sustainability as the effective and impartial conveyance of assets intra-generationally and between generationally after some time with the activity of economic development inside the bounds of a limited ecosystem. Studies suggests that this definition is more grounded than the Brundtland report's definition as it perceives that the economy is a subset of the environment and it expect a long-haul assessment - albeit the long-haul is again communicated as far as human lifetimes. Nevertheless, Dark and Milne (2002) studies relates just to asset requirements and no other, more extensive environmental issues, for example, the commitment of a system execution to climate change. Moreover, sustainability usually alludes to economic, social and environmental; albeit, the accurate connection between environmental, social and economic sustainability is vague (Littig and Griebler, 2005). Research studies by Darker et al., (2006) portray the connection between the economic economy and environment as pursues: characteristic systems give the specific circumstance and sustenance to social systems and subsequently must be regarded, supported, and continued. Social systems give the reason and unique circumstance for economic systems. Specially, the economy is a subset of society which thus is a subset of the environment. As indicated by Van der Vorst et al., (1999), environmental sustainability requires economic and social sustainability relies on environmental sustainability. On the other hand, the three areas of sustainability can be treated with equality as suggested by Newton (2003). A number of research studies suggested participant responsibility, ethics, spirituality and politics as further areas. Henriques (2004) contends that the three bottom line principles of sustainability do not deplete the field of sustainability and that participant responsibility ought to be an extra area. Notwithstanding, ethics ought to be consolidated into the pillars of sustainability. Essentially, ethics are viewed as a different area and should put direction on what ought to be done and must be executed over the three areas (Donaldson and Dunfee, 1994). In this way, Bendell and Kearins (2005) suggested a political area - the impact that commercial system apply as a powerful influence for the open segment to advance sustainability. In fact, this description proposes that such impact is simply a way to the finish of economic, social and environmental sustainability, and thus not a different area of sustainability. Studies by Inayatullah (2005) recommends spirituality as the fourth area and portrays the most profound layer of spirituality as the magical speculative chemistry of oneself. In any case, Inayatullah (2005) infers that it is difficult to gauge since spirituality by its temperament must advise one's pondering on the society, economy and the environment, and is unquantifiable - it is deceiving to think about it as a fourth area. Likewise, it is additionally ostensibly deceptive in light of the fact that, if individuals' spirituality is established, the system ought not be influencing that spirituality.

Consequently, the real issue confronting mankind with respect to the three bottom line principles of sustainability is whether human action is sustainable. More importantly, can human movement as accomplished at present withstand economic, social and healthy environment, and if not, by what means would human be able to change the air conditioning (system) technique with the goal that the environment and society can withstand it? These are worldwide inquiries; they influence the society and environment in the enormous. Nevertheless, the system likewise influences society and environment in the little at the dimension of individual nations, regions and systems. The impacts of a system in one territory may influence the society and environment in regions far away. On a fundamental level, it eliminates the heat from one region and supplant it with chilled dry air and hot air is expelled, typically to the outside environment. In other words, it incorporates the sustainability and bathroom smart/ intelligent control. Additionally, there are inquiries regarding the future: can the society and environment be continued both for the time being and in the long? Social and environmental harm can be created temporarily; however, it might have great impacts; it can take numerous years to invert the harm done by one year's movement.

With the end goal of this investigation, the sustainability of smart bathroom unit - that is, the economic, social and environment effect of the system is taken to be sustainable if, accepting its uncertain continuation, the impacts of that system will add to empower the environment, economic viewpoint and the human culture to accomplish and keep up a condition of comfort. Hence, the proof provided suggests that, as far as sustainable definition is concerned, the present system is unsustainable. The inquiry whether a system is sustainable should be considered in the light of the three bottom line principles of sustainability.

For this study, the system framework is regarded sustainable if:

- the system considers the three pillars of sustainability namely, environment, economic and social respectively as a whole. Whilst this study proposes to focus on the three arms of sustainability, it will however concentrate majorly upon the strong sustainability aspect of the system and, or
- the most efficient means for re-establishing the system to sustainability may necessitate change in the system. In other words, combining both the renewable and smart/ intelligent system as a unique system for the sustainability of the system while improving the indoor air quality and wellbeing of occupants.

Consequently, several policy and theoretical literature occurred in the ten years succeeding the Brundtland account by way of articulating the pillars of sustainable development. However, the issue of sustainable development is one of the main investigations and strategy matters toward the start of the 21st century. Up to this point, there is a range of perspectives. Toward one side of the range are the individuals who take ‘conserve at all costs’ or ‘eco-centric’ opinion that puts worldwide ecosystem first and put boundary to economic and populace development in light of a legitimate concern for supporting and upgrading resources and natural environment. At the opposite end of the range are the individuals who backer an anthropo-centric imminent, which puts people first, contending that we will locate a specialized answer to supplant natural resources or restore the natural habitat. Table 2. 3 represents these two principal bearings together with the sub-ways to deal with characterizing sustainable development.

Table 2. 3: Competing views of sustainable development

Eco-Centric Interpretation	Environmental	Focusing on the consumption of resources, this approach seeks to avoid making a lasting adverse impact on the world's stock of natural resources (Meadows, 1972; Bruntland, 1987).
	Ecological	The ecological approach emphasizes the characteristics of living organisms in communities, such as the ability to self-regenerate, self-sustain and respond to change (Page, 1994; Copus and Crabtree,1996; Ramwell and Saltbum, 1998).
Antropo-Centric Interpretation	Endurance	Sustainability is achieved by undertaking activities which produce lasting benefits, like training, or deal with long term problems (Thake, 1995; Aldboume Associates, 1999).
	Demand Based	Undertaking activities that encourage people to live in communities, equating the definition with popularity and/or quality of life (Smith and Patterson, 1999; Evans and Fordhan, 2000).
	Environmental	This approach seeks to optimize both environmental and human resources, with an emphasis on democratic and participative outcomes. (Local Agenda 21, 1996; DETR, 1999: 2005).

Subsequently, there has been continuous investigations, particularly all through the 1990s on two kinds of sustainability, which have contrasted for the most part as far as the expenses brought about in accomplishing them: Weak Sustainability and Strong Sustainability as demonstrated in Table 2.4. Hence, weak sustainability to the anthropo-driven position and strong sustainability can be identified with an eco-centric translation of sustainability. Moreover, strong sustainability contends that humans should live inside the environmental and natural breaking points of our planet and between the economic, social and environmental elements of sustainability are not permitted. Such a perspective on sustainability is very much lined up with the environmental weight gatherings' perspective on the issues and is ostensibly grounded in the environmental developments created during the 1970s, the exercises of which, it has been recommended, prompted the modem perspective on sustainability created from the exceedingly compelling Bruntland Commission. In other words, strong sustainability contends that negotiating between the key components of sustainability are admissible, attesting that mankind will supplant the common capital lost overuse with mankind-made capital.

Table 2.4: Interpretations of sustainability (Bell and Morse, 1999)

STRONG sustainability	Takes little consideration of the financial or cost aspects of attaining sustainability and focuses mainly on the environment. Some equate this with the so-called ecological sustainability.
WEAK sustainability	The financial and cost aspects associated with attaining sustainability are important and typically based on a costbenefit analysis, which inevitably involves trade-offs between the environment and other social and economic benefits. This can be equated with some sort of economic sustainability where the emphasis is upon the allocation of resources and levels of consumption.

According to Dresner (2002), the development choices of organizations, governments and different performers permit dealings and underscore the economy over every single sustainability element. Thus, scholars practically consistently concur that weak sustainability structure the applied reason for sustainable development. As stated by Common and Stagl (2005), the all-unavoidable nature of neo-classical economics has come to pervade the intuition on sustainable growth, with a wide acknowledgment that inter-generational and intra-generational value must be accomplished inside the limits of economic development. For the Economist (2009), associated to the meaning of the three pillars of sustainability and sustainable development are the different hypothetical frameworks given inside findings endeavouring to help our comprehension of sustainability. The most used of these hypothetical models of sustainability is the three arms concern. Starting from the field of business, this framework aim to evaluate the sustainability of organizations through the examination of their records, pushing that organizations ought to get ready three loads of records: the customary benefit and misfortune primary concern, the 'general population' account which is a main concern that assesses the organization's social exercises, and ultimately the 'planet' account, a primary concern that reflects how environmentally dependable the association has demonstrated to stand.

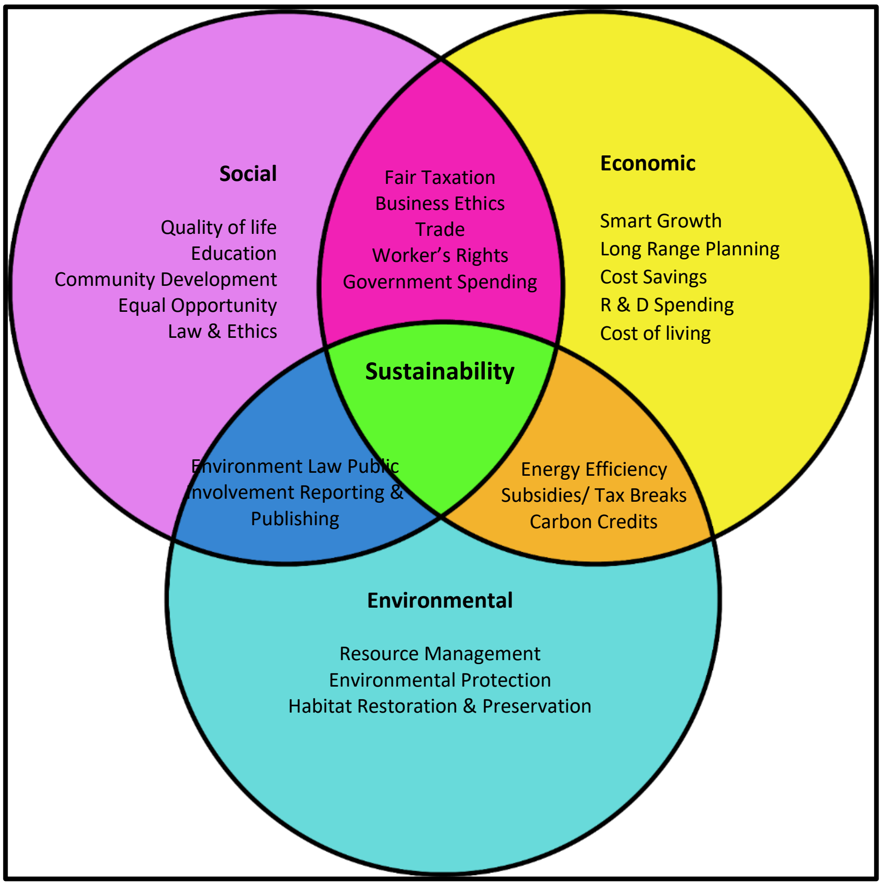


Figure 2.4: The three spheres of sustainability (Wanamaker, 2020).

Even though the framework demonstrated in Figure 2.4 commenced from the business world, it has now turned into a by and large acknowledged framework for the achievement of sustainability, as it unmistakably proves the significance of the interchange between environmental, economic and social performers in the making of sustainable development. Thus, the plan of the framework proposes that the three circles of sustainability are all of equivalent significance, exhibiting the likelihood of a dimension playing field. On the other hand, this procedure has been reprimanded by a few. Adams (2006) contends that such a way to deal with sustainability infers that the client can affect substitutions between the three basic parts prompting a weak achievement of sustainability, hitherto Hill and Bowen (1997) recommend that such substitutions are crucial to actualizing the standards of sustainable development in the development area.

Hill and Bowen (1997) suggested that expanding on the three arms of sustainability infer that the main real work is concentrated on the development area, vis-à-vis the reconciliation of the standards of sustainable development into growth activities would basically be a choice dependent on the enterprise partner's worth judgment. Offering a procedure positioned, four-pillar model of sustainable development, the creators contended that the dimension of sustainability accomplished inside the task was an issue of the substitutions made between the different arms of sustainability. Accordingly, the general plan and, critically the task partners' wants regarding the dimension of sustainability the responsibility is required to accomplish, either strong or weak sustainability could be accomplished. In spite of the fact that pundits of such ways to deal with sustainability recommend that the assistance of such substitutions definitely prompts the achievement of weak sustainability inside development ventures, prompting the nonstop inclination towards the environmental measurement, as this is all the more basically reachable (Bourdeau, 1999; Ding, 2008; UK Green Structure Committee, 2009). However, Kelly and Seeker (2009); Poston et al, (2010) suggested that most of current system used inside the built environment receive a technique which looks to adjust the three arms of sustainability, trying to accomplish a development, which adjusts economic costs, social change and the unavoidable environmental results while additionally guaranteeing that the rare assets are not wasted, either purposely or through obliviousness.

O'Riordan (1998); Dixon (2007), propose various levelled ways to deal with sustainability. For the Russian doll model demonstrated in Figure 2. 4 supports an increasingly mind-boggling perspective on sustainable development. Giving an inserted perspective on sustainable development, it portrays the significance of the communications between the social, environment and economic circles. However, Pearce (2006) suggested the model exhibits the significance of economic movement to worldwide improvement, putting this circle of sustainable development at its centre. Nevertheless, by setting the environmental and social circles of sustainability on the external rings, the model verifies that economic development ought to be impelled so that it both improves social advancement while likewise regarding the normal furthest reaches of the world's environment.

Research study by Wilkinson and Reed (2008) declared that an upset variant of the framework would be increasingly delegate, as putting the common world at the representation's centre would exhibit the significance of environmental friendliness regardless of anything else. Notwithstanding, the connected perspective on sustainability lessens the potential for 'win-win-win' results as upheld by Brundtland, while additionally guiding a way far from the weak sustainability related with the three arms, as substitutions are less simple to make inside this structure. Therefore, Vanages (2003) advised that the significance of such a view is basic to the fulfilment of sustainable development if the development segment is to coincide with the biosphere. Adams (2006) argues that this deal with sustainable development, proposing that, while such frameworks endeavour to build up a various levelled structure and would seem to evacuate the substitution potential outcomes, they do not yet delineate sustainability so that it would encourage sustainable development. Subsequently, Adams (2006) proposes that the three bottom line principles of sustainability must be interlocked, in this way guaranteeing they become better coordinated inside the development management process. While such a methodology gives off an impression of being social case support, not least from powerful political gatherings, for example, the Business and Enterprise Select Committee (2008), rivals of the induction of strong frameworks of sustainability recommend that substitution inside the optimal environment are inevitable, given the divergent and regularly inharmonious, economic and arrangement targets that can redirect or disturb the drive towards genuinely sustainable development (Atkinson et al, 2009; Wolstenholme, 2009; Slope, 2011).

2.9 The Holistic Sustainability Strategy Employed

Recent explorations by IIASA (2012), unfurled that system study examination and a life cycle approach are fundamental when taking a gander at the issue sustainability and potential measures. Momentary contemplations, for example, just introducing unsustainable sorts of air-conditioning during warm summers, are not a sustainable answer. In the long-haul, this change can convert into one innovation dominating the total market to the detriment of the other; alluded to as technical "lock-in". As of now, this can be seen and has likewise caused an established lock-in, as the growth of technologies impacts, and is affected by the three bottom line principles namely, economic, social and environment in which they create (Foxon, 2006). When this lock-in is accomplished, it can anticipate the take up of possibly predominant choices. Foxon (2006) uncovers that the system approach accentuates that discrete technologies are not just upheld by the more extensive technological system, yet in addition by the framework of economic, environment and social standards that fortifies that innovative system. These incorporate formal limitations, for example, economic viewpoints, policies and casual requirements, for example, behavioural and social hindrances.

Consequently, this study recommends that one must deliberate upon all the drivers in sustainability when designing transformations to a bathroom; one also must take into account that individual technologies are not only buttressed by the extensive technological system, but the sustainability framework that underpins the technological system. So, it is important to understand the three bottom line principles of sustainability namely, environment, economic and social, and how the renewable and smart/ intelligent approach can contribute to the overall sustainability of the system. This can even offer substantiated insight into sustainable approaches for promoting novelty and concept of smart bathroom for greater sustainability.

2.9.1 Environmental Sustainability

Research studies by Morelli (2011), characterized environmental sustainability as a state of equalization, interconnectedness and resilience that enables human culture to fulfil its needs while neither surpassing the limit of its supporting biosphere to keep-on recovering the amenities important to address those issues nor by our activities reducing biological variety. In any case, the ecosystem that person rely upon is versatile (Ludwig et al., 1997). This implies it can keep-up its honesty or come back to a condition of balance after an unsettling influence (Morelli, 2011). Nonetheless, unexpected moves in the biosphere can make it lose its flexibility (Scheffer, 2009) and turn out to be “unsustainable”. The earth system has a lot of cut-off points or limits inside which harmony is kept up (Rockström et al., 2009). Exponential development is forcing ever more prominent requests on the ecosystem and putting ever more prominent strain on these breaking points. Rockström et al., (2009) perceived nine planetary limits inside which mankind can work securely. These limits portray the major working of the biosphere. Research studies by Rockström et al., (2009) evaluated seven of these limits and expressed that the transgression of in any event one of these limits could prompt an unexpected and irreversible change to the worldwide environment. As indicated by their estimations, mankind has just transgressed three of the nine planetary limits - degree of biodiversity misfortune (estimated by the rate of eradications per million species), changes to the worldwide nitrogen cycle because of exponential development and climate change (estimated by the CO_2 focus in the environment). Glades et al., (1972) enquire: "Is it superior to attempt to live inside that point of confinement by tolerating a purposeful limitation on development? Or then again is it desirable over continue developing until some other normal cut-off emerges, with the expectation that around then another innovative jump will enable development to proceed with still more? For the previous few hundred years human culture has pursued the second course so reliably and effectively that the main decision has been everything except overlooked". For the previous inquiry, sustainability is basic (Rockström et al., 2009); nonetheless, for the last, it is expected that the biosphere is strong and ready to withstand any sudden interruptions and is consequently likewise sustainable (Plating, 2011). Albeit, people cannot rely upon innovative headway to help proceeded with development (Ehrlich and Ehrlich, 1990).

Therefore, that would be much the same as considering installed values on strategies not yet issued and items not yet created.

Nevertheless, research studies unfolded that the proof to help worries about the sustainability of the environment is expanding (Gilding, 2011). The impacts of climate change give an undeniable contention to the requirement for environmental sustainability. "Climate change" alludes to the noteworthy and durable changes in the climate system brought about by human exercises or by characteristic climate fluctuation (for example "anthropogenic" climate change) (IPCC, 2013). Despite the fact there is a protester studies, the standard of designing and assembled environment studies perceives the reality of anthropogenic climate change. The Intergovernmental Board on Climate Change (IPCC) in 2013 revealed that heating of the climate system is unequivocal, and meanwhile in the 1950s, a considerable lot of the watched changes are remarkable over decades to centuries (IPCC, 2013). Similarly, the changes incorporate warming of the environment and seas, lessening ice levels, rising ocean level, growing foci of greenhouse gases and intensifying fermentation of the seas. Climate change has just started to influence biodiversity. Specifically, higher temperatures have influenced the planning of propagation in plant and creature species, species circulations, movement patterns of creatures and populace sizes. Likewise, the present rate of biodiversity misfortune is more prominent than the common rate of elimination (IPCC, 2002; IPCC 2013). Moreover, the limits of the world's biomes are required to change with climate change as species are relied upon to move to higher altitudes and latitudes and as worldwide vegetation spread changes (Subsides and Lovejoy (1992); Kappelle et al., 1999). On the off chance that species are not ready to change in accordance with new land dispersions, their odds of survival will be diminished. So also, it is anticipated that, continuously in 2080, about 20% of beach front wetlands could be lost because of ocean level ascent. In any case, proposing a sustainable-based smart system can move to tackle some of the environmental concerns that is considered in this study, vis-à-vis combatting global warming and climate change adaptation as a result of sustainable smart bathroom. Figure 2.5 below offers the indicators of environmental sustainability for the proposed system.

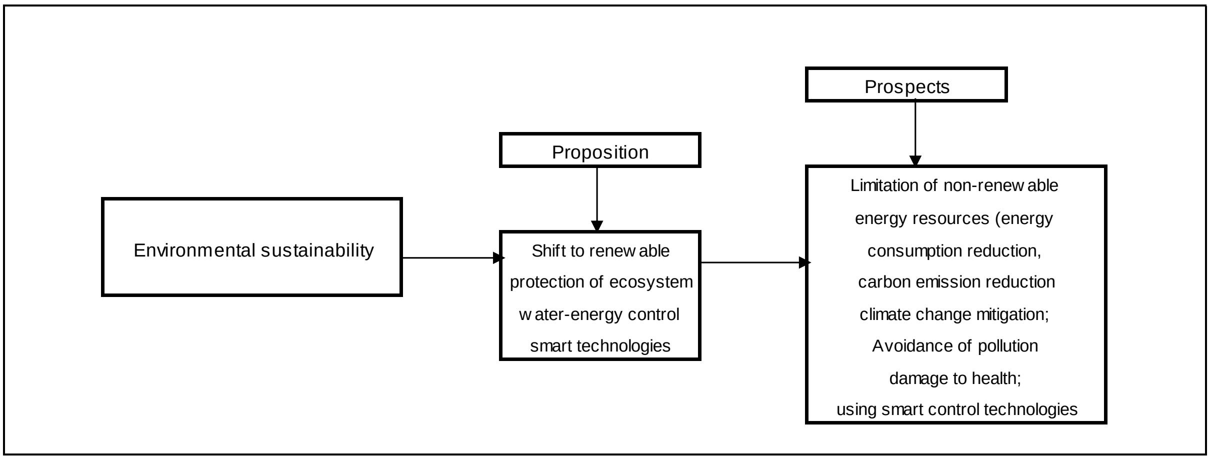


Figure 2.5: Indicators of environmental sustainability for renewable-based Bathroom unit

2.9.2 Social Sustainability

Studies depicted social sustainability as a procedure for making sustainable, positive galaxies that encourage comfort, by means of understanding what individuals need from the suburb they live and work. It joins plan of the physical domain with structure of the social world – framework to help cultural and social life, social comforts, systems for resident commitment and space for individuals and galaxies to grow. Moreover, social sustainability can likewise be depicted as a sustainability that happens when the informal and formal procedures, structures, systems and connections effectively bolster the limit of present and future ages to generate liveable and healthy societies. Socially sustainable societies are democratic, connected, diverse and equitable and give a decent quality of life (Partridge, 2005; Magee et al., 2012; Woodcraft et al., 2012). In any case, various research studies proposed that social sustainability has had extensively less consideration in open exchange than economic and environmental sustainability.

Consequently, the impacts of climate change on wellbeing give proof that social sustainability relies on environmental sustainability. According to the World Health Organisation, the net impact of climate change will be damaging. Very high air temperatures worsen respiratory and cardiovascular illnesses since they raise the dimension of toxins in the air. Also, municipal air contamination causes roughly 1.2 million demises every year (WHO, 2019). The research studies by Haines et al., (2006), likewise suggested that it is required to rise as the normal air temperature keeps on expanding. In addition, the event of irresistible illnesses, for example, jungle fever is required to rise as the environment turns out to be progressively good for broadcast. The predominance of ailing health is relied upon to rise as increasing variable precipitation and air temperatures adversely influence harvest yields in the most unfortunate areas of the world by up to half by 2020 in some African nations (IPCC, 2007; WHO, 2019). Likewise, increasing ocean levels are expanding the danger of floods. This builds the danger of poor indoor air quality (IAQ), interruption of wellbeing amenities, jungle fever, pollution of water supplies, wounds, suffocation and water-borne sicknesses (WHO, 2019). Recently, research studies by Yu and Lin (2015) emphasized that individuals spend around 70% to 80% of their time indoors, hence, indoor air quality (IAQ) is a determining factor for work and wellbeing productivity. The ubiquity of air-conditioning has made relaxed indoor spaces with sensible air quality accessible to numerous individuals. In any case, examinations by Rios et al., (2009) has unfurled that the utilization of the systems builds the measure of contamination in the air in shut spaces in view of an absence of air exchange among outdoors and indoors, showing a noteworthy danger to our wellbeing and health. Contact to air that comprises high dimensions of CO_2 that causes climate change and global warming can prompt vascular choking, headaches, increased heart rate and hyperventilation. Exposure to high CO_2 concentration diminishes oxygen supply to the heart, may result in suffocation and influences breathing (Yu and Lin, 2015). In the light of this, this study recommended that controlling quality of air radiated via air conditioning gadgets is significant in light of the fact that a critical piece of total populace today lives under the dangers of different kinds of diseases caused by poor indoor air quality. Therefore, there is need of a smart/ intelligent system that better control and improves the human adaptation of the wellbeing of occupants utilizing the hot water resources in bathroom system which is in turn focussed upon sustainable future development.

Subsequently, studies suggested that water temperature is part of the constituents of comfort and wellbeing. Likewise, further segments consist of freedom, wealth, employment, education, social capital and living standards (Alkire, 2002; McGillivray, 2007; Dempsey et al., 2011). (The idea of social capital alluded to here, and the comparable ideas of environmental capital and human capital are awkward in that they infer a reductionist perspective on humankind and the environment, for example a perspective that worldwide ecosystem, individuals and the human culture are nonentity, however, their worth to the worldwide economy). Investigations uncovered that people are, however, living on an unhappy planet (The Happy Planet Index Report, 2012). At this point, "happiness" signifies sustainable wellbeing. Similarly, Happy Planet Index measures “the extent to which countries deliver long, happy, sustainable lives for the people that live in them” (Happy planet Index, 2019). The report quantifies the degree of bliss by figuring the quantity of "Happy Life Years" attained per unit of asset use (The Happy Planet Index Report, 2012). The account likewise uncovered that happiness does not really need to come to the detriment of the environment because nations with the uppermost comfort and wellbeing did not really have the most noteworthy asset utilization. For this gives proof that social sustainability is influenced by environmental sustainability.

The ongoing worldwide economic disaster has not just turned into a continuous disaster influencing worldwide debit markets, investment markets and credit markets, however more critically it is turning into a social emergency. As indicated by the United Nations report on the world social circumstance in 2011, the worldwide monetary disaster of 2008–2009 and the progressing worldwide recuperation will have long-haul social impacts (United Nations, 2011). Also, joblessness ascended by 15% somewhere in the range of 2007 and 2009. For it is evaluated that on account of the catastrophe between 47 million and 84 million individuals fell into or were caught in outrageous neediness (United Nations, 2011). Likewise, the World Bank as of late evaluated that almost 65% of the total populace live on under four dollar per day (The World Bank, 2019). This accentuates economic sustainability can successfully affect social sustainability. As a result, there is a crucial prerequisite for smart/ intelligent controller and renewable-based bathroom unit to improve the sustainability of the bathroom and the human adaptation of the wellbeing of its users. In essence, Figure 2.6 offers the indicators of social sustainability for the proposed system.

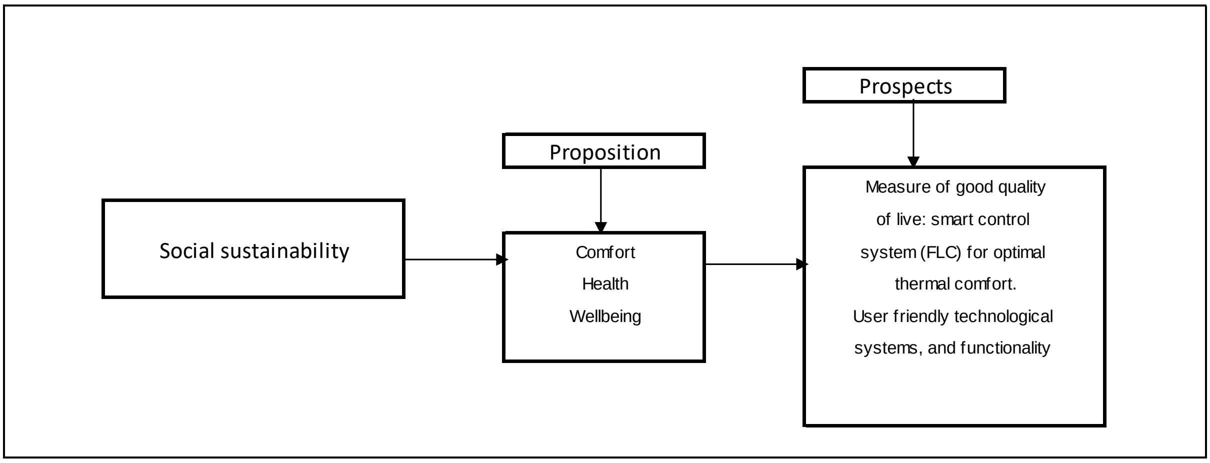


Figure 2.6: Indicators of Social sustainability for renewable-based Bathroom unit

2.9.3 Economic Sustainability

'Economic sustainability' suggests a system of generation that fulfils present utilization levels without trading off future needs. Inside a commercial setting, economic sustainability includes utilizing the varying resources of the system effectively to enable it to keep working productively after some time without contrarily affecting environmental and social part of sustainability (Basiago, 1999). Nevertheless, economic sustainability is inseparably connected to both social and environmental sustainability. For this is exhibited by the points of confinement to development. In any case, Meadows et al., (2013) suggested that economies are unlikely to be sustainable if society keeps-on relying upon marvels that hitherto drove development and if natural assets are utilized past the cut-off points. Also, “The Limits to Growth” as indicated in their book; they revealed that human interest has surpassed nature's supply from the 1980s forth, with interest surpassing supply by 20% by 2000. Around then, they emphasised that, except if unique move has been made, population development combined with expanded asset utilization would not have past what the biosphere can continue, will prompt the decrease in or the breakdown of the society, economy and environment. In fact, Meadows et al., (2004) proposes in their thirty-year update that mankind has gone past its points of confinement (Meadows et al., 2004). Over 10 years after the fact, Turner (2008) affirms that the past movement in global pollution, industrial output per capita, population, services per capita, food per capita and non-renewable resources remaining has been in accordance with the pattern anticipated and that populace decrease is normal by 2030 after economic breakdown. Even more as of late, Gilding (2011) expressed that mankind has outperformed the biosphere's ability to help us. Moreover, Thomson (2013) contends that development in the long-haul fuelled by information technology, dept and cheap oil is arriving at an end. Subsequently, Jones et al., (2013) offer proof to limitations on assets, for example, uranium, flammable gas, coal and oil and delineate that development fuelled by assets is constrained. As a result of this existing issues, it is key to focus upon renewable energy options to contribute significantly to the overall sustainability of the system – the sustainability of the smart/ intelligent bathroom unit. Figure 2.7 offers the indicators of economic sustainability for the proposed system.

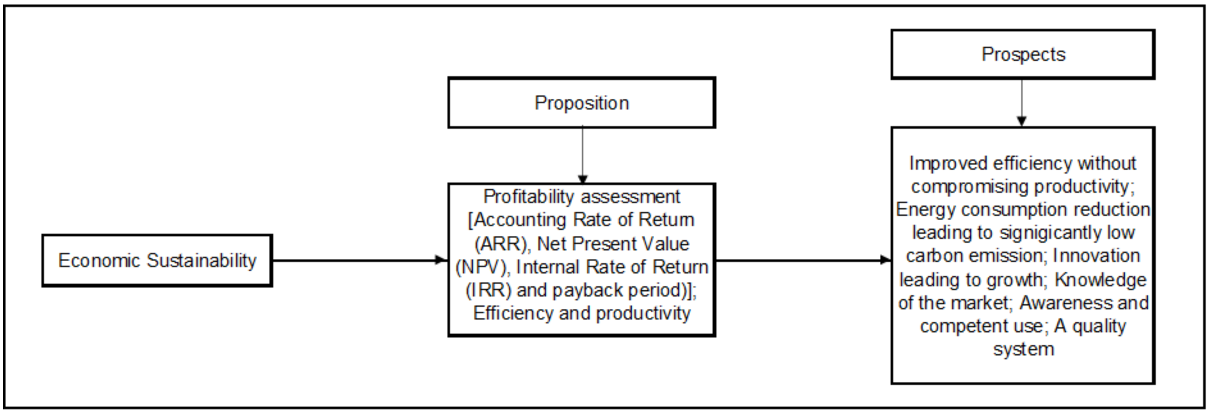


Figure 2.7: Indicators of Economic sustainability for renewable-based Bathroom unit

2.9.4 Relationships among the Environment, Economy and Society

The concept of sustainability appears poised to continue to influence future discourse regarding development science. This, in the view of Porter and van der Linde (1995), implies that the best choices are likely to remain those that meet the needs of society and are environmentally and economically viable, economically and socially equitable as well as socially and environmentally bearable. This leads to three interconnected spheres or domains of sustainability that describe the relationships among the environmental, economic, and social aspects of sustainable development as captured in Figure 2.5. Basically, it can be concluded from Figure 2.5 that, nearly everything man does or plans to do on earth has implications for the environment, economy, or society and for that matter the continued existence and wellbeing of the human race. Akin to this, as argued by Wanamaker (2018), the spheres constitute a set of interrelated concepts which should form the basis of human decisions and actions in the quest for sustainable development. Yang (2019) supports the argument by opining that basically, the Figure 2.4 depicts those proper decisions on sustainable resource management will bring about sustainable growth for sustainable society. Examples of these include decisions on land use, surface water management, agricultural practices, building design and construction, energy management, education, equal opportunities as well as law-making and enforcement (Montaldo, 2013). The argument is that, when the concepts contained in the three spheres of sustainability are applied well to real world situations, everybody wins because natural resources are preserved, the environment is protected, the economy booms and is resilient, social life is good because there is peace and respect for human rights (DESA-UN, 2018). Kahn (1995) and Basiago (1999) provide a vivid illustration regarding the relationships among economic, social and environmental sustainability, arguing that the three domains must be integrated for sustainability's sake.

2.9.5 The Paris Agreement

The Paris Agreement, 21st Conference of the Parties (COP 21), sealed on December 12th, 2015, also reinforces the spirit of interdependence between environment and economic and social development. Recognizing the need for an effective and progressive response to the urgent threat of climate change on the basis of the best available scientific knowledge. Emphasizing the intrinsic relationship that climate change actions, responses, and impacts have with equitable access to sustainable development and eradication of poverty (UNFCC, December 2015).

While the recent Paris Agreement COP26 summit in Glasgow (November 2021) sets a challenge for nations with improved 2030 targets in line with the Paris Agreement's goal of keeping global warming well below 2°C and closer to 1.5°C. However, scientists have warned that keeping temperature rises to 1.5ºC, beyond which the worst effects of climate change will be felt, requires global emissions to be cut by 45 per cent by 2030, and to zero overall by mid-century. In response to this, the UN will also assess climate plans every year, turning annual COPs into a pressure point for nations up their commitments. That means countries with weaker climate plans will be under more pressure to produce bolder plans to meet the ambitious commitment. This agreement, unlike the SDGs not signed by all UN member states, might close the cycle of what could be called a new development paradigm.

2.9.6 Summary

In this chapter, the contextual background of sustainability and sustainable development associated with bathroom has been reviewed by way of considering the research aim of the study. The review deliberated upon the sustainability and sustainable development while reflecting upon the possible ways.

This chapter identified the issues associated with the bathroom unsustainability by way of considering the three pillars of sustainability and as a result, the system sustainability strategy was unveiled that rationally uncovers the indicators of economic, environment and social sustainability of the system for the purpose of achieving the overall sustainability of the bathroom system. The link amongst the environment, economic and social sustainability are revealed - the impacts of thermal comfort on wellbeing gave proof that social sustainability relies upon environmental sustainability, whereas economic sustainability is inseparable connected to both social and environmental sustainability. For the sustainability of a bathroom, it is required to reduce the level of energy consumption and carbon emissions, vis-à-vis combatting global warming and climate change. The unsustainable use of bathroom causes an increase in energy utilization leading to global warming and climate change. As a result of previous research studies, sustainability issues associated with the use of bathroom have been unfolded and the indicators of environment, economic and social principles of sustainability underpinned with bathroom have been revealed for this study.

This chapter has also described part of the interactions between sustainable development and renewable energy and focused on sustainable development goals such as social and economic development, climate change mitigation and the reduction of environmental impacts. Beginning with the more conceptual discussion of sustainable development, there is a tremendous gap between intertemporal measures of sustainability and measurable sub-indicators that needs to be narrowed. In addition, possibilities for relating the two opposite paradigms of sustainability, weak and strong sustainability, need to be explored. One possibility would be to allow for nonlinearities, tipping points, and uncertainty about nonlinearities in intertemporal measures, or to provide framework for consideration of the precautionary principle. In the context of this study, this also means that specific indicators of weak sustainability like genuine savings, but also those of strong sustainability need to be reasonably and logically related to renewable energy systems.

In conclusion, knowledge regarding the interrelations between sustainable development and renewable energy in particular is still very limited for bathrooms. Finding answers to the question of how to achieve effective, economically efficient and socially acceptable transformations of the water-energy system in the bathroom will require a much closer integration of insights from social, environmental and economic system (e.g., through integrated modelling approaches) in order to reflect the different dimensions of sustainability. So far, the knowledge base is often limited to very narrow views from specific branches of research, which do not fully account for the complexity of the issue.

In the light of this, the next chapter deliberated on the sustainable measures that is reinforced upon the requirement for renewable-based bathroom and smart/ intelligent computational control technologies for efficient functioning of the bathroom.

Chapter Three

3.0 Renewable-Based System and the Smart Fuzzy Controller

3.1 Introduction

The aim of this chapter is to deliberate upon the requirement of renewable based system by considering solar hot water system and its components that is associated with bathroom sustainable development. It also highlights how each of these components improves solar collector performance, storage tank thermal performance, heat pump and how to manage the hot water usage pattern in reducing energy and carbon emission. This chapter further dwells upon the application of smart/ intelligent fuzzy logic to control and improve the bathroom water temperature and flowrate of the proposed system.

Extreme energy and water consumption in the bathroom has led to significant growth of energy consumption and carbon emissions. This fact clarifies the requirement for considering utilization of renewable energy sources and computational intelligent control system while focussing upon sustainability. This study has considered the potential of using renewable and smart/ intelligent technologies in order to contribute towards energy savings, carbon reduction and sustainable developments.

3.1.1 Renewable Energy and Global Consumption

Global consumption of energy continues to increase. Especially since many countries in the world are growing rapidly, as the countries of Asia and Europe. Countries today therefore need more energy for their buildings, industries, transport, etc... The conventional energy sources such as nuclear energy or fossil fuels (oil, gas and coal) are finite. These energies are polluting because they emit CO_2 into the air and contribute to the greenhouse effect. This air pollution is at the origin of climate change. Today's society is looking for renewable energy, clean and safe (Nuorkivi, 2016). The use of renewable energy, reduce energy consumption and improve efficiency technologies. Renewable energy appears as the only alternative to existing energy, acceptable environmentally, socially and economically. Urban planning and architecture, environment and energy become the major concern for designers.

Several studies suggest that the utilization of renewable energy is getting a lot of awareness, and considerable examinations are still required for various innovations. Moreover, the state-of-the-art total world energy utilization is displayed Figure 3.1 (Ritchie and Roser, 2019). The expanding utilization of fossil fuels not only leads to quick exhaustion of energy sources but also causes the production of destructive gases, which straightforwardly influences humankind. Comprehending the concealed effects of fossil fuels and their impacts on the wellbeing of humans is crucial for evaluating the sustainability of any system and for reinforcing more noteworthy decisions for future energy generation. Sustainable smart systems should be considered with the feasibility of utilising cleaner energy sources such as solar energy.

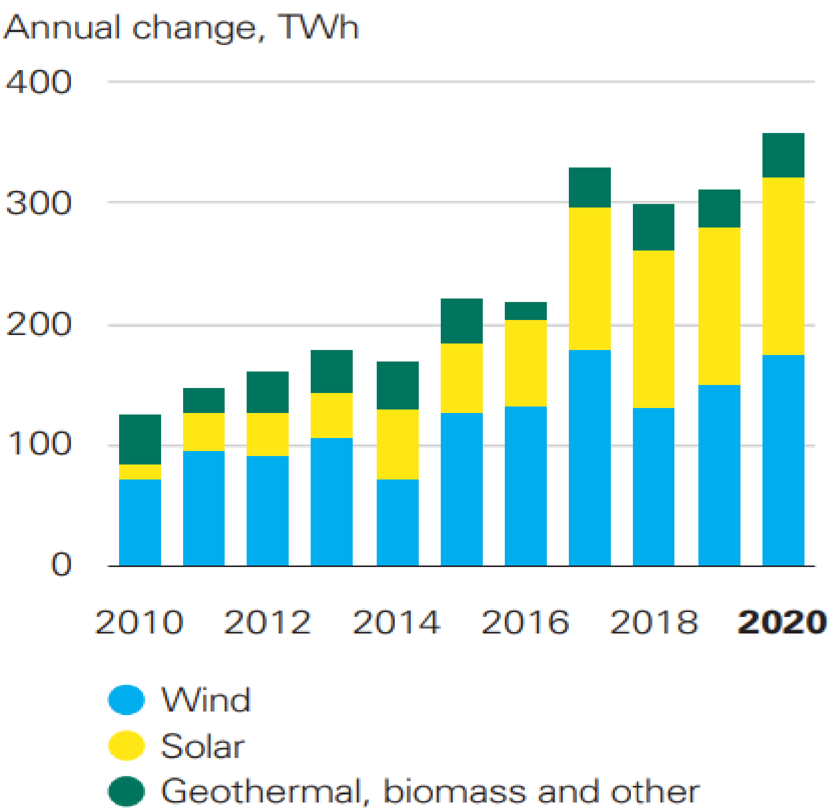


Figure 3.1: The world’s consumption of energy (Eurostat, 2021).

3.1.2 The Renewable Energy Landscape

Energy used for purposes of heating accounts for around 50% of total final energy consumption. Of this, around half is consumed in industrial processes, while another 46% is used in residential and commercial buildings – for space and water heating and, to a lesser extent, for cooking (Nuorkivi, 2016). The remainder is used in agriculture, not only to heat greenhouses but also for drying, soil heating, and aquaculture (IEA, 2019b). Heat demand varies by region mainly due to climatic factors but also to levels of economic development. The majority of final demand in most countries of the Organisation for Economic Co-operation and Development (OECD) stems from residential space and water heating, while in developing and emerging economies most heat is used in industrial processes. On a national level, China accounts for a quarter of global heat demand, some 70% of which is used in industrial processes (IEA, 2019c).

The energy-intensive industrial processes that account for the greatest heat demand are iron and steel manufacturing, cement production, and chemical manufacturing. These processes also have the lowest shares of heat from renewable sources and can be particularly difficult to decarbonise, because in some cases technological advancements will be required if renewable energy is to supply process heat at the required high temperatures (IEA, 2019d). Renewable heat (mainly from bioenergy) commands its highest shares in low-temperature processes such as pulp and paper, wood products, and food and tobacco (REN21, 2020). In the buildings sector, heating and cooling dominate energy use at more than three-quarters of total demand (IEA, 2019c). Globally, energy use in buildings has continued to rise as square footage and population outstrip advances in energy efficiency (Global ABC, IEA and UNEP, 2019).

As a result, the share of renewable heating and cooling in buildings has increased only marginally in recent years (REN21, 2020). Heating demand is climbing sharply each year, having tripled globally since 1990. It is increasing most rapidly in developing and emerging economies (notably in Southeast Asia), driven by expanding wealth and population, changing lifestyles, and extreme weather patterns (*e.g.* higher temperatures) caused by climate change (IEA, 2018a). As the fastest-growing energy use in buildings, it is the leading driver of electricity consumption in heating and cooling (IEA, 2018a).

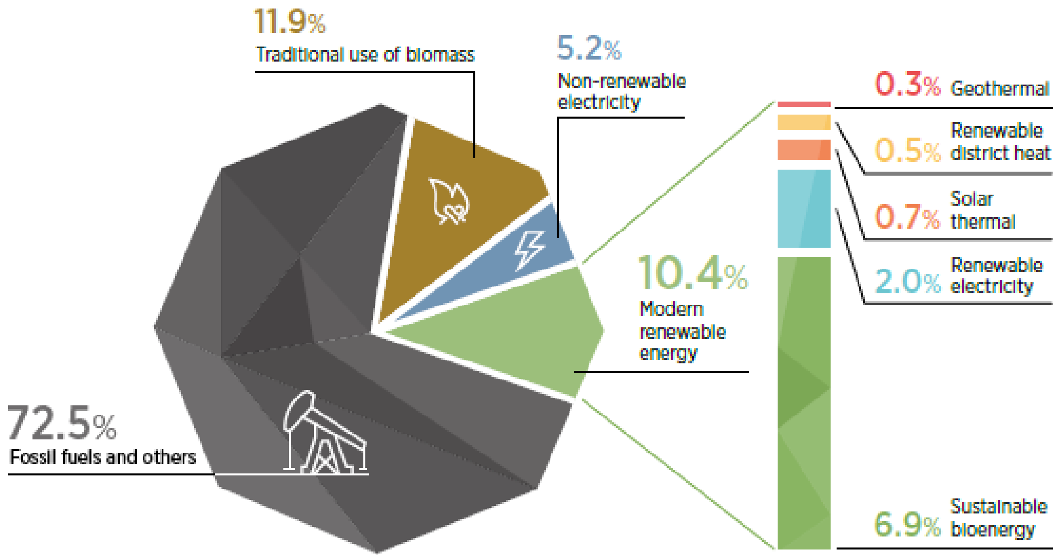


Figure 3.2: Share of energy sources in total final energy consumption for heating and cooling (IEA 2020a).

Most of the energy used for heating in homes continues to be produced from fossil fuels (Figure 3.2). In 2019, fossil fuels and non-renewable electricity met more than 77% of heating demand, with the traditional use of biomass meeting 11.9% (IEA, 2020a, 2020b).

In recent years, the use of modern renewables to meet heating needs has remained limited to some 10% of global demand. The direct use of modern renewables – including sustainable bioenergy, solar thermal and geothermal heat – met 8% of demand for heat and cooling, with renewable electricity accounting for an additional 2% (IEA, 2019c). The weight of heating needs in final energy demand means that the rapid decarbonisation of the energy used to meet those needs is critical for the achievement of climate, environmental and sustainable development goals. Despite this reality, energy use for heating has continued to rise and remains largely based on fossil fuels. As a result of the Covid-19 crisis, renewable heat consumption for 2020 is expected to show a drop of 0.4% from its 2019 level, as industrial and commercial activity has been dramatically reduced (IEA, 2020d). The need is urgent, then, to reduce and even reverse growth in energy demand for heating and cooling, while rapidly scaling up the deployment of renewables. Although the climate crisis is the most commonly cited argument for deploying renewable energy for heating and cooling, there are many other complementary reasons to do so.

3.1.3 Interactions between Sustainable Development and Renewable Energies

Renewable energy technologies provide energy services, including lighting and electricity, heating and cooling, mechanical energy and mobility. Further, relative to other types of energy (from fossil fuels, nuclear power, and traditional biomass), moderns renewables provide a variety of additional socio-economic benefits. In most jurisdictions, these socio-economic benefits are a major force driving policymakers to adopt renewable energy targets and support policies.

The relationship between renewable energy and sustainability can be viewed as a hierarchy of goals and constraints that involve both global and regional or local considerations. In this chapter, and consistent with the conclusion of the chapter two, a starting point is that mitigation of carbon emission will be one strong driving force behind increased use of renewable energy technologies in the United Kingdom and worldwide. To the extent that climate change stabilization levels (e.g., a maximum of 550 ppm CO_{2e} (carbon emission equivalent) atmospheric GHG concentration or a maximum of 2°C temperature increase with respect to the pre-industrial global average) are accepted, there is an implicit acknowledgement of a strong sustainability principle, as discussed in chapter two.

Renewable energy is projected to play a central role in most GHG mitigation strategies, which must be technically feasible and economically efficient so that any cost burdens are minimized. Knowledge about technological capabilities and models for optimal mitigation pathways are therefore important. However, energy technologies, economic costs and benefits, and energy policies, as described depend on the societies and natural environment within which they are embedded. Spatial and cultural variations are therefore another important factor in coherently addressing sustainable development. Sustainability challenges and solutions crucially depend on geographic setting (e.g., solar radiation), socioeconomic conditions (e.g., inducing energy demand), inequalities within and across societies, fragmented institutions, and existing infrastructure (e.g., electric grids) (NRC, 2000), but also on a varying normative understanding of the connotation of sustainability (Lele and Norgaard, 1996). Analysts therefore call for a differentiation of analysis and solution strategies according to geographic locations and specific places (Creutzig and Kammen, 2009) and a pluralism of epistemological and normative perspectives of sustainability (e.g., Sneddon et al., 2006).

These aspects underline the need to assess both the social and environmental impacts of renewable energy technologies to ensure that renewable energy deployment remains aligned with overall sustainable development goals. Some of these important limitations have been addressed in previous chapter, like evaluating these impacts from the perspectives of the weak and strong sustainability paradigms elucidates potential trade-offs between de-carbonization and other sustainability goals. Hence, efforts to ensure sustainable development can impose additional constraints or selection criteria on some mitigation pathways, and may in fact compel policymakers and citizens to accept trade-offs. For each additional boundary condition placed on the energy system, some development pathways are eliminated as being unsustainable, and some technically feasible scenarios for climate mitigation may not be viable if sustainable development matters. However, as also discussed in this chapter, the business-as-usual trajectories to which climate mitigation scenarios are compared are probably also insufficient to achieve sustainable development.

3.1.4 Buildings

The buildings sector consumes around one-third of final energy and releases some 28% of global energy-related CO_2 emissions (IEA and UNEP, 2019). Energy use in the sector is growing at around 1% per year, as global increases in both population and the building floor area continue to overcome any reductions in demand resulting from energy efficiency measures (IEA and UNEP, 2019). Renewable energy is the fastest growing source of energy for buildings, yet in 2017 it met less than 14% of total energy demand in the sector (Building Sector Efficiency, 2020). Energy efficiency remains critical for curbing demand and for increasing the share of renewables in final energy consumption in buildings. Around 77% of global final energy demand in buildings in 2017 was for heating and cooling end-uses, including space heating and cooling, water heating and cooking. Total heating and cooling demand has grown slowly (0.6% annually since 2010), although energy used for cooling (around 6% of building energy consumption) – the fastest growing energy end-use in buildings – rose 4% per year between 2010 and 2018. The remaining final energy demand in buildings (23% in 2017) is for electrical end-uses, including lighting and appliances. Global electricity use in buildings rose moderately during 2010-2018, at more than 2% per year (Building Sector Efficiency, 2020). Overall, energy for heating and cooling remains highly dependent on fossil fuels. In 2018, modern renewables contributed an estimated 10.1% of heating and cooling demand in buildings, up from 8% in 2010. Most of this increase was due to growth in renewable electricity for heat and in solar thermal, while the share of modern bioenergy remained stable (Building Sector Efficiency, 2020).

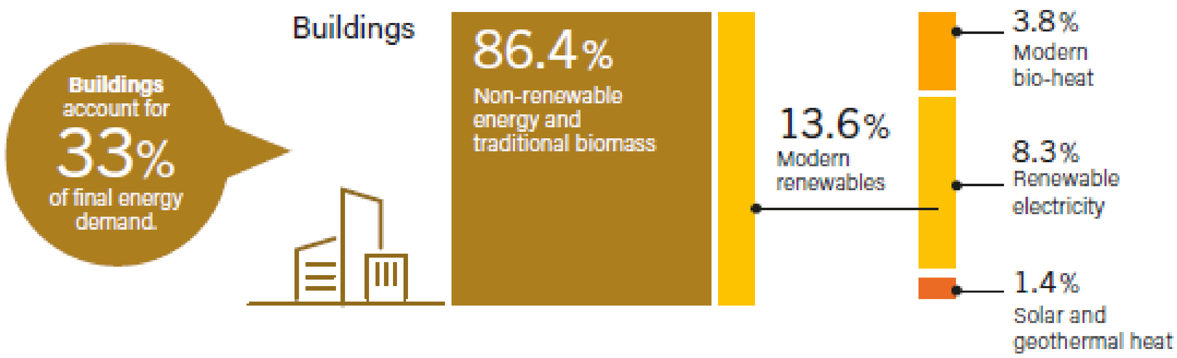


Figure 3.3: Renewable Share of Total Final Energy Consumption in Buildings (IEA, 2019a)

Compared to heating and cooling, renewable energy supplies a higher share of electricity end-uses in buildings, at around 26% (CEC, 2020). This share continues to grow, with the majority of the electricity provided by utility-scale, grid-connected renewables and a growing share by rooftop solar PV systems. In some places, solar PV self-consumption grew and met high shares of building electricity use throughout the year. Direct policy action to stimulate renewable energy uptake in buildings is lacking, particularly related to heating and cooling end-uses. California (United States) was the only jurisdiction to introduce a new technology mandate for renewable energy in buildings in 2019 (BDC, 2019). However, policies prohibiting fossil fuel use for building heat can encourage the adoption of renewables and are a main factor driving the electrification of building heating. Many sub-national (and at least four national) governments introduced or committed to sanctions certain types of fossil fuels for heating in buildings during the year. In terms of climate commitments, renewable energy in the buildings sector continues to be underrepresented in countries' NDCs for reducing emissions under the Paris Agreement. Of the 136 countries that mentioned actions on buildings, only 51 identified actions related to renewables in buildings; meanwhile, only 25 countries mentioned policies related to renewable heating and cooling.

3.1.5 Renewable Thermal Heating

Reducing the use of fossil energy for heating remains one of the biggest challenges of the energy transition. Heating needs – including those for space heating and cooling in buildings, domestic hot water, cooking, industrial process heat, and agriculture – account for the largest share of global final energy consumption and more than 40% of global energy-related carbon dioxide (CO_2) emissions (IEA, 2019a).

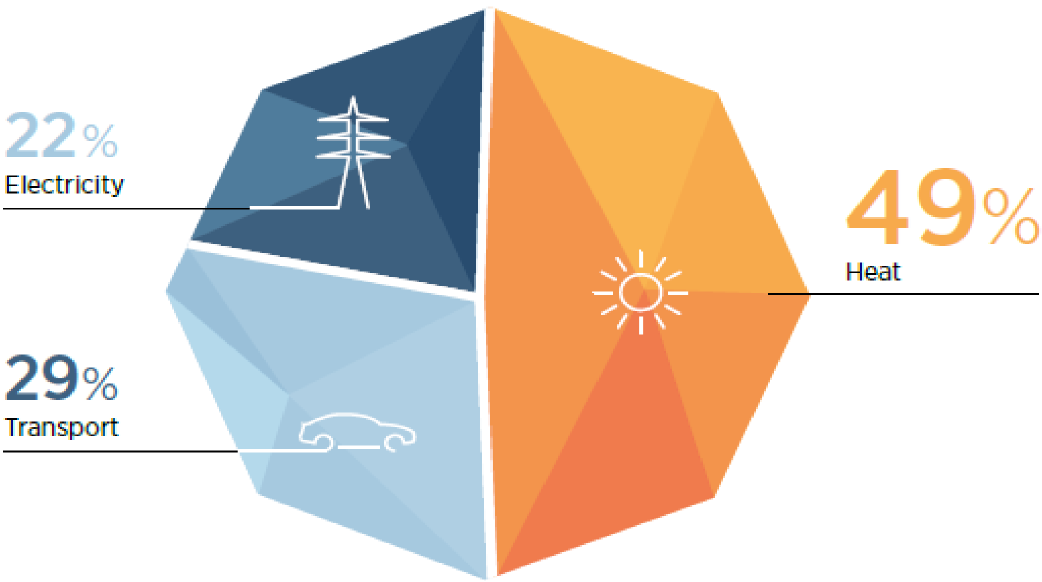


Figure 3.4: Total final energy consumption (IEA 2020b).

Transforming the energy uses for heating is a crucial step toward meeting global goals for decarbonisation, among other key environmental and development objectives. Improvements in energy efficiency are one important strategy for slowing demand growth and mitigating the sector's negative effects on health, the economy and the environment (REN21, 2020). Energy efficiency measures such as building codes and appliance standards often are cost-effective options for decreasing the thermal demand of buildings. Lowering energy demand addresses only part of the problem, however, and is not enough by itself to reduce greenhouse gas (GHG) emissions and meet the goals for sustainable development and access to energy. Alongside efficiency, renewable energy will play a fundamental role in decarbonising the energy used for heating. Renewables have grown rapidly in recent years, having repeatedly broken annual records for newly installed power capacity and continually increasing their share in electricity generation (IRENA, 2020). In the early stages of the Covid-19 crisis, generation of renewable electricity continued its growth, reaching record penetration in some countries despite an overall drop in electricity demand. However, modern renewable energy still supplies only a small share of final demand, mainly in the power sector. Despite its potential for advancing the energy transition, the use of energy for heating hot water in homes has received relatively little attention from policy makers (IEA, 2019a).

3.2 Solar Domestic Hot Water System

The use of green technology as an alternative for electric energy is vital to combat excess carbon emission. Studies from (Tiwari and Mishra, 2012) has emphasized that renewable energy is the best, effective and most efficient solutions for environmental sustainability in the 21^{st} century.

The utilization of renewable solar energy system is a positive technique for minimizing the consumption of fuels and carbon emission reduction in the air. Though, solar systems lack price instability of other and is significant in creating mechanical motion. Although, solar system's availability is sporadic and the request for energy supply during the winter months is at peak. In solar systems, solar radiation from the sun is transformed to heat energy with the use of solar plate collectors (Sharma, 2009). The collector comprises of a fluid that absorbs the heat radiation that is absorbed from the collector. During the winter seasons, the collector antifreeze protection measures should operate below freezing temperatures. Radiations are normally received by direct radiation (parallel ray in clear sky) and diffuse radiation (scattered radiation in a cloudy sky (Aisa and Iqbal, 2016).

The efficiency of solar system is contingent on different factors below:

- The quantity of solar radiation the collector is exposed to
- The brightness of the sun that falls on the collector
- The efficiency of the collector material component and rate of heat loss
- The efficiency of the solar thermal system

3.2.1 Categories of Solar Hot Water System for Bathroom

3.2.2 Open and Closed System

This system embedded with an open container at the top of the solar circuit and it operates by absorbing the volumetric increase of the liquid triggered by the change in temperature. The pressure in the open system correlates at its peak to the inert pressure observed in the liquid column. Whilst the closed systems function with greater pressure and it impacts the solar liquid's physical parameters i.e. evaporation temperature. A distinct safety device is necessary for a closed system (Edenhofer, 2011).

3.2.3 Thermosiphon and Forced Circulation Systems (TFC)

This type of system functions without the need for pumps as gravity is employed for transporting liquid, while the use of pump is essential in a forced circulation system.

3.2.4 Direct and Indirect System

The direct type of system allows for the circulation of water to and from the collector via the storage vessel. The indirect system contains a separated double circuit, water circuit and solar circuit (Mousa et al., 2019). The solar circuit comprises of the solar pump, pipes, collectors and heat exchanger. Water and antifreeze agent mixture can be utilized for effective transfer of heated fluid. The water circuit consist of storage vessel, hot and cold-water installation for the bathroom.

3.2.5 Filled and Drain Back Systems

As indirect system can only contain a collector circuit and can only be partly filled or totally filled. In drain back system, the collector circuit is totally drained each time the collector pump is switched off.

The solar hot water system that is commonly used in the United Kingdom uses a solar collector that converts solar radiation and direct radiating to heat. The collector contains a solar fluid (glycol and water mixture) which is circulated via the collector utilizing pump activate by a controller (Mousa et al., 2019). This process allows the solar liquid to collect heat as soon as it is available and transfer the heat energy to the main hot water tank through solar coil. This process continues only if there is adequate difference in temperature between the inlet and the temperature outlet of the collector. The auxiliary heating of the system switches on if there is need for more hot water than what the collector can supply to the system (Magalhães, 2012).

3.2.6 A Schematic Diagram of Solar Water Heating System

In simple terms, the operation of solar water heating system comprises of a pump or pumps (depending on the number of solar systems) that circulates the heat transfer fluid i.e., water/glycol mix or water via the solar collector for heating. The hot fluid flows via the heat exchanger from where its heats up the cold feed water before it re-circulates back. The storage tank stores the cold feed water and it is continuously heated while the system is functioning. As the water user draws water from the remaining hot water, it is refilled with solar warm water (Aisa and Iqbal, 2016). In this manner, the solar water heater works like a pre-heater and the heating load on the conventional hot water is minimised to a great extent, but it doesn’t serve as a substitute to water heaters. This hybrid method minimize energy and ensures a continuous supply and consumption of hot water at the user chosen temperature (Bennet, 2007). Below is the schematic diagram for a solar hot water system.

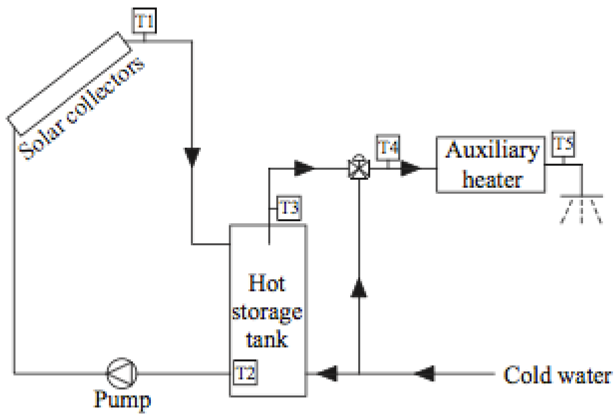


Figure 3.5: Schematic diagram of a solar water heating system Marken (2009).

3.3 Component of Solar Hot Water System

The use of solar energy is reliant on a huge solar fraction to the entire load profile. Solar factor is comparatively straightforward metric for measuring the performance. Solar systems typically comprises of fixtures like control valves, controllers, pumps and components like the solar collection loop which centres on the heated fluid system that is directed into the tank via pipes, pumps, collectors and heat exchangers (Grant, 2007: Chow, 2010).

Domestic solar heat comprises if diverse components based on the type of design. It consists of three major components.

- Solar collector- it converts solar radiation from the sun into energy.
- Heat Exchanger- it transfers heat from the collector into cold water.
- Storage tank- this store the solar heated water. (Chow, 2010).

3.3.1 Solar Energy Collector

These collectors are distinct type of heat exchangers that convert radiation from the sun into inner energy of the transport medium. These are the key processes of any solar energy collector system. They absorb incoming radiation, transform it into heat energy with the aid of a heat transfer fluid flowing via the solar collector (Li et al., 2014). The collected solar energy is transported from the circulating fluid to the incoming potable water in the bathroom system or directly to the hot water storage tank.

Solar collectors can be classified into two: concentrating and non-concentrating. Non-concentrating collectors have equal area for absorbing and intercepting solar radiation, while a concentrating collector basically consist of a concave reflecting surfaces to focus and intercept radiation from the sun into a smaller receiving area and consequently increasing the radiation flux (Li et al., 2014).

Solar collectors can also be characterized by their motion, that is, two axes tracking, single axis tracking, stationary and operating temperature. For this study, stationary solar collector is considered. These types of collectors are permanently in a fix position and does not track the sun. Compound parabolic collectors, evacuated tube collector and flat plate collector falls into the category aforementioned and only flat plate collector is considered in this research because of its cheapness and are mostly installed in most of the existing system in UK (Dupeyrat et al., 2011).

3.3.2 Flat Plate Collectors

Figure 3.5 show the schematic diagram of a flat plate collector and its component employed in this study. For flat plate collector, solar radiation passes via a translucent cover and imposes on the darkened absorber surface of high absorptivity, a big portion of this energy is absorbed by the plate and then transferred to the transport medium in the fluid tubes to be carried away for storage or use (Bhowmik and Amin, 2017). The underside of the absorber plate and the side of the casing are well insulated to reduce conduction losses. The liquid tubes can be welded to the absorbing plate, or they can be an integral part of the plate. The liquid tubes are connected at both ends by large diameter header tubes (Bhowmik and Amin, 2017).

The translucent cover is utilized to minimize convection losses from the plate absorber via the restraint of the stagnant air layer between the glass and plate absorber. It also minimizes loss of radiation from the flat plate collector glass is transparent to short wave radiation received by the sun but it is nearly opaque to long-wave thermal radiation emitted by the absorber plate (Mousa et al., 2019). The orientation of the flat plate collector should be focused directly towards the equator i.e. facing north in the southern and facing south in the northern hemisphere. The collector's optimal tilt angle is equivalent to the latitude of the given location with angle variations of 10-15^{o} horizontal contingent on the application. A simple conventional flat plat collector were designed primarily for use in sunny and warm climatic conditions. Their merits are significantly reduced once weather conditions become adverse during windy, cold and cloudy days (Mousa et al., 2019).

Consequently, climatic influences such as moisture and condensation can cause fast deterioration of the inner components and as a result leads to declining performance and system failure. At present, flat plate collector have been manufactured in various designs and from variety of materials (Felipe et al., 2016). The key purpose is to absorb as much sun's solar energy as possible at a reduced cost. The collector should also have a lengthy effective life, notwithstanding the hostile effects of the sun's ultraviolet radiation, clogging because of acidity, corrosion and or deposition of dust, moisture on the glazing, and alkalinity or hardness of the heat transfer fluid, freezing of water, hail, breakage of the glazing because of thermal expansion etc. these effects can be reduced by using tempered glass (Felipe et al., 2016).

3.3.3 Glazing Materials

Glass is a key material used in glazing solar collectors since its capable of transmitting up to 90 percent of the incoming short-wave solar radiation and transmitting none of the longwave radiation produced externally by the plate absorber. Low content iron glass transmits solar radiation at high rate (0.85-0.90) produced by the sun heated (Karki et al., 2019).

3.3.4 Absorbing Plates

The flat plates component in the collector absorbs much irradiation via the glazing material though losing the smallest possible heat up to the atmosphere and down via the back of the collector casing. The collector plates transfer the retained heat to the transport fluid. The absorption coefficient of the collector surface for shortwave solar radiation hinge on the colour and nature of the coating and on the incident angle (Antoniadis and Martinopoulos, 2019). Generally black is utilised, though numerous colour coatings have been suggested by (Struckmann, 2008) mainly for aesthetic reasons.

Using appropriate chemical treatment, surfaces can be designed to produce high solar radiation absorption coefficient and low longwave emittance values. Principally, typical selective surfaces consist of a thin upper layer, which is highly absorbent to shortwave solar radiation but relatively transparent to longwave thermal radiation, deposited on a surface that has a high reflectance and a low emittance for longwave radiation. Selective surfaces are particularly important when the collector surface temperature is much higher than ambient air temperature (Antoniadis and Martinopoulos, 2019).

3.3.5 Evacuated Tube Collectors

These solar collectors comprise of a heat pipe inside a vacuum-sealed tube. The vacuum envelope reduces convection and conduction losses, so the collectors can operate at higher temperatures than Flat plate collector (FPC). Like FPC, they collect both direct and diffuse radiation. However, their efficiency is higher at low incidence angles. This effect tends to give Evacuated tube collector (ETC) an advantage over FPC in day-long performance (Bhowmik and Amin, 2017).

Heat pipes are structures of very high thermal conductance (Li et al., 2014). They permit the transport of heat with a temperature drop, which are several orders of magnitude smaller than that for any solid conductor of the same size. Heat pipes consist of a sealed container with a small amount of working fluid. The heat is transferred as latent heat energy by evaporating the working fluid in a heating zone and condensing the vapour in a cooling zone, the circulation is completed by return flow of the condensate to the heating zone through the capillary structure which lines the inner wall of the container (Bhowmik and Amin, 2017). These tubes are mounted, the metal tips up, into a heat exchanger (manifold). Water or water/glycol mixture flows through the manifold and picks up the heat from the tubes.

3.3.6 Tanks

The tanks coveys the hot water that has been heated by the collector fluid. The hot water is stored in the preheating tank before it moves down to the backup tank. Solar hot water system can either come in a single tank or double tanks for energy efficiency and integrates heating elements. This backup tank delivers hot water in the event there is not enough solar-heated water (Carotenuto et al., 2017).

In cold climatic conditions, double tanks are essential to store adequate solar-heated water over very cold or cloudy periods (Renaldi and Friedrich, 2019). In these cases, a solar storage tank to which the solar loop is plumbed is connected in a series to an auxiliary water heater or boiler that has "back-up" electric or gas heating. Furthermore, solar thermal systems that provide heated water for applications other than potable domestic water such as space heating may also utilize a minimum of two storage tank (Renaldi and Friedrich, 2019).

3.3.7 Heat Exchangers

In solar hot water system, heat exchanger is utilized for conveying energy collected from the solar collector's heated fluid to the pre-heating tank and can either be external or internal to the pre-heating tank (Solar Heat Exchangers, 2020). Heat exchanger comprises of different types such as shell-in-tube, coil-in-tank, tube pipe, wraparound-plate and side arm design. Heat transfer happens when one fluid moves via the inner tube while a second fluid moves in a different direction in the space between the inner and outer tubes (Solar Heat Exchangers, 2020). This classification of heat exchanger is generally utilized in smaller systems e.g., bathroom in domestic systems. Moreover, for an indirect system using a pipe in tube heat exchanger, the collector heat transfer solution would be in the inside tube while the potable water would be in the space between the inner tube and the outside of a tube. Systems with heat exchangers can experience a 10-20% loss in total efficiency in the transfer of heat from the collection solar loop to the potable water. Nevertheless, economic savings and fail-safe freeze protection may offset that efficiency loss (Benakopoulos et al., 2021). For example, heat exchange systems can use corrosion-inhibiting heat-transfer fluids that allow the use of less-expensive aluminium or steel in collectors, exchangers, and piping.

The sizing of heat exchangers is normally centred on their heat-transfer abilities, the temperatures of outgoing and incoming fluids flow-rates. For packaged and approved or certified systems, the manufacturers have sized the heat exchanger and matched its performance to the collector array and flow rates of the system. Under-sizing the heat exchanger is a common mistake of home-built systems and might lead to inefficient functioning of solar thermal systems (Benakopoulos et al., 2021).

3.3.8 Pump

In a pressured solar hot water system, pumps are utilized to transfer heated fluid from the collector to the pre-heating tank and vice-versa (Marco et al., 2020). Pumps are sized to obtain a good head pressure and static demand to give exact system design and flowrate performance. For solar system that requires a very high pressure to elevate water from the tank to the collector, the use of powerful pumps such as centrifugal pumps are significant but pump determination depends on different factors (Eicher, 2012), such as:

- Type of solar hot water system
- Operating temperatures
- Friction heat losses
- Heat collection fluid
- Required fluid flow rates

3.3.9 Piping

Piping is utilized in a solar hot water system to provide a network path for hot water to be transported. Subsequently, appropriate piping for the system is paramount and these is contingent on different factors like pressure, temperature and the connectivity to other system components (Carotenuto et al., 2017). The applicability of piping components for solar hot water system is dependents on material contents like copper, bronze and brass. Majority of solar hot water system utilize copper pipping due to its resistance to corrosion, withstand high temperatures and its durability. When installing long-system piping runs, the tube is commonly used for support. Subject on the kind pipe, the piping may be flexible due to high temperatures (Marco et al., 2020).

3.4 Solar Water Heating System Performance Studies

There has been extensive work regarding how to improve the performance of solar water heating systems both experimentally and analytically. A number of studies have concentrated on the relationship between performance and design variables. Some examples of the latter are: the storage tank size, the number of tanks, the solar collector area, the collector and heat exchanger flow rates, the hot water load profile, the hot water consumption, the auxiliary water heating device configurations, the cold make-up water replenishment profile, and the heat exchanger configuration.

Buckles and Klein in 1980 investigated the effects of the number of storage tanks, the storage capacity, insulation, hot water load profile and the tempering value. Their simulations studied four basic system configurations employing three representative collector areas and hourly weather data for Madison in Wisconsin, Albuquerque in New Mexico and Charleston in South Carolina. One of the main outcomes of this work was a modified f-chart design method which can be used to predict the long-term performance of various types of solar water heating systems. The four system configurations studied are single tank with internal heat exchanger, double tank with internal heat exchanger, single tank with external heat exchanger, and double tank with external heat exchanger. The six hourly hot water load profiles were the RAND average profile, 24-hr constant profile, early morning profile, late morning profile, early afternoon profile, and late afternoon profile. The authors found the performance differences between one tank and two tank systems were small and the internal heat exchanger and external heat exchanger with the same effectiveness provided the same performance was found to have little effect on the monthly average system performance. They also concluded that the overall system performance is not sensitive to the hot water load distribution during a day as long as the storage tank is sized to be sufficient and the overall daily hot water consumption remains the same.

Shariah and LÖf (1997) simulated a Thermosyphon solar water heating system with an electric auxiliary heater using TMY weather data for Los Angeles, California. Using a TRNSYS simulation, the effects of hot water delivered temperature (60 and 80 ˚C), daily hot water load (250 and 150 litre), type of hot water load profile, and locations of auxiliary heating were studied. They found the system's annual solar fraction is largely affected by the hot water load profiles and the delivered temperature.

Fanney and Klein (1988) investigated the effects of heat transfer fluid on the performance of a forced circulation solar water heating system which either directly circulates the domestic hot water through the solar collector or employs an external heat exchanger to transfer the collected solar energy to the domestic hot water. Two identical single tank solar hot water heating systems with and without an external exchanger were set up at the National Bureau of Standards Solar Hot Water Test Facility in Gaithersburg. The side-by-side experiments showed that, for the single tank direct system (without an external exchanger) equipped with conventional return tubes, the overall system performance was improved by lowering the solar collector heat transfer fluid flow rate; however, if a specially designed return tubes minimizing mixing in the storage tank was operated with the same collector fluid flow rate, only a small improvement in system performance occurred as compared with the same system operating with the conventional fluid flow rate. A simulation of the indirect system (with an external heat exchanger) operating with a range of heat exchanger design and collector and tank side flow rates showed no improvement in system performance when reducing the collector fluid flow rate.

Solar fraction is an important performance indicator for solar water heating systems because it quantifies the conventional energy replaced by solar and reflects potential operating cost savings. Hobbi and Siddiqui in 2009 modelled an in-direct, forced circulation, solar water heating system employing a flat-plat collector for a single-family residential unit in Montreal, Canada by using TRNSYS. Their work examined the impact of various design parameters on solar fraction. Optimized values of design parameters for a specific system were found by performing two sets of simulations. One simulation was for the determination of optimum system parameters, and the other was for optimum collector design parameters. The system was simulated subject to only one hot water load profile. The results indicated that the solar domestic hot water system being modelled was able to provide 53-67% and 30-38% of hot water demands in summer and winter, respectively. Knudsen, 2002 showed that mixing of cold make-up water inside the storage tank reduces the tank's performance by destroying the thermal stratification in the tank. In reality, thermal stratification can be easily broken by either an immersed heating device which heats the water at different levels creating uniform tank temperature in short time, or high collector flow rates which result in short tank turnover times causing a nearly uniform tank temperature. Kulkarni et al., 2008 proposed a novel strategy for cold water replenishment to improve the overall system performance even without stratification. The results of a case study showed that about 14% of the annualized system cost, 13% of the collector area, and 10% of storage volume can be reduced for the cost-optimal system configuration.

Yi-Mei et al., (2012) experimented with eight typical solar water heaters that were connected in series. Degree of temperature stratification and thermosyphon flow rate in a horizontal tank were evaluated. The system was tested under no-load, intermittent and continuous load conditions. Results showed that after a water draw-off period, the tank water would redistribute itself and temperature stratification was redeveloped within a short period under intermittent load conditions. The thermal efficiency for intermittent load conditions is about 5.8% to 7.0% higher than the value for the no-load condition. Under continuous load conditions, the temperature stratification in tanks is only preserved at flow rates less than the thermosyphon flow rate. The discharge efficiency decreases significantly for systems comprised of more than four thermosyphon SWHs, and there is no useful energy transferred to the water. The overall efficiency increases with an increase in the flow rate. Studies by Huimin et al., 2015 investigated the performance of SWHS based on FPC. The test data were analysed from the aspects of different solar irradiation, ambient air temperature and initial temperatures in water tank. Results show that (1) more solar irradiation could achieve higher system efficiency. When the solar irradiation reached 21MJ MJ, the daily system efficiency could be 56%. The daily effective heat gain was nearly 1050MJ. (2) Under different ambient air temperature conditions, the maximum value of daily average system efficiency was 62% with small difference between the collectors' temperature and the ambient temperature. While the daily average system efficiencies were nearly 55% on other days. Xilian et al., 2021 also performed a one-year experimental study of the solar water heating system of a solar hot-water system. A comprehensive evaluation was conducted by analysing the instantaneous collection efficiency of the hot-water system, the average daily collection efficiency, average monthly collection of thermal efficiency, heat, electric heating, power consumption, and users of the solar hot-water system. The main conclusions highlighted that the ambient temperature or solar irradiance were correlated positively with the thermal efficiency when the solar irradiance or ambient temperature were constant, and the maximum thermal efficiency was 56.63%.

The literature indicates that many of the earlier studies on solar water heating focused on how to improve solar collector performance, storage tank thermal performance, and how to manage the hot water usage pattern. In practice, mechanical systems designers are not able to change many design parameters because they are determined by equipment manufacturers. Systems designers only select the equipment with the performance closest to the design requirements using standard product catalogues. At the moment, demand side management, such as changing the hot water usage pattern, and reducing the hot water consumption, is beyond the system designer's control. The most common hot water load profiles being used by earlier studies are the Rand profile, a continuous use, an evening, and a morning profile. All of them are on an hourly basis profiles which are usually enough to investigate the system's long-term average performance; however, in principle, the hot water load profile is affected by several factors and can vary from day to day, season to season and family to family (Hobbi and Siddiqui in 2009). Hourly load profiles usually overestimate the piping heat loss and do not accurately reflect short duration hot water consumption (NAHB, 2012).

Table 3.1: Recent studies on solar thermal systems

System Types	Reference	Study Simulation	Experimentation	Collector	Working fluid	Thermal efficiency (η)/COP
Direct circulation system	Yi-Mei et al. (2012) Huimin et al. (2015) Walker et al. (2021)	- - ❖	❖ ❖ -	FPC FPC Evacuated tube heat pipe	Alcohol Water Water	η = 56% η = 34% η = 28%
Indirect circulation system	Chong et al. (2011) Chaturvedi et al. (2015) Bhowmik and Ruhul (2017) Kenneth et al. (2021) Siuta-Olcha et al. (2021)	❖ ❖ ❖ - -	❖ - - ❖ ❖	V-trough reflector Flat plate with tubes FPC with reflector FPC ETC	Water R-12 Air Water antifreeze Water	η = 65.05% COP = 2.5 η = 20.30% COP = 0.201 η = 45.50%
Thermosyphon system	Esen and Esen (2005) Fu et al. (2019) Arab et al. (2012) Jasim et al. (2021) Renaldi and Friedrich (2018) Bany et al. (2019)	❖ ❖ - - - -	❖ ❖ ❖ ❖ ❖ ❖	FPC FPC FPC Evacuated tube heat pipe Evacuated tube heat pipe FPC	Alcohol Alcohol Alcohol Water Water Water	η = 48.72% η = 49.43% η = 50.84% η = 61% η = 63% η = 59%

Table 3.2 Different studies using indicators to measure the performance of solar thermal system.

Authors	**Purpose of Study**	**Selective Performance Indicators**
Dasaien and Elumalai (2017)	Performance enhancement studies in a thermosyphon flat plate solar water heater with CuO nanofluid	Performance ratio, solar fraction
Hong et al. (2014)	Performance investigation of a combined solar thermal heat pump heating system	Heat pump COP
Maram et al. (2019)	Performance Study of Different Types of Solar Water-Heaters Collectors	Primary energy savings
Beccali et al. (2020)	Solar and Heat Pump Systems for Domestic Hot Water Production	Mean daily efficiency, Environmental impact
Benakopoulos et al. (2021)	Overview of Solutions for the Low-Temperature Operation of Domestic Hot-Water Systems with a Circulation Loop	Overall efficiency
Renaldi and Daniel (2019).	Techno-economic analysis of a solar district heating system with seasonal thermal storage in the UK	Cost of energy saved
Bhowmik and Amin (2017).	Efficiency improvement of flat plate solar collector using reflector	Energy efficiency, COP

Kenneth et al. (2021)	Experimental analysis of solar enhanced water heating system with energy storage	Efficiency and Energy fraction for hot water
Siuta-Olcha et al. (2021)	Experimental studies of thermal performance of an evacuated tube heat pipe solar collector	Overall efficiency
Aisa and Iqbal (2016)	Modelling and Simulation of a Solar Water Heating System with Thermal Storage	Storage tank thermal efficiency, heat loss
Jasim et al. (2021)	Numerical and experimental investigation of a thermosiphon solar water heater system thermal performance used in domestic applications	Hot water volume, Energy utilisation factor
Jahangiri et al. (2021)	Assessment and Modelling of Household-Scale Solar Water Heater: Technical, Environmental, and Energy Analysis	Solar fraction, renewable energy fraction, performance ratio.

3.5 Smart Control Systems

Report published by Water-Wise, 2014 have concluded that more than 66% of the energy utilized for hot water heating in domestic applications can be saved using smart technical developments. The efficiency of building in a domestic application relies on several factors i.e., the operational performance of the control system, the boiler efficiency and the building physics (Deakin et al., 2015). According to studies from Pomianowski et al., (2020), it was assessed that majority of the domestic hot water heating functioned inefficiently apparently because of good control systems and thereby costing an extra million in pounds every year. The author concluded laying significant emphases on using an appropriate control system as a requirement to save energy in a building and without proper control systems for heating supplies, a big quantity of energy will be squandered and as a result costing millions of pounds/year.

There are various approaches to the design of controllers. Among them, the Proportional Integral Derivative (PID) controllers have turn out to be famous for hot water control. PID controllers can be designed to sustain the level of water flow, but the limitation is its feedback type controller that is after the output is affected by error that the controller will take control action. Also, it doesn't recognize the unanticipated alteration in the set point and thus, the transitory performance of the (PID) controller system is oscillatory (Bai and Wang, 2007). Conventional control approaches are not convenient to solve the complex issues in this highly non-linear system. To overcome the difficulties, innate in controlling water level, a controller based on fuzzy logic was employed.

Neural networks and fuzzy logic control have emerged over the years and became one of the most active areas of research. There are many works in literature that addressed the liquid level control issues using neural networks and fuzzy logic. Due to its simplicity, fuzzy logic control method became most famous in this application.

3.5.1 Applications of Fuzzy Logic

The application of FL in control systems is useful to define some terminology use to describe the fuzzy systems. The first concept is the one of linguistic variable, which are variables representing inputs or outputs of a system with a related range of expected values (Nguyen et al., 2019). In the application of FL to the control of a single-input single output (SISO) systems, one input linguistic variable and one output linguistic variable are requested. Instead, in the case of multiple-input multiple-output (MIMO) systems where two or more inputs and outputs linguistic variables are required to control the linguistic variable (Almahdi et al., 2018). The number of linguistic terms (or linguistic values or categories) of the input or output needed to represent the universe analysed, is chosen based on the physical quantity represented and the application (Nguyen et al., 2019). Normally the linguistic variables have an odd number of linguistic terms, with a middle category and symmetric linguistic terms at each extreme. The linguistic terms (or categories or values), assumed by the linguistic variables considered, are defined mathematically by numerical functions called membership functions (MF) (Arpit and Abhinav, 2020). A membership function represents the degree of membership of linguistic variable within their linguistic terms. The degree of membership is a real number between 0 and 1 where 0 is equal to 0% membership and 1 is equal to 100% membership. There are some different normalized standard membership functions of different shapes: triangular; trapezoidal; bell (gaussian type); - vertical line (singleton type) (Arpit and Abhinav, 2020).

Some of the common shapes used in the membership functions are reported with the mathematical definition. Regarding the definition of the membership functions, as reported in (Arpit and Abhinav, 2020), the effect of the overlapping of membership function on the input, strongly affect the response of the fuzzy system. Instead of this effect, the overlapping degree of membership functions on the output (consequent part) has no significant influence on the result on the output signal of the fuzzy system. Normally is used to overlap the different membership functions at 50% of the definition (Arpit and Abhinav, 2020). Regarding the membership functions of the outputs, as reported in (Vassilyev et al., 2020), the result of the fuzzy system does not depend strongly on how much the MFs are overlapped if they cover the universe of discourse. Sparse MFs can instead affect the response of the fuzzy system.

The last central concept of the FL are the rules that are used to describe the relationships between input and output linguistic variables based on their linguistic terms. “Rule-base” is normally referred to a set of rules for fuzzy system. Rules are composed by an “Antecedent”, or “If portion”, where one or more inputs are combined and “Consequent” or “Then portion” with the outputs (Espitia et al., 2019). Normally rules appear in this form:

If (“Antecedent”) Then (“Consequent”) for this reason, sometimes is it used as “If-Then” logic referring to FL. If the “Antecedent” an input linguistic variable is combined with a corresponding linguistic term while the “Consequent” an output linguistic variable is associated with the corresponding linguistic term. The results of the rule represent the action desired that fuzzy control is done if the linguistic terms of the inputs linguistic variables in the rule are met (Raid et al., 2021). As an example:

If A is A1 AND B is B1 OR C is C1 Then U is U1

Where A, B, C and U are fuzzy variables while A1, B1, C1 and U1 are linguistic terms described by their membership functions. AND, OR are connectives that will be explained later; this rule is formed by three antecedent and one consequent. From the operative point of view, the rules are developed to compute the inference process of the fuzzy system that allow to know what the output is when certain combination of the inputs is given. The total of possible rules for a fuzzy system is defined in function of the number of input linguistic variable (m) and the number of linguistic terms used for each input (p). The total number of rules possible (N).

The rule base is normally reported in a table, in this manner the inconsistency or the rule missing could be easily detected. In case of a large number of inputs a cascading fuzzy system is used in order to avoid a large number of rule basis. In this solution, the first fuzzy system serves as the inputs of the second fuzzy system until the last controller (Raid et al., 2021). For a controller with multiple input (e.g. MIMO) the two (or more) input linguistic variables and terms are normally combined using connectives.

The AND minimum specify to use the smallest degree of membership of the antecedents as the truth value of the aggregated rule antecedent, while the AND product specifies to use the product of the degrees of membership of the antecedent. Instead, the OR (Maximum) compute the maximum between the two degree of membership of the two antecedents, while the probabilistic OR specifies the use of the sum of the degree of membership of the two antecedents (Md-Tanvir, 2020). In this way the inputs are combined using connectives in order to determine the truth value for the aggregated rule. In the consequent of the rule, one (for SISO systems) or more (for MIMO) outputs are defined (Md-Tanvir, 2020).

3.5.2 Summary

A review of literature also revealed that some studies have been carried out to determine the technical specifications and performance of different designs of variables within solar water heating systems. However, studies have also shown that the solar hot water systems are well-known and researched technology and many of the earlier studies on solar water heating have focused on how to improve solar collector performance, storage tank thermal performance, and how to manage the hot water usage pattern but have not demonstrated how the use of holistic and integrated interactions of system components can further improve the efficiency of the solar hot water system. In practice, mechanical systems designers are not able to change many design parameters because they are determined by equipment manufacturers. Systems designers only select the equipment with the performance closest to the design requirements using standard product catalogues.

Review from the literature shows that, demand side management, such as changing the hot water usage pattern, and reducing the hot water consumption, is beyond the system designer’s control. None of these studies have drawn on this message and discussed or mapped out how hot water usage pattern can further contribute to the efficiency of the bathroom and provide thermal comfort for its users. This study tends to capitalize on this fact and designed smart and intelligent energy efficient controller for a bathroom system that is associated with hot water use and can influence environmental parameters and provide thermal comfort for its user. The design also offers an efficient, smart and automatic control of water-flowrate and temperature in the bathroom that is tailored to the user hot water usage pattern that can also save energy in the bathroom system.

The previous sections have shown that renewable (solar) energy can contribute to sustainable development as highlighted in this chapter to varying degrees. While benefit with respect to reduced environmental and health impacts may appear more clear-cut, the exact contribution to, for example, social and economic development is more ambiguous. Integrated models may be in a favourable position to better link the sustainable development, renewables and smart system paradigms for decision-making processes. Within well-defined guardrails, integrated models could explore scenarios for different mitigation pathways, taking account of the remaining sustainable development goals by including important and relevant bottom-up indicators.

Consequently, this study offers a system to link sustainability, renewable and smart systems for achieving significant energy savings, carbon reductions and environmentally friendly goals. More importantly, there is a significant need towards the advancement of knowledge development, improving the understanding and providing a framework for a future smart renewable-based bathroom. As a result, the next chapter deliberated upon developing conceptual and mathematical modelling of solar bathroom and smart fuzzy control that sustainably contributes towards thermal comfort, achieving significant energy savings and reduced carbon emissions.

Chapter Four

4.0 Modelling of Bathroom Solar Water Heating System and the Smart Water-Energy Controller

4.1 Introduction

This chapter is centred on modelling a sustainable solar-based water heating system for a bathroom unit and a smart programmable controller. With the adoption of conceptual modelling, this study has designed and implement a bathroom unit that is environmentally sustainable and smart. The conceptual modelling of the bathroom unit is meticulously studied and each component of the system which is in accordance with the manufacturer's specifications were described. The actual system components were examined and applied as a basis for the system's description in this chapter. Consequently, the model of bathroom system and the smart controller are designed to improve the overall system efficiency with necessary optimization while achieving substantial energy savings, carbon reductions and tackling global warming climate change. Parametric analysis was also conducted to know how change in variable parameters, location, load and switch-on temperatures will affect the performance of the system designed.

Furthermore, a smart control for the bathroom system is designed to use the fuzzy logic controller, it was used because of its easy adaptability to the bathroom user’s pattern. Likewise, its control execution is mostly founded on accurate determination of fuzzy and an inappropriate determination of the parameters will prompt poor control execution. Accordingly, the intelligent fuzzy controller is projected to direct the parameters of the fuzzy logic controller naturally to guarantee output control optimisation.

4.2 The Modelling Approach

The strategies and methods applied in the modelling process in this study is referred to as modelling approach. There are various modelling strategies that can be applied in this study. However, this study employed conceptual modelling approach that are suitable and principally connected to the scope of this study. The conceptual modelling approach are employed to model the bathroom solar water heating system and the smart/ intelligent fuzzy controller. Basically, the conceptual method with the justification and basis in existing study are discussed in the following section in this chapter.

4.2.1 Conceptual Modelling and Justification

Conceptual model is a representation of a system, made of the composition of concepts which are used to help researchers know, understand, or simulate a subject the model represents. According to Yilmaz et al., (2015), the conceptual model is a consolidation of all goal-relevant structural and behavioural features of a system that is presented in a predefined format. It provides foundation for the development of the simulation program. Due to its different utilizations in the field of science and technology, agreeing to a unified operational definition in terms of modelling has been difficult.

There is a lot of focused studies in artificial intelligence and software engineering on conceptual modelling that spotlights on demonstrating ontologies and techniques, for example, UML (Unified Modelling Language) for knowledge, ideas, and thoughts modelling. With regards to operational research ventures, the utilisation is more extensive that in general allude to the entire exercise (anyway it is done) of choosing what to incorporate into the model. Different researchers unfolded the advantages of a basic model contrasted with multiplex model together with being more to comprehend, faster to analyse and run, requiring fewer resources and less data, simpler to update and transform and possessing a more noteworthy possibility of acknowledgment (Ward, 1989; Salt, 1993). A straightforward model is recognized as a key factor in operational research accomplishment in the study by Tilanus (1985). In this regard, this study offers a straightforward modelling concept of the system by way of utilising conceptual modelling techniques.

Figure 4.1 demonstrates the main conceptual modelling artefacts adopted for modelling the proposed system in this study. The projectiles in this chart signify progression of data, for example, data about real world provides into the description of the system. The projectiles are not illustrative of sequence stages inside the modelling procedure (Balci 1994; Willemain 1995).

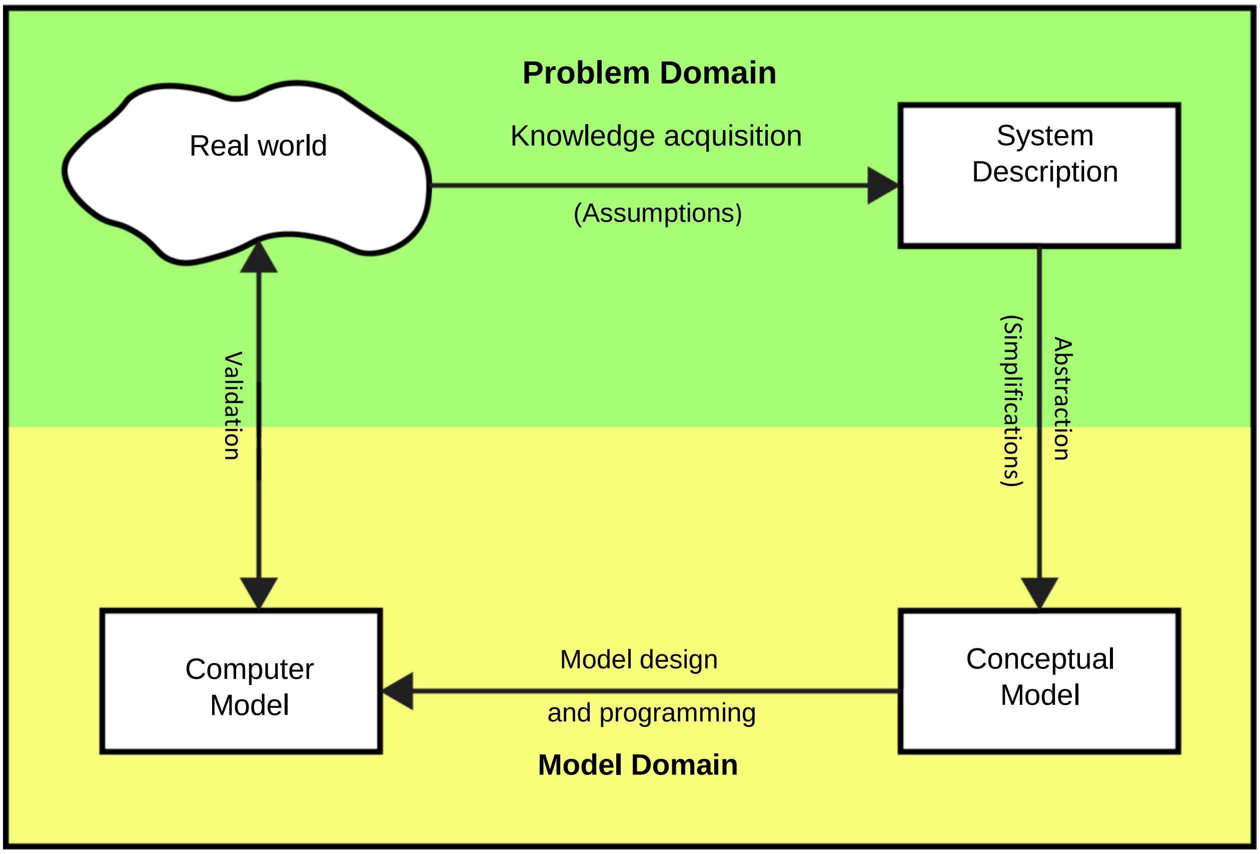


Figure 4.1: Conceptual modelling artefacts (Balci 1994; Willemain 1995).

The real world (future or current) as signified by the cloud in Figure 4.1 is where the problem state exists in. Precise artefacts of the conceptual modelling procedure are signified by the three rectangles as presented in Table 4.1.

4.2.2 The Modelling Processes

Table 4. 1: Modelling procedure

The modelling process	
System description	a system description of the problem situation and the system in which the problem situation resides
Conceptual model	‘the conceptual model of non-software specific description of the computer simulation model (that will be or has been developed), describing the objectives, assumptions, input and output content of the model
Computer model	A software specific design and software representation of conceptual model

The artefacts are very isolated. It is not necessarily the case that they are in every case unequivocally communicated, except for the computer model. For example, conceptual model and the description of the system may not be (completely) archived and can stay inside the modeller thoughts and the issue proprietors. It is obviously, frequently great modelling exercise to archive both conceptual model and the description of the system.

As highlighted from the research study by Robinson (2008), the computer model is firmly not the portion of conceptual modelling, however it does, obviously, typify the conceptual model inside model code. For the computer model alongside by model plan, and validation are incorporated into Figure 4.1 for entirety. It is essential to perceive the difference between conceptual model and the description of the system. The description of the system identifies with the issue area otherwise known as the domain of problem - meaning it portrays the issue and this present reality. The conceptual model has a place with the model area that portrays which portion of the system depiction will be incorporated into the model simulation and at which LOD (Level of Detail). The researchers' knowledge is that these dual artefacts are regularly confounded and realised as undefined. The definitions at this point are near those utilized via Zeigler (1976). This real world according to studies is typically identical to 'base model' as revealed by Zeigler; the conceptual model directly relates to 'lumped model', the description of the system to the 'experimental frame'.

For the reason that conceptual models are just portrayals of theoretical ideas and their individual connections, the possible advantage of interest of actualizing a conceptual model are numerous. However, to a great extent rely upon the technicality and knowledge to devise a solid model and in light of the fact that a conceptual model is so dynamic, and in this way, is just as obliging as the system is devised. There can also be a couple of cautions or disadvantages when executing a conceptual model. Generally, the next subsection offers the advantages and disadvantages of conceptual modelling.

4.2.3 The Advantages and Disadvantages of Conceptual Modelling

Advantages of conceptual modelling

1. Defines system scopes: A solid conceptual modelling can be used to define the system scope and assist with time management and scheduling (Robinson 2008; Wazlawick; 2014; Yilmaz et al., 2015).
2. Establishes the system concept: By establishing and defining all the different concept that are likely to come up in the life cycle of the system, a conceptual model can help ensure there are fewer system short comings where the system might be otherwise be neglected or forgotten (Johnson, 2008; Parush, 2015).
3. Base model for other models: For most systems, additional and less abstract models will need to be generated beyond the rough concept in the conceptual model. It serves as a great start off point from which more other models can be established (Thalheim, 2011; Yilmaz et al., 2015).
4. High-Level Understanding: Conceptual models serve as a great tool by providing a high-level understanding of a system throughout the system life

cycle. This can be particularly beneficial for researchers and executives, who may not be dealing directly with coding or implementation but require a solid understanding of the system and the relationships therein (Robinson, 2008; Parush, 2015).

Disadvantages of conceptual modelling

1. Creation requires deep understanding: while conceptual model can be adaptive, proper creation of conceptual model requires a straightforward and deep understanding of the system along with associated system (Thalheim, 2011; Yilmaz et al., 2015; Parush, 2015).
2. Potential time sink: Improper modelling of the system in a conceptual model may lead to time wastage and potential cost sunk, where development and planning have largely gone astray of what was necessary in the first place (Bredehoeft, 2005; Tappenden, 2012; Yilmaz et al. 2015).
3. Possible system clashes: Since conceptual modelling is used in representing abstract systems, it is possible to create clashes between different components. In this case, a clash simply indicate that one component is conflicting with another component. This may be seen where design or coding clash with deployment as the initial assumption of scaling during design and coding were proven wrong when the actual deployment is correct (Geva, 2008; Thalheim, 2011).
4. Implementation Challenge Scales with Size**:** While conceptual models are not inherently ill-suited for large applications, it can be challenging to develop and maintain a proper conceptual model for particularly complex systems, as the number of potential issues, or clashes, will grow exponentially as the system size increases **(**Parush, 2015; Becker et al., 2015).

Hence, the justification for using conceptual model in this study is the suitability of the model for the proposed bathroom solar water heating to effectively describe the objectives, inputs, outputs, content, assumptions and simplifications of the system. Research studies reveal that conceptual model for a system establishes a straightforward consolidated holistic view of what the system is, what it does and the users it will help (Robinson, 2008; Yilmaz et al., 2015; Parush, 2015). The model consolidates the components and mechanisms of bathroom solar water heating to reduce the level of energy consumption and rates of carbon emissions. Likewise, the bathroom hot water control conceptually consolidates the FLC temperature, and pressure to maximally optimise the level of thermal comfort within the bathroom environment. As a result, conceptual modelling is justified in this study and applied for modelling of the solar hot water bathroom and the design of smart control.

The bathroom solar water heating is simulated through utilising Polysun software in chapter five of this study. Research studies by Broman (2015), Džiugaitė-Tumėnienė (2014) and Koke (2018) unfolded that a number of software collections like Polysun have been used and the results are equivalent to TRNSYS. There are several software that have been successfully applied in solar energy study i.e., Insel, PVSyst, Polysun, T*Sol, commercial, PVGIS, RETscren).

Studies from Kyriaki (2017) and Koke (2018) have described Polysun as the most effective software range for simulation-based planning, design, and optimization of holistic and integrated energy systems for buildings. It enables effective simulation for solar-thermal and photovoltaic systems with reliable results in terms of functionality, energy efficiency and profitability. Polysun simulation software allows for renewable energy systems to be created and combine different technologies with each other (solar thermal, PVT, photovoltaics, boiler system, ground-source loops, cogeneration units etc.). Therefore, Polysun software model-based capacity is able to effectively describe the objectives, inputs, outputs, content, assumptions and components of the bathroom unit.

Research studies by Milrad (2013), likewise revealed that computer simulation software programs that is applied in general engineering (for example Matlab, EES, Berkeley Madonna, Stella) are basically less appropriate for the study of solar energy because the software's are extra multifaceted and possesses absolutely no built-in orientation or references to the systems of renewable energy and as a result, TRNSYS and Matlab software are not employed for bathroom solar water heating in this study. In the light of this, conceptual modelling utilising Polysun simulation software is justified in this study and applied for both modelling (chapter four) and simulation (chapter five).

4.2.4 Conceptual Modelling in Existing Study

Conceptual modelling technique was utilised to model the domestic hot water systems by their classifications (Krantz, 2012; Paw et al., 2018; Berman et al., 2019; Chirenje et al., 2021). According to Koke (2018), a few software programs present certain multifaceted nature by modelling systems utilising conceptual modelling - warm zone connections through algorithm control. In this manner, despite the fact that the system of conceptual modelling is applied, the procedures of the system are not totally overestimated. Their association with the structure is more practically displayed since their attributes can be incorporated into terms of viewpoints, for example, radiant split/ convective, time of response, flux limit values and extraction point/heat injection. Conceptual modelling approach was in like manner applied to models of the system of groundwater and system manufacturing (Streams, 1996; Rivulets and Tobias, 1999). This can likewise be a decent procedure in a modelling venture, especially where the primary point is to expand the understanding of what has previously been experienced (Rivulets et al., 2001). Research study by Ghiaus and Hazyuk (2010), also utilised the theorem of superposition for electrical circuits to attain the parameters of model. Their study presumed that the building thermal model is linear and thermal capacity is lumped and reflected on the time disturbance series, (for example, internal load and weather) and word related projects are recognised in light of the fact that their studies utilized Model Predictive Control (MPC) which projected an unrestrained ideal control calculation to unravel the load approximation issue. Research studies by Krantz (2012) and Paw et al., (2018) have required numerous presumptions to encourage the estimations of hot water load, which prompts absence of exactness in the outcomes. Likewise, a single output and single input model type utilised did not appraise the transmission of moisture - a significant component in choosing thermal comfort in the domestic environment. Conceptual modelling is also employed in numerous recent research studies of artificial intelligence and software engineering which focuses on demonstrating ontologies and techniques, for example, UML for knowledge, ideas and thoughts modelling (Abdullah, 2006; Bernald et al. 2012; Kamran and Sheraz, 2018). Methods utilized in distinguishing great model disentanglements in their investigations included optimisation examination and looking at the thorough activities of the model and the outcomes. Moreover, this study exploits recent approach in modelling to perform the system modelling for solar bathroom hot water and smart control at runtime.

4.3 Sensitivity Analysis

Study from Pang and O'Neil (2018) highlighted that, the use of solar hot water requires the utilization of sensitivity analysis. Sensitivity analysis is broadly expressed as the study of the impacts of uncertainty of a model output (Pang and O'Neil, 2018). It assists to assess and classify the degree of the robustness of a possible future choice of an alternative based on methodical variation of the reference model. Pang and O'Neil (2018) emphasized that, the consideration of solar hot water heating is subject to many variations due to the dynamism of operations if optimum approaches are selected. This suggest that solar hot water heating should require the utilization of sensitivity analysis. Farr in 2011 stated that in using sensitivity method of analysis, the foundation relies upon the "what-if" concept of decision-making. The method of employing sensitivity analysis includes isolating main variable(s), and consequently assessing the impact of the variations in the values ascribed to main variables. Sensitivity analysis assist in the determination of the effects of variables on probable outcomes on projects by assuming a specified variation in each of the key variable at a time, with other variables held constant (Keršytė, 2012), and might offer key knowledge on the part that needs most consideration. Sensitivity analysis though, has its disadvantages; it only assumes that only one key variable change at a time, with no corrective or preventative procedures, taken in response to any change in that variable (Yao and Jaafari, 2003). It also does not consider the probability of occurrence, associated with both the variable and project outcome (Keršytė, 2012).

4.4 Validation

This refers to how much a model or framework precisely mirrors the proposed ideas that the scholar is expecting to measure (Jonker and Pennink, 2010). The validation for this study has been employed by utilizing different knowledge types to validate the quantitative and qualitative outcome of this study.

4.4.1 External Validity

This alludes to the level at which the outcome obtained in a study can be reproduce or generalized to other study outcomes, strategies, or research methods (Fellows and Liu, 2009). The external validity employed in this study for the developed framework analysis can be referred to be moderate as the purpose is to make an analytical generalisation as opposed to quantifiable generalisation for the sustainability of solar hot water bathroom unit. Though the framework developed for the bathroom unit can be extended to include commercial bathroom or even household unit in the future. Subsequently, a semi-structured interview was carried out with five people with engineering and sustainable background in the industry to externally validate the sustainability concept of the proposed framework. The type of interview undertaken was a qualitative interview research while the key aim is to bring together a global view and interpretation from the interviewee with respect to the developed framework. This method aligns to the studies undertaken by King (1994), if an interview method of validation is utilized after conducting a quantitative study then, the purpose of the interview is to validate a specific measure, prove or clarify the meaning of the quantitative findings. For this study, the interview was employed to illustrate or give meaning to the quantitative outcome of the development of solar hot water bathroom unit of this study. The outcome of the external validation is described in chapter 8 of this thesis.

4.4.2 Internal Validity

This refers to the level that scholars reach true conclusions about the impact of an independent variables (Fellows and Liu, 2009). Internal validation centres around the way in which the outcomes uphold the conclusion of a given study. Consequently, the internal validation checks if what was acknowledged as the causes really yielded what has been deciphered as the "impact" or responses’’ (Amarantunga et al., 2002).

However, in order to verify the accuracy of the model, a validation test has been carried out comparing numerical results with field experimental data obtained by Ayomope (2015).

4.4.3 Reliability

This refers to the level of replicability of the study though conducted yet again (Yin 2014). The aim of the reliability is to reduce biases and errors in a given study (Amarantunga et al., 2002). It essential lures its value from the trustworthiness of the research strategy. The level of reliability of this study is improved by the clarity of the reporting process and principles of the models and framework that have been deliberated upon.

4.5 Heating Water in United Kingdom and London Homes

The water industry collects, treats, and supplies more than 16 billion litres of water every day for domestic and commercial customers in the UK. The Environment Agency estimates per capita consumption to be around 150 litres per day. Report from the Water Energy Calculator (2012), it is estimated that the average home consumes 349 litres at the minimum each day and individuals use an average of 142 litres a day.

Households with water meters pay bills charged proportionately with their usage, based on a per litre tariff on top of a fixed standing charge. For unmetered homes, Ofwat's 2015/16 estimate for the average water bill is £404.

On average, 60% of a household's energy bill is from water-using activities, split across both gas and electricity usage. This equates to extra £536 per year of the typical respondent's combined energy bill. Heated water (for activities such as baths, showers, washing up and water-using electrical appliances) contributes a lot to energy bills. But this link, and its implications, often goes unnoticed by householders.

The Energy Saving Trust (2016) recommends that water efficiency should be a core part of energy efficiency, fuel poverty, carbon reduction agendas and advice provided by those engaging with domestic customers''.

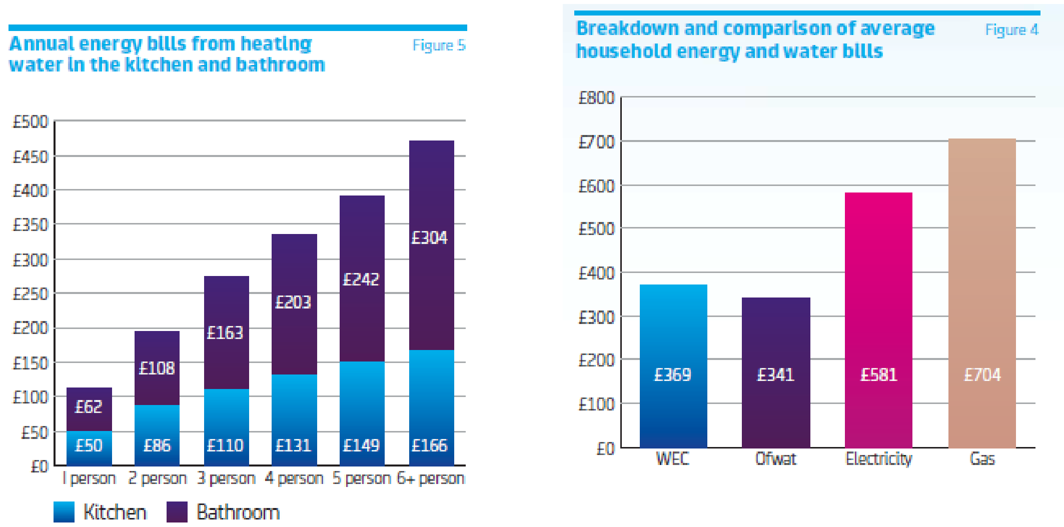


Figure 4. 2: Annual breakdown of energy bills (Water Wise, 2014)

The energy used to heat water for devices and appliances emits an average of 875kg of CO2 per household per year. This is equivalent to the CO_2 emissions from driving more than 1,700 miles in an average family car. The bathroom uses the most hot water in the home, and so it is the room responsible for the most water-related carbon emissions.

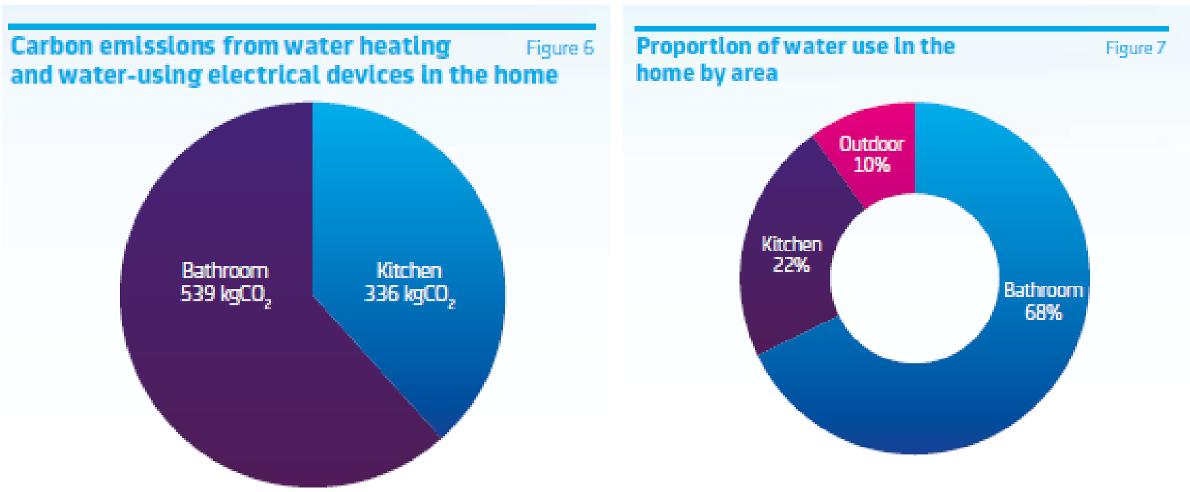


Figure 4. 3: Annual carbon emission and water use (Water Wise, 2014)

Showers, lavatories, baths and bathroom sinks consume more than two-thirds (68%) of household water (Figure 4.3).

Changes in housing standards have led to much greater access to bathing facilities and flushing toilets. This has inevitably led to an increase in cold water consumption and a more dramatic rise in heated water use. Although water use per person over the past two decades has been consistent, the breakdown of how and where we are using water has changed.

Water use from showers is a factor of showerhead flow rate and how long we spend in the shower. The average reported shower was seven and a half minutes. Although this might not seem too excessive, households reported a wide range of durations. 13% of showers took longer than ten minutes; some of these were for more than 20 minutes (Water Wise, 2014). If every household in the UK took just one minute off one shower every day, it would save £215 million on our collective energy bills a year. If everyone in a four-person metered household with a power shower did this, it could save them £60 on energy bills and a further £60 on water bills every year.

Most houses in United Kingdom are heating waters via heaters or gas boilers, these methods require an enormous amount of energy, which means that using hot water in the bathroom are expensive. However, some methods can help homeowners save on energy consumption and reduce heating costs. Additionally, reducing greenhouse gases that are produced by using energy generated from fossil fuels is also an important step in the fight against climate change. After home heating, the second largest energy use in most UK homes is the heating of water in tanks, which accounts for approximately 60% of household energy costs.

On average, the typical family of four or five uses 200 to 350L, but this depends on the demands of each person needing hot water; there are some days when they may use more or less hot water, depending on their activities.

4.5.1 Site Information and Data Collection

London, United Kingdom, was chosen as the preferred location for this study since it boasts more solar resources than most other region in United Kingdom. While parametric study was also conducted to determine the system performance in different weather conditions i.e., Aberdeen city of Scotland and Rome in Italy. The location used for London in this study is positioned at latitude 51.5°, longitude -0.17° and elevation of 36m. In this study, it is assumed that the home is a 3-bed house and uses a boiler gas as auxiliary hot water heating system and position the storage tank and the pre-heating tank are relative to each other and at a short distance from the collector. This study uses a standard 400-litre pre-heating and backup tank and insulated piping.

4.6 Modelling Software Limitations

The Polysun software models have introduced a few limitations to the software's range. Because of these changes, three important assumptions must be made when evaluating of Solar Water Heating Project using the Polysun software. First, assume that the daily volumetric load is constant, regardless of the time of year or solar irradiation levels. Secondly, must assume that the four residents of the will display relatively efficient hot water usage habits (e.g., taking short showers instead of baths, turning water off while shaving). Thirdly, the software assume that the default control method used is the traditional off and on control type (thermostat).

4.6.1 System Description

The working principle for this model assumes the use of two solar flat plate collector connected in parallel, a backup hot water tank, pre-heating tank, solar heat exchanger, a gas water boiler to serve as auxiliary, circulators, pumps and mixing devices. The solar flat plate collectors are to be connected in parallel for them to be operating under the same conditions.

The solar radiation from the sun that is absorbed from the solar collector is transformed into heat energy. The collector heat transfer fluid (mixture of glycol and water) circulating in-between the solar heat exchanger and the solar collector transfer heat energy to the incoming potable water from the solar pre-heating storage tank and at that point the heat fluid returns to the solar collector for the next circulation and so on.

Each time the bathroom system requires hot water, the hot water stored in the storage tank is delivered to the outlet point i.e., the shower, tap, basin and the bathtub. The working principle is such that the incoming cold water from the main first enters the solar preheating tank with equivalent flowrate as the hot water delivered. Consequently, the heated hot water in the pre-heated tank flow directly into the storage tank. In the event that the pre-heated water temperature from the solar pre-heating storage tank is above the set temperature set point from the water heater, then, the auxiliary water heat would not be activated and as a result, the hot water is delivered directly via the pre-heating tank to the hot water storage tank and then to the bathroom system once the system requires hot water. The auxiliary water heater is only switch on when the hot water temperature is lower that the temperature set point. If the water temperature from the solar pre-heating tank is above the circulator's deactivation set point, the circulation is shut down and no heated fluid is transported in to the solar-preheating tank. In scenario that the demand for hot is very high, or the solar energy is inadequate, the hot water temperature will be below the set point and the auxiliary water heater is activated. Generally, the hot water temperature from the hot water storage tank is higher than the bathroom hot water temperature demand, subsequently, the hot water is mixed with cold water in the mixing device component to obtain the user desired temperature. Also, since to the cold-water system makeup is pre-heated by the solar energy and the system components operations are collectively integrated, much energy savings is expected.

4.6.2 Component Modelling and Parameters

The component modelling of the solar hot water bathroom systems is described using mathematical equations. The parameters unfolding the key components properties are defined as the process of producing hot water load profile.

Hot Water Storage Tank and Pre-heating Modelling

The hot water storage tank is modelled with the assumption that the hot water are well mixed in the tank and has an even temperature and can be shown by a differential equation in time. The differential equation from (Duffie and Willian, 2012) unfolding the instant energy equilibrium of the storage tank as a time function regrading temperature is

$$m_1 C_p \frac{dT_s}{dt} = \sum m_2 C_p \left(T_i - T_f\right) + Q_{gain} - Q_{Loss} \quad \text{……… equation 4.1}$$

Where

- m_1 equals the total mass of fluid in the tank (determined by the volume)
- m_2 equals the water flow rate into the tank.
- Cp equals the heat capacity.
- T_i is the initial temperature,
- T_f is the final temperature,
- Q_{gain} is the energy gain in the storage tank
- Q_{Loss} is the energy loss in the hot water storage tank..

The storage tank model balances the temperature with a time variation function of stored energy in the storage tank via heat losses to the environment, transfer of energy via in and out water flows and auxiliary heat input (heater).

The solar pre-heating tank model balances energy build-up with solar gain and losses occurs majorly because of energy flux from flow of cold water and flawed insulation in the tank can be represent by

$$(m_3 C_p)_{PHT} \frac{dT_{PHT}}{dt} = q_{SC} - q_{LOSS} - m_4 C_p (T_{PHT} - T_c) \quad \text{……… equation 4.2}$$

Where

- m_3 is the mass of water in the preheating tank.
- Cp equals the heat capacity of water in the preheating tank.
- T_{PHT} equals the water temperature inside the solar pre-heating tank.
- q_{SC} is the solar gain in the preheating tank.
- q_{LOSS} is the thermal loss in the preheating tank
- Tc is the cold-water temperature make-up
- m_4 is the mass flow rate of the incoming cold-water entering the solar pre-heating water storage tank each time the system demands for hot water.

The solar pre-heating tank assumes decent exchange between incoming cold water and the tank and resulting to the water leaving the tank is at T_{PHT} i.e. uniform temperature. The auxiliary heat pump heating the storage tank is modelled with matching equations employed for the pre-heating tank though, the energy source is now the heat pump and not of solar gain.

4.6.3 Solar Flat Plate Collector

As explained in chapter 4, solar collectors are distinct type of heat exchanger for absorbing solar radiation and converts it into heat energy. One of the most utilized type and simplest solar flat plate collector is shown below.

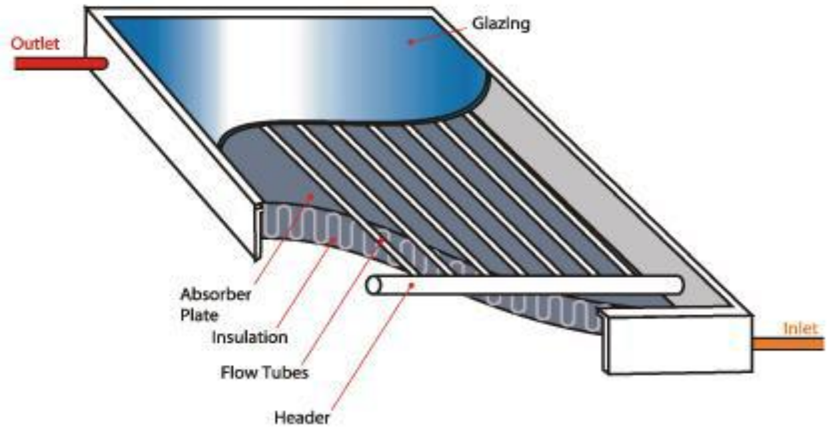


Figure 4. 4: Solar flat plate collector

The valuable solar energy distributed to the pre-heating tank (together with heat exchanger effectiveness) is modelled employing the linear equation as defined in (Duffie and Willian, 2012).

$$q_{SC} = A_C F_R (\tau\alpha)_n K_{\tau\alpha} G_T - A_c F_R U_L (T_{PHT} - T_a) \text{ .... equation 4.3}$$

Where

- q_{SC} is the solar heat gain from the solar collector.
- A_C is area of the collector.
- F_R the effectiveness of the counter-current heat exchanger between the solar collectors and solar pre-heating water storage tank.
- $(\tau\alpha)_n$ is the transmittance-absorptance product at normal incidence for a flat plate solar collector.

- $K\tau\alpha$ is the incidence angle modifier.
- U_L is the overall heat loss coefficient of the solar collector, W/m^2 ^{o}C.
- T_{PHT} is Temperature of delivered domestic hot water from pre-heating storage tank ^{o}C.
- T_a Outdoor ambient air temperature, ^{o}C.
- I_T equals the global solar irradiation on a tilted surface
- G_T equals the global incident solar radiation (W/m^2).

$$G_T = I_T * \frac{1}{60}$$

The transmittance-absorptance product at any angle of incidence can be 40 derived by introducing the incidence angle modifier $K\tau\alpha$ and its general expression as suggested by Duffie and Willian, (2012) is defined as the following:

$$K_{\tau\alpha} = 1 - b_0\left(\frac{1}{cos\,\theta} - 1\right) \text{ .... equation 4.4}$$

Where

- b_0 is defined as a constant called the incidence angle modifier coefficient and can be found from a solar collector's technical specifications.
- θ is the incident angle of solar radiation.
- F_R, defines the effectiveness of the counter-current heat exchanger between the solar collectors and solar pre-heating water storage tank and is the revised heat removal factor of the solar flat plate solar collector under the real operating scenario. The heat exchanger effectiveness ε is a function of the ratio of $\frac{F'_R}{F_R}$.

$$\frac{F'_R}{F_R} = \left[1 + \left(\frac{A_C F_R U_L}{(mC_p)_C}\right)\left(\frac{(mC_p)_C}{(mC_P)_{min}} - 1\right)\right]^{-1} \text{ .... equation 4.5}$$

Where

- A_C is the area of the collector.
- F_R is the solar collector heat removal factor.
- F'_R is the modified solar collector heat removal factor.

- U_L is the heat lost per unit area via the collector to the surroundings by radiation, convection, and conduction.
- $(mC_p)_c$ is the heat transfer fluid heat capacitance of the solar collector.
- $(mC_p)_{min}$ is the initial value of the heat transfer fluid heat capacitance of the domestic hot water.

4.6.4 Solar Heat Exchanger Modelling

The collected solar energy is directed to the pre-heating tank via heat exchanger. The Figure representing counter current heat exchanger with outlet temperatures and inlet temperatures, rates of capacitance of fluid heat transfer and the circulating hot water in the bathroom.

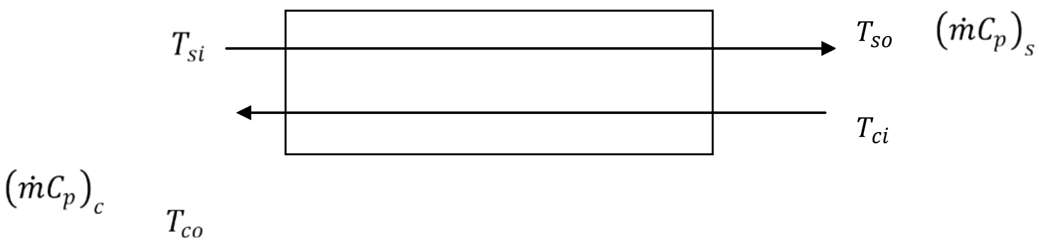


Figure 4. 5: Schematic of an adiabatic counter-flow heat exchanger (Duffie & William 2012).

The above description explains the impacts of solar heat exchanger utilizing the effectiveness that can be determined by

$$\varepsilon = \begin{cases} \frac{1-e^{-NTU(1-C^*)}}{1-C^{*-NTU(1-C^*)}} & if\ C^* \neq 1 \\ \frac{NTU}{1+NTU} & if\ C^* = 1 \end{cases} \quad \text{......... equation 4.6}$$

Where

- NTU equals the number of transfer units and its represented as

$$\frac{U_A}{(mC_P)_{min}}$$

Where

- $(mCp)_s$ is heat capacitance(W/K) of the circulating bathroom hot water
- $(mCp)_c$ is the fluid heat transfer capacitance (W/K) of the solar collector
- $(mC_p)_{min}$ is the initial value of the heat transfer fluid heat capacitance of the domestic hot water.
- $(mC_p)_{max}$ is the initial value of the heat transfer fluid heat capacitance of the domestic hot water.
- U_A Overall heat transfer coefficient-area product.
- e is the emittance of the heat exchanger.
- C^* is the capacity rate ratio

If the circulating bathroom hot water and the rate of heat transfer of the flow volume is equal, then, the mass flow rate and the capacity of the heated water are bigger than the transfer of heat fluid consequently

$(mC_P)_{min} = (mC_p)_C$

and

$(mC_P)_{max} = (mC_p)_s$

In the above equation in, C^* is the capacity rate ratio and is demonstrated by

$$C^* = \frac{(mC_P)_{min}}{(mC_P)_{max}} \text{ ....equation 4.7}$$

The solar collector heat transfer fluid specific heat capacity and the overall coefficient of heat transfer of the exchanger are already defined.

4.6.5 Gas Boiler

The total amount of heating energy supplied to the bathroom hot water system by the auxiliary water boiler is defined by

$$Q_{HP} = \int(COP \times W_{GB}) \text{ .... equation 4.8}$$

Where

- W_{GB} equals the power consumed by the gas boiler
- $Q_{H\mathrm{P}}$ equals the overall heating energy supplied by the gas boiler.
- COP is the water heater performance coefficient.

The coefficient of performance is dependent on condensing temperature and condenser inlet. The condenser inlet's temperature is assumed to be equals to the ore-heating tank temperature; therefore, the value is a function of time and this makes COP differ in time.

4.7 Simulation Assumptions and System Parameters

The performance of each bathroom hot water system component will be simulated, (as defined in preceding section). Each simulation will be completed with a one-hour time-step using load profiles and parameters that will be defined below. The main components for each system component are modelled based on actual product technical specifications provided by the manufacturer. The following sections describe the key parameters and any assumptions.

4.7.1 Solar Collector

Solar collectors are significant part of the bathroom hot water system employed in this study, the operating conditions are grounded on the solar collector to increase the heat fluid temperature of the collector that is used in moving heat energy to the heat exchanger and afterward, convert the absorbed radiation in the collector's fluid to heat energy. The converted energy is hence used in providing heat energy to the system.

Although, solar collectors differ from each other and are classified according to their working temperatures. For the system employed in this study, the flat plate collector utilized has added benefit of higher amount of solar radiation absorption and heat transfer that flows through the collectors' internal pipes i.e. the pipes are coated with copper and absorbs heat from solar collector via conduction. To minimize the loss of heat, the volume of the collector fluid must be minimized to less than 10-2 bar.

The minimization of fluid volume circumvents losses through heat conduction though losses by radiation cannot be accomplished via minimization of collector's fluid. Additionally, by installing Vaulted metal strip in either flat of upward direction, or as coating fabricated to the internal glass tube of the in an evacuated glass will make the water heat flow directly through the solar collector and consequently stores in the pre-heating tank. Studies have proposed that this technique will enhance the solar collector's heat behaviour. Each time the ambient temperature is equivalent to the temperature of the collector inlet then a maximum efficiency is said to be achieved.

The main parameters for the solar collector are summarized in Table 4.2 below. As shown in the Table, three flat plate solar collectors designed by Thermo Dynamics Ltd. are selected. Two were collectors used as the total area created is consistent with industry recommendations for domestic hot water consumption average of 250 l/day (Solar collector, 2018). The total aperture area of the two solar collectors is 5.566 m^2. They are assumed to be arrayed in a parallel arrangement so that each of them functions under the matching working conditions.

Table 4.2 Collector System Parameters

Parameters	Value
Type of Solar collector	G Series Glazed Liquid Flat Plate
Number of Solar Collector	3
Collector Arrays	Parallel
Total Collector Aperture Area (m^2)	7.5
$F_R U_L$ (W/m^{2o}C)	4.933
$F_R \tau\alpha$ (-)	0.7

Heat Transfer Flow Rate (l/min)	1.2
Incident Angle Modifier Coefficient (b_0)	– 0.154
Solar Collector Slope, (°)	Local Latitude
Surface Azimuth Angle (°)	0

As shown in the above Table 4.2, the values of $F_R(\tau\alpha)$ and $F_R U_L$ for each collector are 0.7 and 4.933 W/m^2°C, respectively. The collector heat transfer fluid is water-glycol solution i.e., 60% water and 40% glycol. The volumetric flow rate of the fluid heat transfer is 1.2 l/min that is suggested by the designer.

According to the specifications, the incident angle modifier of the collector is

$$K\tau\alpha \ = \ 1 - 0.154\left(\frac{1}{cos\theta} - 1\right) \quad \text{......... equation 4.9}$$

Where

- $K\tau\alpha$ is the incident angle modifier.
- θ is the incidence angle

The equivalent incidence angle modifier coefficient is – 0.154

When the incident angle of solar radiation θ is between A and B great amount of solar radiation is assumed to be absorbed. Consequently, the amount of solar radiation absorbed by the collector between the hours of 0800 and 1600 is the useful solar energy involvement to the bathroom water heating system. In this research study, the solar collector is assumed to be installed at a fixed slope on the roof which is the same as the local latitude and the surface azimuth angle γ is assumed to be zero. Wind effects on the overall loss coefficient U_L are not included since the $F_R U_L$ value is provided as a group parameter from the first order efficiency equation by the manufacturer.

4.7.2 Solar Heat Exchanger

Solar heat exchanger basically the process how the solar energy absorbed from the collector is transported to the bathroom hot water system. The type of heat exchanger this study assumes is the counter flow heat exchanger with overall heat transfer value of 260 W/K (Duffie and William, 2012). The circulating bathroom hot water from the pre-heating tank is assumed to have equal water temperature as the tater in the tank. The effectiveness ε solar heat exchanger is a calculated value which is 0.90 (Duffie and William 2012).

4.7.3 Gas Boiler

The water heater assumed in this study is manufactured by ETECH with heating capacity of 310 kW and cooling capacity of 5 kW. The highest supplied bathroom hot water temperature is 60˚C and the working rage for the ambient temperature for the water heat is between 5˚C and 40˚C. The chosen ambient temperature range is 18˚C and assumed to be installed in the household residence. The boiler gets switched on if water temperature in either the pre-heating tank or the storage tank is lower than the user set point.

4.7.4 Solar Pre-heating Tank

The solar pre-heating tank is considered to have equal physical size and heat insulating as the storage hot water tank. The initial temperature for the preheating tank for the summer months and winter months are assumed to be 60˚C and 30˚C respectively.

4.7.5 Hot Water Storage Tank

The use of pre-heating and storage tank for heat energy storage is largely more efficient. The goal is to store adequate hot water in the tank and via the supply system and to the end use. The water consumption profile mostly determines the sizing of the tank volume. The energy storage capacity of the storage and pre-heating tank are significant for water supply efficiency in the bathroom. Moreover, the tank should be able to store sufficient water to satisfy the daily needs. The demand of water and its consumption pattern i.e. if household residents use more water in some particular months or for a specific occasion should be considered when sizing the tank. In determining the suitable tank size, the consideration of monthly and yearly values per person or per family as the volume varies is vital.

For this study, the tank size is determined by the amount of utilized hot water utilized and household's size. A tank that is designed poorly will lose huge energy due to high flue temperatures. A good tank design like a boiler will extract more heat energy and transfer it to the water and consequently, resulting in 0.9 recovery efficiency or higher.

4.7.6 Pipe Data

Pipe connects the water heating components and the water tanks to the fixtures. Most pipe connections are designed to be indoors for conventional water heating system. For a solar water heating system, some pipes that connects the flat plate collector and the external heat exchanger is located outdoor. The pipe networks are also vital to the system efficiency due to potential thermal loss and mass. In this research study, the impact of piping networks and characteristic are accounted for in a direct method.

The indoor total pipe length between the flat plate connector and the pre-heating tank is assumed to be 10 m while the outdoor total pipe length is assumed to be 20 m. The diameter of the indoor and outdoor are assumed to be 25 mm. The convection coefficient of air on the external surface of the pipes is considered to be 10 W/(m^2K). The heat insulation of the pipe is considered to be 25 mm thick and the equivalent thermal conductivity is considered to be 0.02 (W/m.K). The hot water temperature in the pipe is assumed to be constant at each location in the pipe.

4.7.7 Hot Water Draw Profile

The availability of solar radiation is a function of many parameters i.e., location, hours of the day and years of the month and so also the demand of energy. Though solar energy supply to the system differs than the demand of hot water. To meet the objective of matching the demand for hot water, it is essential to have the clear picture of the demand pattern and profile.

Daily hot water draw pattern and profiles have been studied for many decades. Authors like Stevenson (1983), Perlman and mills (1985), Parker (2003), Energy Saving Trust (2013) have all highlighted that hot water draw patterns shows high daily peak in the morning and evening, the amount of water consumed is a function of number and types of occupant and concluded that based on hot water consumption for a typical family of four, between 240 and 250 litres of daily consumption will satisfy the user demands.

The standardized bathroom daily hot water profiles utilized in this study is taken from Energy saving Trust (2013) and DEFRA (2008). The average daily hot water draw for four person’s consumption pattern is 250 litres with maximum end use of temperature of 60°C.

4.7.8 Load Demand Calculations

The performance of bathroom solar hot water heating is controlled by diverse factors with the use of storage and pre-heating tank. These factors are solar radiation, ambient air temperature, load characteristic, sizing of the system components are significant in reaching the best performance level of the bathroom and to satisfy the load required. In this study, model was used to model the hot water requirement for the bathroom system. The determination of the annual energy demand is vital.

4.8. Integrated Energy Performance Analysis of the System Component

Solar hot water systems are generally rated by the energy factor (EF) of the domestic hot water tank. The energy factor is calculated by using standardized test procedure. Though this metric is not well suitable for some unconventional system as it does not consider the entire hot water system efficiency but it is well suitable for solar hot water systems. Few metrics are described in the section below to measure and compare the effects of using diverse energy saving technologies for bathroom hot water heating.

The objective is to evaluate the effect of the main components of the system from the overall performance point of view. The energy performance indices assessed in this study include:

- energy collected,
- energy delivered,
- solar fraction,
- collector efficiency
- system efficiency

4.8.1 Delivered Energy

The energy delivered Q_{DELVD} is the actual thermal energy (kWh) delivered by the bathroom hot water system. The value of *delivered energy* depends on the daily hot water usage profile, the cold make-up water temperature and the actual delivered hot water temperature (Duffie and Willian, 2013). It is defined as:

$$Q_{DELVD} = \int \left(mC_p\right)_s (T_s - T_c)dt$$ .... equation 4.9.1

Where

- $(T_s - T_c)$ equals the temperature difference between the actual delivered hot water and the cold make-up water.
- C_p is the heat capacitance of the hot water.
- m is the actual mass flow of the delivered domestic hot water from the main hot water storage tank and can be further calculated by

$m = \rho * \sum_{i}^{n} v_i$

- ρ equals the water density (998 kg/m^3)
- $\sum_{i}^{n} = v_i$ equals the instantaneous total volume flow rate of the hot water delivered to "*n*" plumbing fixtures.

4.8.2 Collected Solar Energy

The *collected solar energy* Q_{SC} (kWh) is the total solar energy collected by a solar collector over a given period, τ. It is defined as:

$$Q_{SC} = \int_0^{\tau} (q_{sc}) dt \text{......equation 4.9.2}$$

where

- q_{sc} equals the instantaneous heat flows collected by a solar collector.

4.8.3 Total Heating Energy

The total heating energy is the total heat energy generated by the hot water system components, which is the sum of the heating energy collected by a solar collector, the energy produced by the heat exchanger, and the auxiliary energy provided by the gas water heater. (Duffie and Willian, 2012). The *total heating energy,* Q_{THE}, can be presented as equation

$$Q_{THE}=Q_{SC} + Q_{HE} + \text{ .... equation 4.9.3}$$

where,

- Q_{SC}, Q_{HE}, and Q_{WH} are heating energy (kWh) generated from the solar collector, the heat exchanger water, and the auxiliary water heater respectively.

The hot water storage tanks accept energy to be gathered in excess of that delivered. When this happens, the system will have gained *residual energy* at the end of the day. This means the temperature of the water storage tank at the end of the day is higher than the beginning of the day. In some cases, even though, there is insufficient solar energy available in the morning, the residual energy is large enough to cover the first hour's hot water consumption of the day. From an energy balance, the *total heating energy* can also be presented as equation

$$Q_{THE} = Q_{DELVD} + Q_{RESIDUAL} + Q_{LOSS} \text{ .... equation 4.9.4}$$

where,

Q_{THE} is the total heating energy of the system.

Q_{DELVD} is the actual thermal energy delivered by the bathroom hot water system.

Q_{LOSS} is the *daily storage tank's thermal loss*.

$Q_{RESIDUAL}$ is the *daily residual energy*.

4.8.4 Delivered Solar Heating Energy

The delivered *solar heating energy* $Q_{SC.\,DELVD}$ (kWh) is the quantity of solar energy delivered to the bathroom hot water system that is essentially consumed for one day. Hence, some quantity of energy is substituted by the delivered solar heating energy. This quantity is regulated by the enthalpy change of the water flowing via the pre-heating tank. The value hinge on the mass flow rate of the delivered pre-heated water from the solar pre-heating tank, $m._{PHT}$, the actual temperature of the delivered pre-heated water T_{PHT}, and the cold make-up water temperature T_C. Because the mass flow rate of the delivered pre-heated water and its temperature are dynamically changing within one day, the *delivered solar heating energy* is defined as:

$$Q_{SC.DELVD} = \int_0^{1day} m_{PHT} C_p (T_{PHT} - T_c) dt \text{ .... equation 4.9.5}$$

The mass flow rate of the delivered pre-heated water from the solar pre-heating tank is the same as the water delivered from the main hot water storage tank to the bathroom hot water system, i.e. m_{PHT}=m.

4.8.5 Carbon Emission

Carbon emission calculates the entire emitted CO_2 (kg), produced directly from the auxiliary water heater. This quantity can be calculated by:

$CO_2 = ICO_2 \times W_e$ ……… equation 4.9.6

where,

- ICO_2 represents the CO_2 intensity of a conventional energy source.
- W_e is the daily consumed energy, kWh.

The CO_2 savings of the system is the annual reduction of CO_2 emissions. To define this index, it is necessary to evaluate the amount of primary energy saved from consumption of the system as expressed in equation 4.9.7 (Duffie and William, 2012):

$$CO_{2,save} = \frac{\Delta PE_{energy\ savings\ of\ the\ system}}{CO_{2conversion\ elec}}$$ ………………equation 4.9.7

When the system's conventional energy is electricity, the unit of this conversion coefficient is $kgCO_2/kWh$. If the systems conventional energy is natural gas, the intensity is ~49.7 $kgCO_2/GJ$ (Duffie & William 2012). The CO_2 emission is an important indicator to determine if a specific technology has environment benefits and to put a value on them.

4.8.6 Solar Fraction

The *solar fraction* Fs is the percentage of daily total heating energy provided by solar. Hence, it specifies how much of the system's really provided heating energy is from solar energy. It is defined as:

$$F_S = \frac{Q_{SC}}{Q_{THE}}$$ ……… equation 4.9.8

Where,

Fs is the solar fraction,

Q_{THE} is the daily total heating energy flow into bathroom water heating system.

Q_{SC} is the amount of solar energy collected in one day.

It is significant to note that based on these descriptions, it is likely for the collected solar energy Q_{SC} to surpass the actually delivered energy Q_{DELVD} to the system. This can happen since energy is lost via different system components (storage, tank, pipes etc.) and, because of the existence of storage tanks, it is likely for solar energy to be absorbed and stored in the storage tank to form the residual energy. Another meaning of solar fraction might be:

$$F_{S2} = \frac{Q_{SC.DELVD}}{(Q_{DELVD}+Q_{lOSS})} \text{ .... equation 4.9.9}$$

Where,

$Q_{SC.\,DELVD}$ is the portion of solar energy actually delivered to the domestic water heating system.

4.9 Design of a Smart Control Strategy for Hot Water Bathroom Unit

Design of heating control is very fundamental in bathroom and on the energy consumption of water heating systems. This energy consumption is majorly dependent on weather conditions. To reduce household energy consumptions, academic scholars in the area of thermal comfort have emphasized that the required indoor temperature in the household is not a fixed value. Subsequently, the ideal heating for a bathroom system is a system that works with high efficiency supplying only the amount of hot water that is needed to maintain the internal conditions at a level providing the required thermal comfort to the bathroom user.

The conventional water heating control allows the water temperature to be kept between two predefined limits. These limits may however be selected or changed by the user. It is also required that the process operate between these limits at an economic optimum. Besides these two main requirements, many additional conditions may exist, such as input and output constraints, stability requirements and rate constraints.

Previous works from (Siddique, 2014; Ahmed and Ifeanyichukwu, 2015) reviewed the three widely used smart control systems and are:

1) on-off controller

2) Proportional–Integrate–Derivative (PID) controller

3) Fuzzy logic control.

The on-off controller and the proportional integrate derivative controller are generally good in feedback although the proportional integrate derivative controller need information concerning the system dynamics for good performance. In a domestic building, the least problematic type of control to operate is the on-off controller which can also be called bang-bang control since its principle of operation is to switch sharply between on and off conditions. However, despite its simplicity, overshooting in a dynamic controlled state were not avoidable. The basic type of on-off controller that is normally used for residential dwellings is the “temperature control thermostat” (Ahmed and Ifeanyichukwu, 2015; Shahri et al., 2021). In overcoming the problem of overshooting and complex dynamic or nonlinear systems, developers have preferred the use of FLC (fuzzy logic controls) systems.

Fuzzy logic like human logic has no limits and is based on decision making methods. Therefore, to make a better decision, controlling the operation is needed which has in turn led to use fuzzy control mechanism that is based on logic. Fuzzy logic controller systems do not require full knowledge of the model, while in other known controller (PID) this knowledge is required. The use of uncertainty tests of fuzzy systems and expert’s knowledge as controls has become popular and used in many different fields of science (Dounis and Caraicos, 2009; Tariq et al., 2020).

This section focuses on the smart control strategy employed for a bathroom hot water heating. Fuzzy logic control works fine with most classes of non-linear system that has variability and uncertainty, this kind of control is well suited and appropriate for controlling water boiler or heating system which shows non-linearity between water flowrate and water temperature.

Their performance is evaluated based on the results of computer simulations. In controlling the input and output flow of the system, the controller should read the temperature and the flowrate at every sampling period. To design a simulation of this system, MATALB software is used. Fuzzy logic controller is designed using fuzzy logic toolkit of MATALB and simulations are performed in Simulink.

4.9.1 Control Objectives

The main idea behind the control system is to give a temperature set point to the controllers by opening and closing the hot- and cold-water valves swiftly and attaining user desired temperature as quick as possible. The core objective is to minimize the energy consumption for heating hot water without influencing the user's comfort. This can be achieved with fuzzy logic system.

4.9.2 Design Model for Fuzzy Logic Controller

Generally, hot water systems are controlled by typical thermostat or PI controllers; however, there is increasing interest these days in the use of fuzzy logic control (FLC) strategies since fuzzy inference systems (FIS), which are based on the understanding and knowledge of the physical systems, have intelligent properties and therefore they are well suited for designing energy efficient control strategies (Yousef et al., 2020). More and more real-world applications of FLC in hot water usage have been found. To improve control system performance and thermal comfort level and save operating energy, the water temperature could also be regulated based on varying water mass flow rate in the bathroom system. This control strategy is studied by designing and simulating fuzzy logic controllers. Since the exact supply water temperature and flowrate from the system can vary due to several environmental factors, the fuzzy logic theory was employed to infer this relationship. The fuzzy logic inference systems such as Mamdani is employed and embedded in the control system. Mamdani type FIS infers the supply water temperature and flow set point of the overall system based on the understanding of the nature of relationship between the supply water temperature and the water flow rate.

For the propose design, the fuzzy inference system such as Mamdani can be obtained in five steps: fuzzification by fuzzifier, fuzzy operation (min), implication (min), aggregation (max) and defuzzification by de-fuzzifier (Jurenoks and Novickis, 2017). The process from fuzzification to defuzzification can be interpreted as follows. The consideration of two inputs i.e., hot water and flowrate. To model their impact on output such as boiler water temperature set point, one can use the degree of membership function (fuzzification). The effect of each input on the output is thus captured in the operation and implication steps.

4.9.4 Membership Function

A membership function (MF) is a curve that defines how the value of a fuzzy variable in a certain region is mapped to a membership value (or degree of membership) between 0 and 1 (Arpit and Abhinav, 2020). The fuzzy membership functions are required for the input and out-put variables for defining linguistic rules that controls the relationship between them.

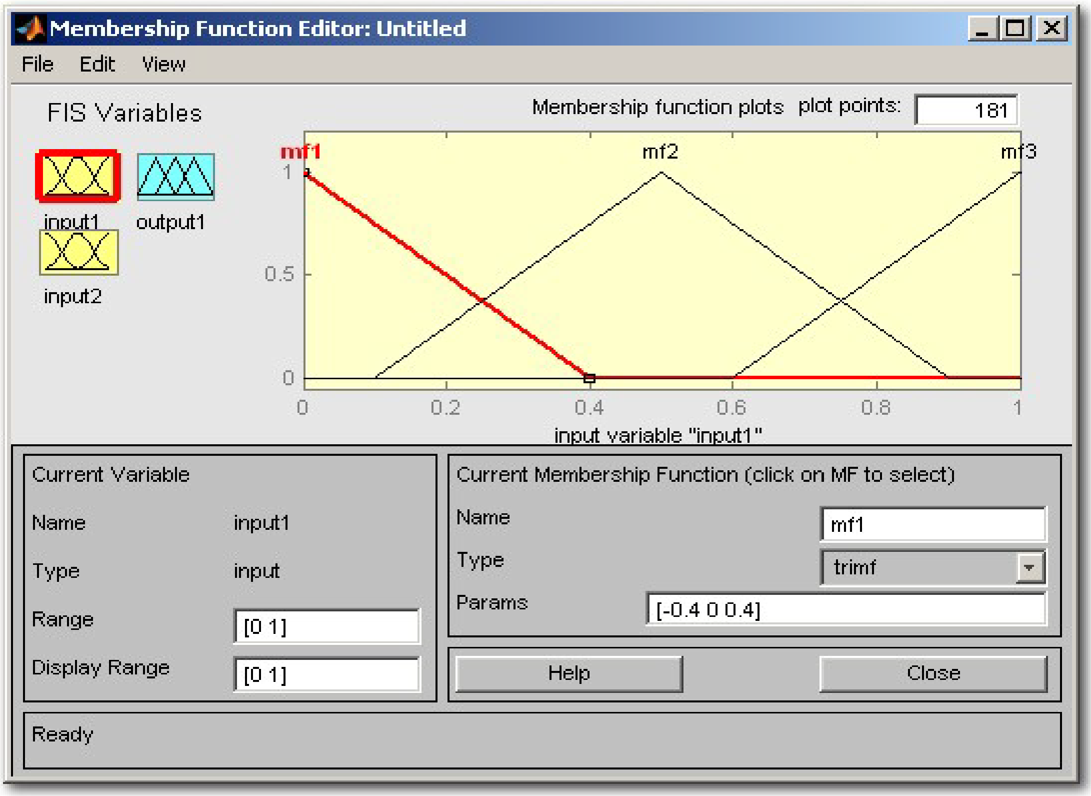


Figure 4.6: Membership function (Arpit and Abhinav, 2020).

The fuzzy controller for bathroom system switches between two input controllers namely, (temperature and flow controllers) and produces two required outputs (cold and hot). This output will control the valve opening. The fuzzy inference system editor is shown in Figure 4.8 below.

The rules are defined in the fuzzy logic controller.

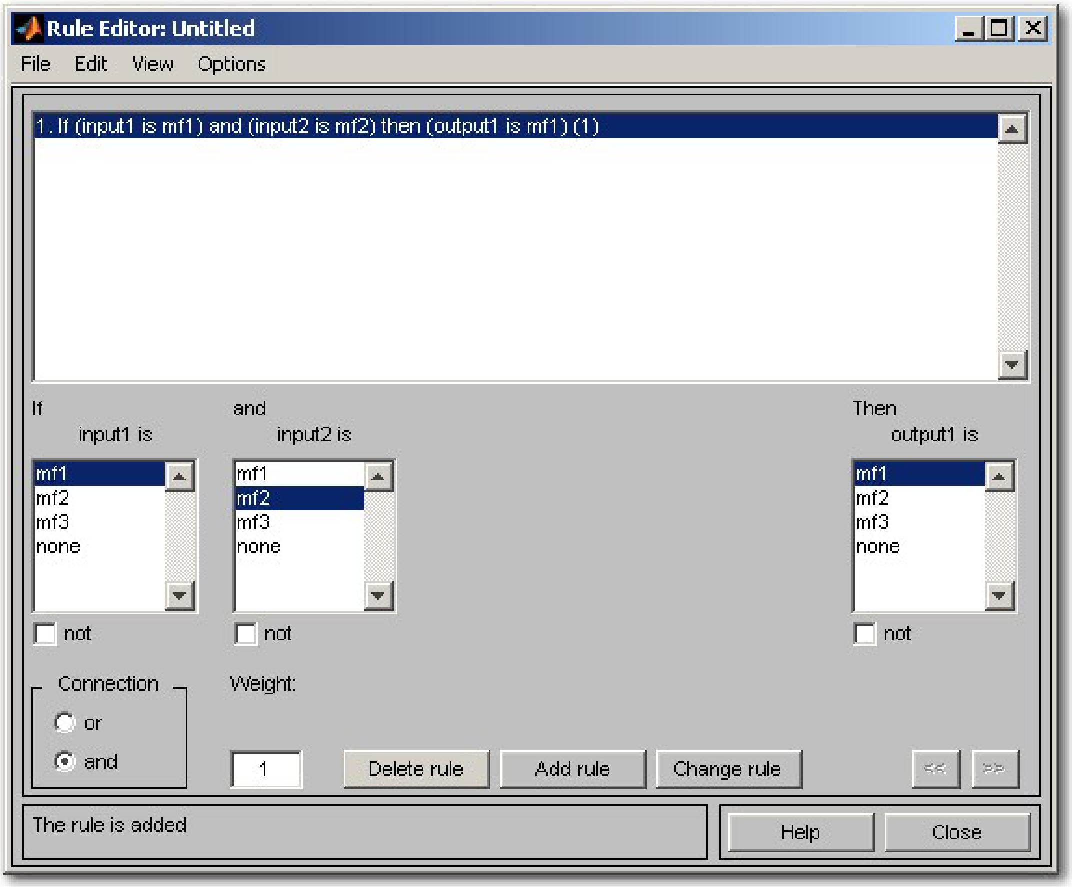


Figure 4.7. FIS Rule editor (Arpit and Abhinav, 2020).

The rule editor is developed using graphical rule interface and its based-on input and output variables that is defined with the FIS editor, this allows the automatic creation of rule statements.

4.9.5 Summary

The conceptual modelling of the bathroom unit and the smart fuzzy logic controller have been applied in this chapter. The application of conceptual is justified with their application in existing study. The modelling approach employed have proved to be suitable for the scope of this study. The conceptual modelling of bathroom unit examined can feasibly give the anticipated efficiency to an integrated controlled system and each component of the system is in accordance with the manufacturer's instructions as described. In line with the basis of conceptual modelling, the components of the system are simulated as a whole in the next chapter by using the Polysun software to provide the energy efficiency of the proposed system. The design was intended for a bathroom solar water heating system for an average house or flat in the United Kingdom, the main objective of the system is being smart, optimal in technical performance, minimal cost, high reliability, and sustainable.

This thesis has further demonstrated a method of designing an integrated solar water heating system that is water and energy efficient in providing sufficient hot water to the bathroom unit and ultimately contributes to the overall sustainability of the household. Thus, significant control parameters, for example, the water temperature and water flowrate are examined and must perhaps be properly controlled for growing demand of expectation for everyday comforts in the bathroom. In any case, significant difficulties exist as presented below that basically cut-off the control innovations development for the control of bathroom hot water system.

Control Restriction

- Difficulty to predict the system response and to employ the appropriate comfort indices to search for the optimal set point(s) in accordance with the system response
- Time delay
- They are either 100% ‘‘on or off ’’ regardless of where the reading is with respect to the set point. This can cause considerable overshoots and undershoots at any given time.

To resolve these difficulties, this chapter evidently designed smart/ intelligent fuzzy controllers (FLC) for controlling water temperature and water flowrate. The controller designs which incorporate the algorithms and logic control can predicts the amount of energy and pressure required to reach the desired temperature and flowrate. They can be combined easily and deliver improved efficiency with conventional control systems with minimum over or undershoot.

To attain and sustain the appropriate level of water temperature and water flowrate, fuzzy logic controller is designed in this study to make-up for the shortfall in the Polysun software.

Nevertheless, the next chapter of this study focussed upon the simulation results of the proposed solar bathroom system and the smart/ intelligent fuzzy controller by means of using computer model to analyse the effectiveness and efficiency of the projected scenario system which in turn contribute towards achieving better energy savings and reduced carbon emissions while combatting climate change.

Chapter Five

5.0 Simulation Results of Solar Bathroom Unit and the Smart Bathroom Controller

5.1 Introduction

The preceding chapter unfolded the detail designs of the proposed solar bathroom system and the smart/intelligent fuzzy controller. In view of the reason to accomplish the strong sustainability goal for the system; the solar bathroom unit and the smart/ intelligent controller must mirror the three pillars of sustainability. Hence, the proposed bathroom solar unit and the intelligent fuzzy logic must be environmentally sustainable and able in that sense to accomplish a user comfortable environment while reducing the rate of energy consumption and carbon emissions.

Furthermore, the performance of the proposed solar bathroom system and the controllers of the hot water temperature and flowrate are also presented in this chapter. The simulating tests of bathroom system and the smart/ intelligent controller of the system are theoretically grounded upon the conceptual modelling that are deliberated upon in the previous chapter. The simulations have been simulated on the platform of Polysun and Matlab-Simulink respectively. The system components of the solar bathroom unit were simulated using Polysun software. Also, the simulation of the smart controller is systematically performed using Matlab-Simulink while carefully considering the performance of system such as the stability, adaptability, speed response and overshot.

5.1.1 Simulation of Integrated Solar Bathroom Unit

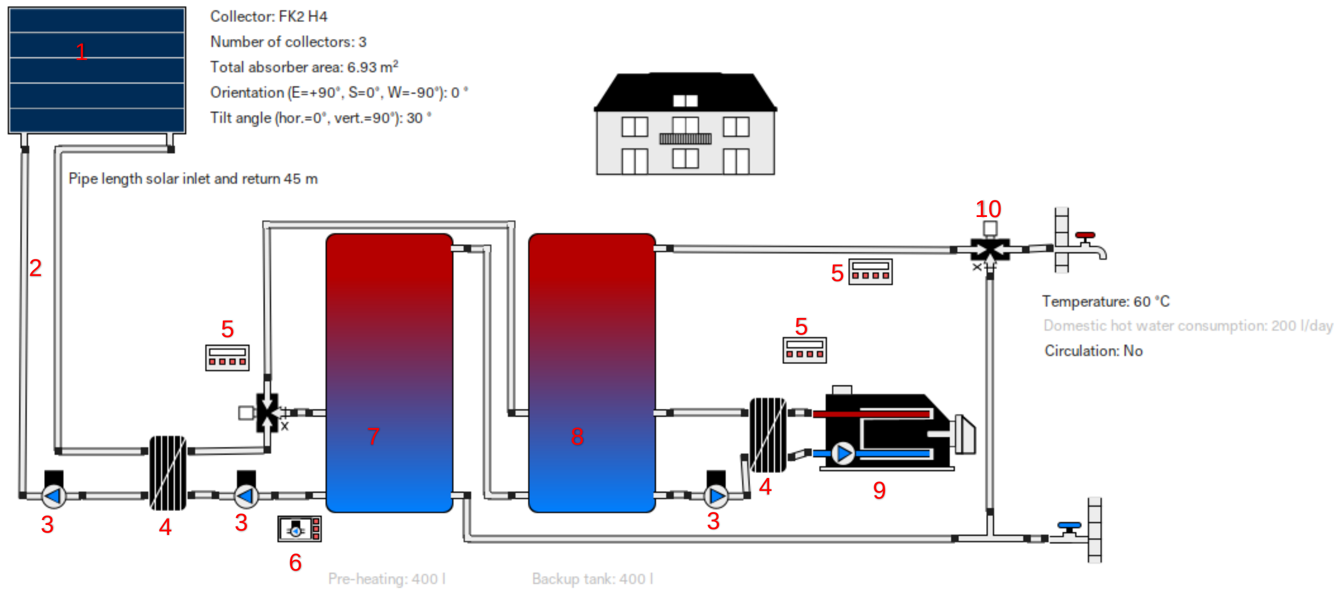
The simulation software Polysun provides a comfortable and attractive graphical user interface, where different integrated system model can be created. Even more it permits a comfortable and clear input of all system parameters with the analysis and design of energy systems. It runs with time steps 1 h, thus simulation can be more stable and exact.

The theoretical modelling and the descriptive fundamental mechanisms are offered in chapter four. Therefore, the simplified representation of the proposed system is revealed below in Figure 5.1.

In this system, the main components are solar collectors, connecting pipes, external heat exchangers, pre-heating tank, storage tank, pumps and the auxiliary heating system. The solar collector is a kind of heat exchangers which is the key parts of the system. Solar collector absorbs the light falling on its surface, converts it into heat energy, and transfers this heat to the working fluid flow in solar collectors.

The solar collector is connected to the 400l main water storage tank and a pre-heating tank. Thermal energy is transferred into the fluids travelling in the fluid flow pipes. The heat energy in the pipes is then transferred via the tanks. The heat allows the water in the main water storage to heat up to 60° C. The pipes is then also connected to a 10kW boiler.

Solar collectors produce thermal energy most depending on global solar irradiation and outdoor temperature. The higher the global irradiation level, the better efficiency, and higher thermal performance of collectors. If the temperature is increased, collector heat loss decreases. It is also seen that the quantity of energy required for auxiliary heating decreases with increase in solar fraction.



1 = Collector, 2 = Connecting pipes, 3 = Solar pump, 4 = Heat exchanger, 5 = Auxiliary heating control, 6 = Variable speed controller, 7= Pre-heating tank, 8= Backup tank, 9= Auxiliary boiler, 10= Mixing valve controller

Figure 5. 1: Simplified representation of the solar bathroom unit

5.2 Result and Analysis

The energy and environmental performance indices investigated in this study are:

- Solar fraction
- Energy supply or yield
- Total energy consumption of the system
- Primary energy savings,
- System performance and efficiency
- Reduction of CO_2 emissions

5.2.1 Performance Analysis of the Solar Fraction (Monthly and Annual)

Table 5. 1: The average outdoor temperature and global irradiance

Month	Average outdoor temperature/ ^{o}C	Average direct irradiance/ kW	average scattering irradiation/ kWh	average global irradiance/ kWh
January	6.5	147	102	249
February	6.7	151	173	324
March	8.4	259	303	562
April	10.9	417	364	781
May	14.1	452	502	955
June	17.1	368	543	912
July	19	450	494	945
August	18.8	466	451	917
September	16.2	379	327	706
October	13	298	219	517
November	9.3	179	119	298
December	7	103	83.3	188

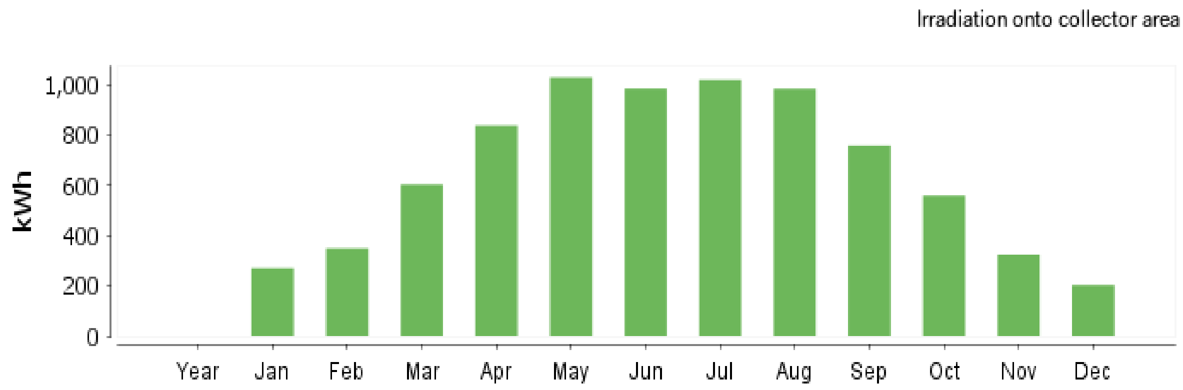


Figure 5. 2: Radiation into the solar collector

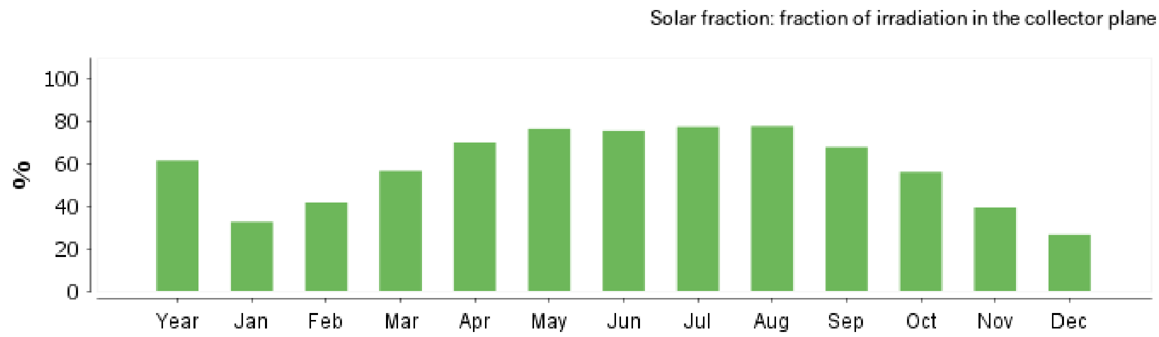


Figure 5. 3: Solar fraction of irradiation in the collector plane

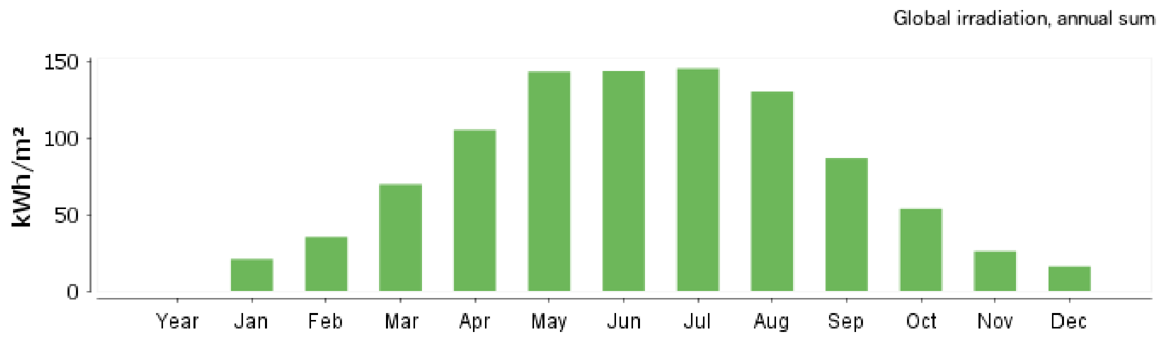


Figure 5. 4: Global irradiation

In Table 5.1 above, the average outdoor temperature and global irradiance time series are list over a one-year period. The annual average direct irradiance and diffuse irradiance for London are 2117 kWh/m^2 and 2384 kWh/m^2 respectively. The definition of seasons used in this study are according to fixed dates at even intervals of months as shown in Table 5.1. The highest amount of solar radiation is received in Spring-Autumn (April to October) period, whereas in winter (December to February) there is the least amount of radiation. Therefore, according to the measured irradiance Figures, the solar collector's energy yield is expected to be larger in spring to summer months than in any of the other season. Consequently, a lower energy yield is expected in winter than in any other season.

The monthly solar fractions obtained by simulation for the bathroom configurations of the solar hot water heating system are shown on Figures 5.2, 5.3 and 5.4 respectively. The peak of efficiency of the solar system is clearly reached between April and October. In May to August, the model predicts the maximal efficiency. Monthly solar fractions reach values from 20% for the least efficient output to 65% for the most efficient one. These Figures are in the range of the estimation of SPF for solar pre-heating (25%) discrepancies, this is due to the different components embedded in systems. The solar fraction increases markedly in spring and decreases markedly in autumn; variations of more than 10% from one month to another are expected. At the same time the difference between configurations becomes evident: it decreases in autumn and grows in spring. Still, the pre-heating can provide an appreciable amount of energy, which (depending on the system configuration) remains in the range of 20 to 30 % minimum in December to January. The difference between January's results and December's ones is weak. In any case, the solar pre-heating system will provide a small, if not negligible, part of energy needed during these months. These results are coherent with the estimated evolution of solar insolation in Bristol given by the Solar Electricity Handbook 2016. This model gives a coherent result relatively to what could have been expected.

On days where the solar panel is unable to extract enough heat energy due to lack of solar irradiation, the boiler is used as auxiliary in providing energy to heat up the water in tank. The design shows that the system is capable of more than 95% performance for 5 months, from May to September. This correlates to the availability of solar irradiation during the spring-summer period. Based on the result, the energy deficit is 493.2 kWh. This deficit occurs between the months of November to February, when the solar irradiation is low. During this period, the gas boiler is utilized more.

A total of 4688.596 kWh energy saving is possible. The reduction in CO_2 emission at 1.398 tonnes annually is also very high. The solar thermal energy that is generated into the system for the energy consumption for the entire bathroom unit is 10,799 kWh. The solar collector system provides 65% of the required energy for the bathroom unit, in which 85 % is used for hot water consumption. The total heat loss to the surrounding of the bathroom is about 15 % of the supplied thermal energy.

5.2.2 Performance Analysis for Energy Supply and Total Energy Consumption

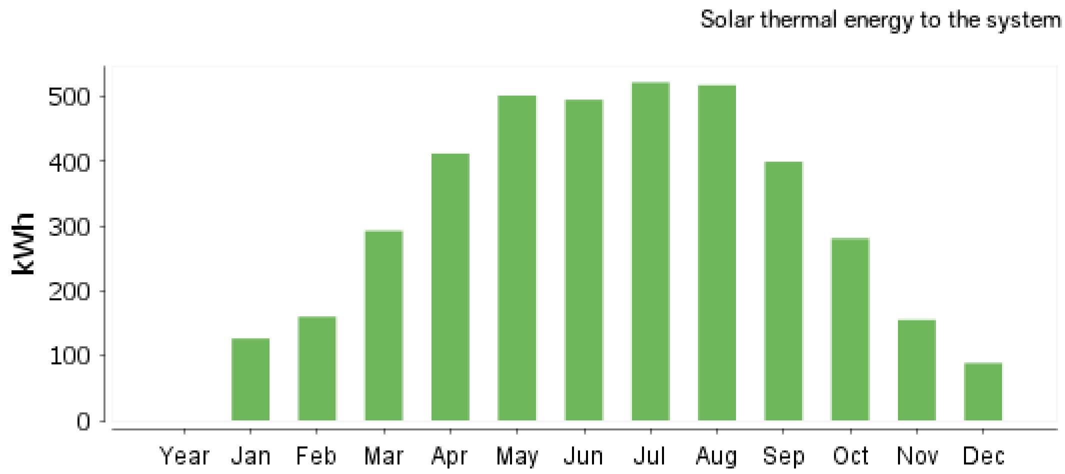


Figure 5. 5: Solar thermal energy to the system

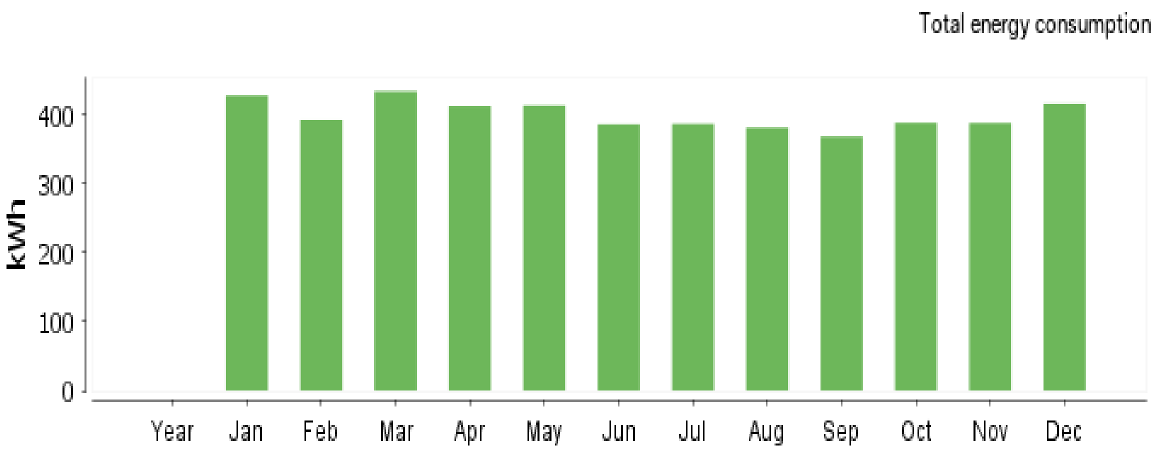


Figure 5. 6: Total energy consumption

Energy Supply or Yield

The result (Figure 5.5) shows that, the total annual energy supplied to the bathroom system is 4,878 kWh. Energy supplied during the winter months is low as it can only provide 20% of the energy required, this means the auxiliary heating system works more during winter. Consequently, the auxiliary heating system is optimised to increase the efficiency of operation and to save significant amount of energy especially during the winter months. In the spring to summer season (April – October), enough useful energy is supplied to the bathroom system with little auxiliary heating from the boiler for energy demand to be covered.

Total Energy Consumption of the System

The result (Figure 5.6) shows that, the total annual energy consumed by the system is 8,675 kWh. This includes solar energy consumed, auxiliary energy consumed, and energy required to power other components for operation e.g., pumps, boiler, heat exchanger. The efficiency of the consumption is determined by the energy balance in the tank. The energy balance in the tanks are negative during the winter months due to energy lost to the environment. As a result, the system will consume more energy to make up for the lost energy.

Consequently, Figure 5.5 and Figure 5.6 unfolds the outcome of the energy production of solar thermal yield to the bathroom system with the auxiliary electricity consumption from the consumption profiles and the electricity consumption from the thermal components. The monthly solar energy and the load results for the bathroom hot water system were analysed to verify that the model output energy values are reasonable as total energy demand was covered. It also showed that the monthly total load and the collected useful solar energy for a hot water system in London house with 7.5 m^2 collector area and a 250 litter per day DHW draw are a good fit for the system.

For the bathroom hot water usage to stay in the range of comfort temperature, the control must be able to switch sharply between high and low temperatures to maintain optimum performance for the system i.e., the system should self-regulate itself if the user set temperature is below or above the output of the system irrespective of the required power that is used up to operate the fluid pumps and auxiliary heating system. In the spring to summer season (April – October), the solar flat plate collector produces enough useful energy through to the system with little auxiliary heating from the boiler. As a result, the integrated solar bathroom system can perhaps completely provide enough energy independently with overall annual solar CO_2 savings of 1,398 kg as presented in Figure 5. 7. Additionally, the remaining produced energy may perhaps be stored and retained for future use. This suggests that optimization of top possibilities is concealed in the accessibility of the solar integrated bathroom systems together with the consumption of small electric power for auxiliary hot water heating.

5.2.3 Performance Analysis Energy Savings, CO_2 Savings and System Performance

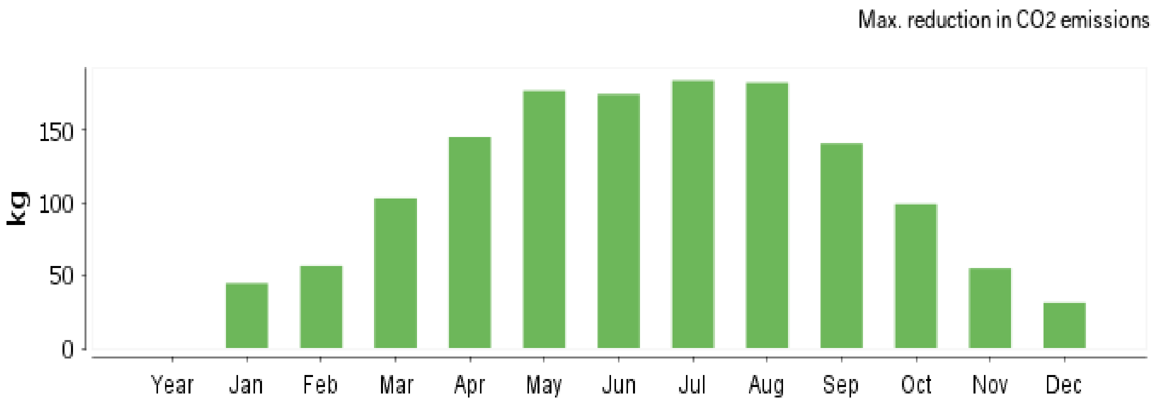


Figure 5. 7: Maximum reduction of carbon emission

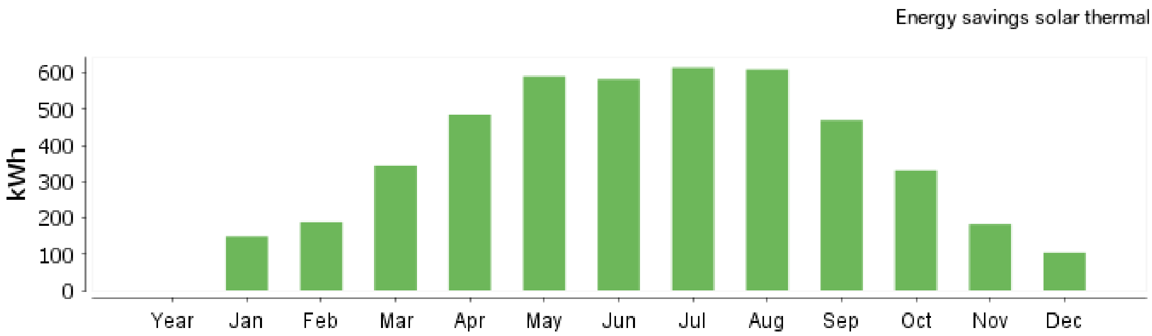


Figure 5. 8: Energy savings solar thermal

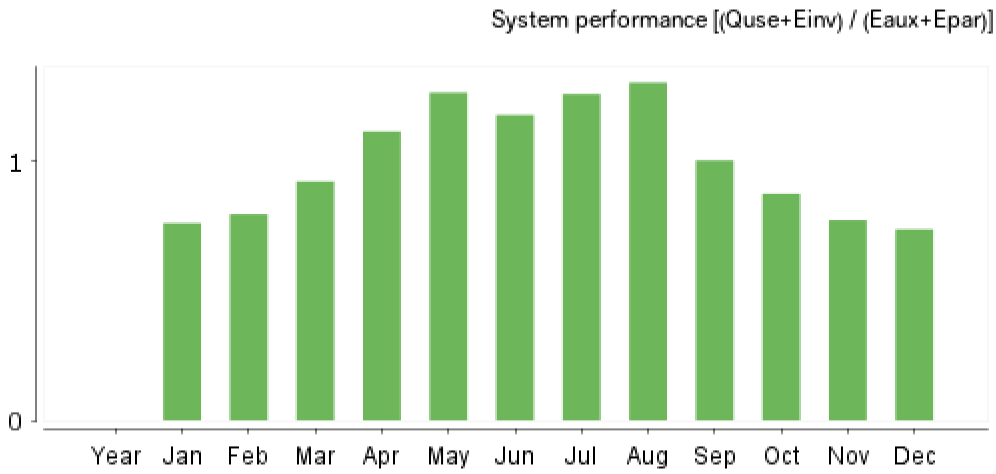


Figure 5. 9: System performance

Figures 5.7 and 5.8 shows that there is significant energy and carbon emission savings, this is because solar thermal systems provide more hot water during the summer than during the winter. This also means that an auxiliary heat source will still be required to heat the water during the winter months. However, solar thermal systems are still able to save between 50% and 60% of the energy that would have been required annually to heat up the hot water using conventional energy sources, such as gas or electric alone.

Similarly, during the winter months, the solar collector is not able to completely cover the hot water consumption i.e., the total energy consumption of the system and domestic hot water loads of the heating. So, there is a necessity for an auxiliary heat basis. The auxiliary gas heater is utilised in this situation for heat-up whenever the system is unable to meet up the set hot water temperature required.

The auxiliary heat provided by the heating system is transmitted to the backup tank storage for preheating of bathroom hot water. This operation makes energy usage to be efficient and subsequently enhances the performance of the overall system as well by making sure the system only uses the required hot water needed in the bathroom.

Accordingly, the auxiliary boiler is optimised to increase the efficiency of operation and to save significant amount of energy and CO_2 during operation especially during the winter months. The simulation has shown that a solar collector coupled with integrated bathroom component can not only yield high energy savings but can also achieve an appreciable annual reduction of CO_2 emissions.

The energy balance in the tanks is negative during the winter months due to energy lost to the environment. As a result, energy is added to the tank by the auxiliary boiler to supply energy through the external heat exchanger. During this time, little energy storage in the tank occurs. In contrast, during the summer months, more energy is being delivered to the tank by solar collector through the heat exchanger and that energy is being stored in the tank. During this time period, the tank losses and auxiliary heating are at minimum.

Also, additional energy savings is gained since the system component has very low electricity consumption i.e., the modelled auxiliary gas boiler power is 10 kW with internal electricity consumption less than 500 W. Energy savings related to the solar thermal contribution are observed since heat energy is driven by the auxiliary boiler when heating power is required by the system component and the solar radiation is not enough.

The system performance as shown in Figure 5.9 is a function of the solar fraction, energy savings and the efficiency of the integrated interaction of the system component. It takes into consideration not only the internal energy consumption of the main components such as heat exchanger and DHW but all the auxiliaries and distribution pumps as well. The higher the value the better the performance of the system. Higher system performance equates to higher efficiency, lower energy consumption and consequently lower operating costs.

Figure 5.9 shows that in winter months, despite the auxiliary heating source consuming the most energy, the system performance is at a minimum of 0.7 while in the spring to summer months the system performance reached a pick of 1.4. This revealed the system is generally performing at an excellent level. This implies that the system performance had a significant effect on the energy-saving effect. It also showed that the hot-water system can fully meet the design requirements under the condition of relatively sufficient solar energy, and can operate stably, which has a certain guiding significance for the design and application in the bathroom unit.

Energy Savings

This indicates the percentage of the energy saved is high in comparison to a conventional system where the same energy consumptions have to be covered and no renewable energy sources are used. After optimizing the system, the modelling results shows that solar thermal systems are still able to save between 50% and 60% of the energy that would have been required annually to heat up the hot water using conventional energy sources, such as gas or electric alone. Most of the savings occurred during the summer months while there was maximum 20% energy savings during the winter months.

Reduction of CO_2 Emissions

After optimizing the system, the integrated solar bathroom system completely provided enough energy independently with overall annual solar CO_2 savings of 1,398 kg. This signifies that the energy usage is efficient which enhances the performance of the overall system by making sure the system only uses the required hot water needed in the bathroom. This is one of the key benefits of system optimizing as opposed to individual component optimization.

System Performance and Efficiency

The system performance is a function of the solar fraction, energy supply and savings and the efficiency of the integrated interaction of the system component.

The system performance also points out how much energy is consumed per thermal energy distributed into the system. It takes into consideration not only the internal energy consumption of the main components such as heat exchanger and tank storage but all the auxiliaries and distribution pumps as well.

How efficient the system components interact together to generate effective outcome is summed up into single value. The higher the value the better the performance of the system. Figure 5.9 has demonstrated that there is generally better performance of the system during the summer months compared to the winter months. Although even during the winter months, the performance is still good. The average year performance of the system is 0.95.

5.3 Parametric Study

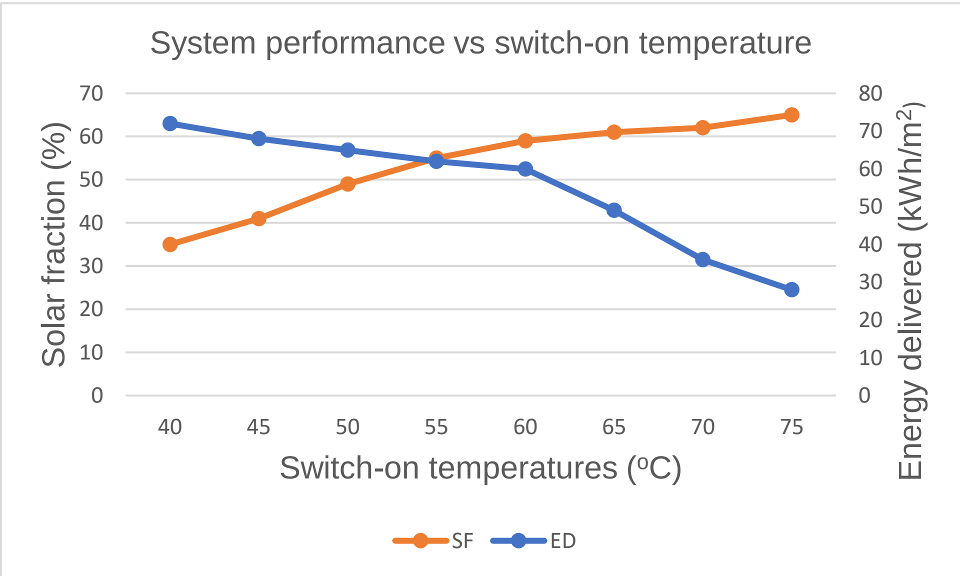
Introduction

The behaviour of a solar thermal system depends on many parameters related to its main components, such as collector inclination angle, collector area, pipe length, tank volume, auxiliary heating, and controller settings etc. In this chapter, a parametric study is conducted on the Polysun model, which from now on will be referred to as the reference system, in which the effect of various design- and operation parameters on system performance is examined. The analysis was focused on control strategies for auxiliary heating, hot water load profiles and different climatic conditions. The solar fraction was used to compare the relative performances of the system configurations. This expression compares the annual energy use of a solar domestic hot water system with the reference bathroom solar hot water system model presented in this chapter of this study.

Once the system is installed, the design parameters are in general more difficult and expensive to change, whereas the operation parameters are often considered easier to adjust. In addition, selected user-related parameters, like bathroom hot water demand and, will be assessed to see how they influence the overall performance. In doing so, a more holistic approach is achieved, which will make it easier to make general assumptions of the solar thermal systems of London and United Kingdom as a whole. To find the improved value of each parameter, or, if possible, the optimum value, only one parameter was changed at a time while the other parameters were kept at their initial settings. The input values of the different parameters used in this parametric study are mainly based on recommendations and information from the literature review and methodology in chapter three and four of this study.

5.3.1 Control Strategies for Auxiliary Heating

The maximum switch-on temperature for auxiliary heating is set to 60°C in the reference system, which is much higher than the draw-off temperature setting of 40ºC − 50°C. This variation influences not only the comfort but also the energy performance. Zijdemans (2012) lists the pros and cons of having a high-water temperature in the tank. The benefits include a reduction in necessary tank size and increased safety against formation of the Legionella bacteria. On the downside, a higher temperature results in a greater tank heat loss and reduces the utilization of low temperature energy sources for preheating of hot water, due to the higher need for after-heating. To study the impact of different switch-on settings for the auxiliary heating, the model was simulated for selected switch-on temperatures ranging from 40°C − 75°C. The impact of various switch-on temperatures on the amount of solar and auxiliary energy supplied to the tank temperature was constantly set to be 2°C higher than the switch-on temperature at each instance during simulation. The simulated annual solar fraction and the corresponding specific delivered energy are presented in Figure 5.10.



SF- Solar fraction, ED- Energy delivered

Figure 5. 10: System performance vs switch-on temperatures

5.3.2 Analysis from Graph

As depicted in the graph (Figure 5.10), a higher switch-on temperature results in a diminishing annual specific delivered energy to the system as well as a considerably higher annual solar fraction. This is because of the significant increase in necessary auxiliary energy that is required to compensate for the increased energy demand for after-heating. Furthermore, a higher temperature setting increases the utilization of solar energy.

The performance of the switch on temperature relative to hygiene regulations for the bathroom systems is also of particular interest. With the aim to prevent Legionella growth in hot water systems, guidelines notably suggest increasing boiler set point temperatures (Van et al., 2019). With higher boiler temperatures, system losses inevitably increase i.e. (i) the temperature difference between the boiler and ambient air increases, and (ii) hotter water stagnates in the pipes between consumption events. From the graph (Figure 5.10), a switch on temperature at 55^{o}C will prevent Legionella growth in hot water systems in agreement with (Van et al., 2019).

5.3.3 Parameters Related to the User

In this section, the impact of selected user-related parameters is studied. Doing so may make it easier to reveal important design features that can contribute to the evaluation of other solar systems, located in the other passive households in the United Kingdom. These solar systems are similar to that of the reference system but may be subject to other heat demands and consumption habits.

5.3.4 Different Bathroom Hot-Water Load Profiles

Since the load profile can influence the system performance, five different measured bathroom hot load profiles were analysed. According to Energy Saving Trust (2010), the following categorization of daily hot water consumption was applied:

- Low consumption: 30-55 l/day per person

- Normal consumption: 60-75 l/day per person
- High consumption: 80-100 l/day per person

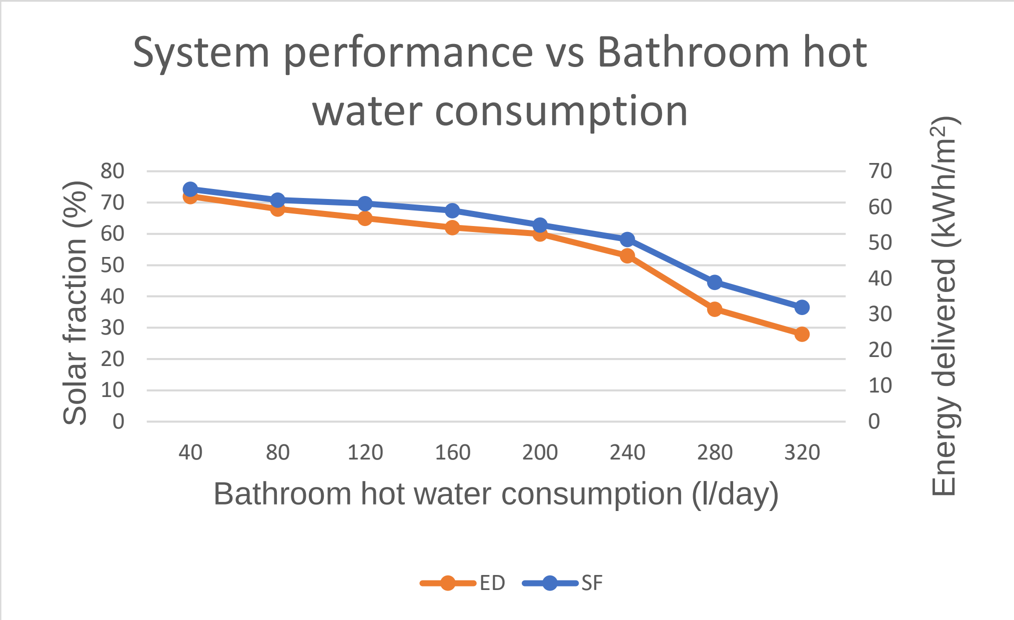
In a domestic household, it is rational to assume that the number of residents may vary from only one person up to a family of five, which causes significant variations in the total hot water consumption. Based on the three consumption groups identified above, the approximated hot consumption (l/day) of a dwelling is roughly estimated according to the number of inhabitants in Table 5.2

Table 5. 2: Different bathroom hot-water load profiles

No of occupants	Low consumption l/day	Normal consumption l/day	High consumption l/day
1	40-55	60-75	80-100
2	60-70	80-120	150-180
3	70-100	100-150	190-250
4	110-140	180-250	260-300
5	150- 190	200-290	300-350

To investigate how the annual domestic hot water consumption affects the performance of a solar thermal system, the model was simulated for average daily consumptions ranging from as little as 40 l/day (1-person, low consumption) to 250 l/day (3 persons, high consumption). The results are presented in Figure 5.11.

Analysis from graph



SF- Solar fraction, ED- Energy delivered

Figure 5. 11: System performance vs hot water consumption

5.3.5 Analysis of Average Daily Consumption vs Annual Solar and Energy Consumption

The results in Figure 5.11 suggest that a lower hot water consumption is directly related to higher performance of the solar fraction of the collector and hence, higher energy delivered to the system. However, this is not in itself a guarantee of higher performance; the solar fraction decreases slightly along with a higher consumption only up to an average daily consumption of approximately 250 l/day, where it reaches a maximum and starts decreasing sharply. This is because the auxiliary energy consumption becomes more dominating in the bathroom system.

Interpreting from Figure 5.11 suggest that, to maintain a specific performance resulting to the user consuming the same amount of hot water in the bathroom every day throughout the year is not realistic, the results still provide an indication of how a change in bathroom hot water consumption affects the system performance and energy delivered i.e., the higher the hot water consumption the lower the energy delivered to the system. This gives an indication that for a consumption that is more than 250 l/day, the system will start performing badly and consequently, additional collector is necessary to augment the diminishing energy delivered from the solar collector. Also, from the reference system, an average daily consumption of 250 l/day corresponds to an annual consumption of 4,804 kWh and falls within the range of a household of three to four people with normal consumption habits (based on the values in Table 5.2) and there is no need for additional collector.

5.3.6 Analysis of Different Climatic Locations

The distribution of the solar radiation throughout the year in different climatic locations influences not only the annual solar fraction, but also the system performance. The annual energy performance of the designed systems was evaluated under different climates, that is, in London climate and in two other cities i.e., Aberdeen (United Kingdom) and Rome (Italy). The three cities, London (reference system), Aberdeen and Rome were selected because they can represent most of the similar climatic region in the United Kingdom and Europe. The modelling of the annual performance was performed based on the hourly weather data of individual cities in Polysun. All cities were assumed to have the same load profile as in London and thereby creating a common basis for comparison.

Table 5. 3: Analysis of Different Climatic locations

System	Unit	London	Aberdeen	Rome
Collector area	m^2	7.5	7.5	7.5
Solar fraction total	%	65	44.6	83
System Performance	-	0.95	0.72	1.74
Total solar annual field yield	kWh	3952	3351.4	6107.3
Total energy consumption	kWh	4804	4116	3720

Primary energy factor	-	1.17	1.55	0.64
Comfort demand	-	Energy demand covered	Energy demand covered	Energy demand covered
Energy savings	kWh	4649	3942.9	7185.1
CO_2 savings	Kg	1398	1186	2160

Table 5.4: Meteorological data for Aberdeen, Rome and Reference system

Meteorological data-Overview	Reference system	Aberdeen	Rome
Average outdoor temperature	12.3°C	8.6°C	17.1°C
Global irradiation, annual sum	976 kWh/m²	882 kWh/m²	1,530 kWh/m²
Diffuse irradiation, annual sum	549 kWh/m²	515 kWh/m²	652 kWh/m²

Subsequently, Table 5.4 unfolds the climatic conditions of Aberdeen city for the proposed system. Unlike Rome and London districts, Aberdeen region is one of the coldest parts of the United Kingdom, and may be described as cold climate, having cold temperature for majority of the time during the year. Nevertheless, there may be some hot days in the summer with temperatures above 20 degrees and very cold days in the winter. The average temperature during the year is around 8.6°C and the coldest month is around -9°C.

Table 5.31 also unfolds the climatic conditions of Rome for the proposed system. Unlike London and Aberdeen, the district of Rome has a subtropical/ Mediterranean climate with some slight continentality elements. Winter is quite rainy and mild, nonetheless it can get cold at night. Winter season are cold in Rome, and the average low temperature drops to 2.8°C (37°F) during winter peak while the summer periods are sunny and hot with a few afternoon thunderstorms, and the average annual temperature is around 17.1°C.

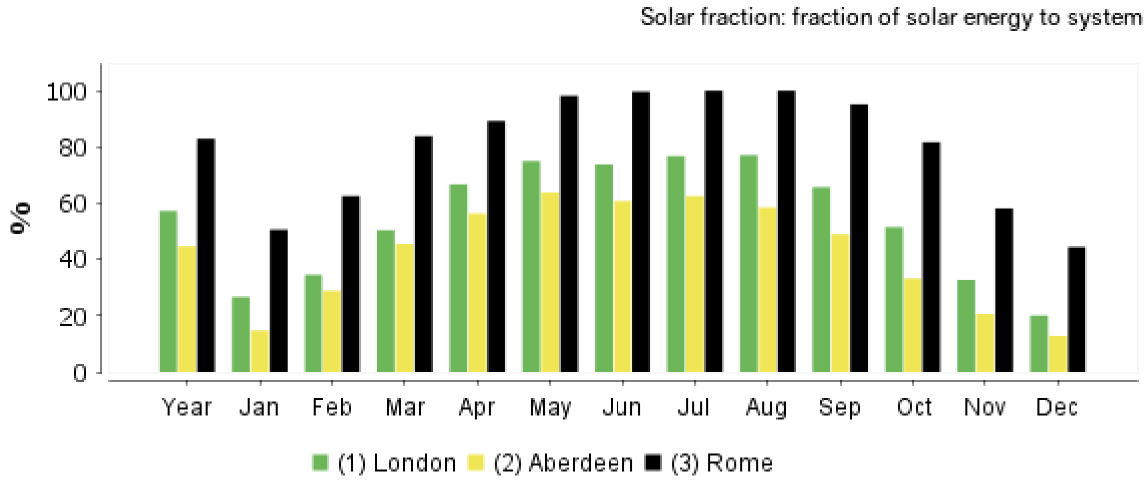


Figure 5. 12: Fraction of solar energy to system

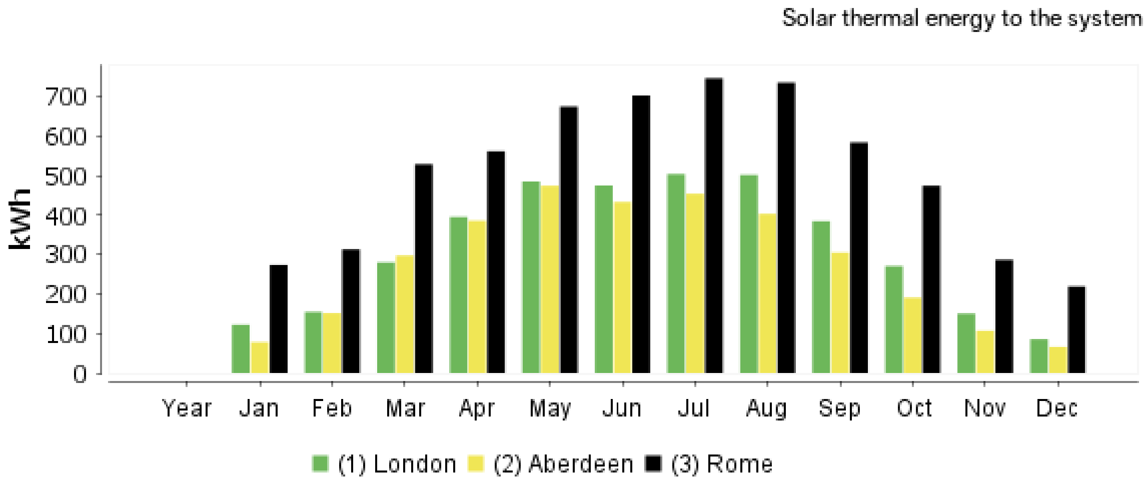


Figure 5. 13: Solar thermal to the system

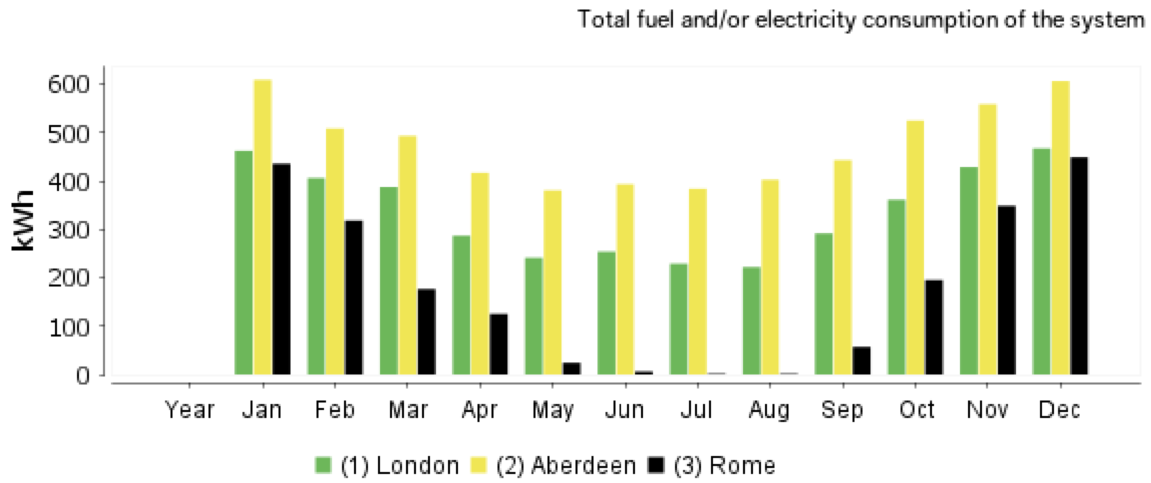


Figure 5. 14: Fuel/electricity consumption of the system

The impact of climate on the energy performance is examined to determine which climates provide the greatest additional energy saving benefit and system performance from the configuration as a representation of climatic conditions in the United Kingdom and Europe. The comparison of energy results in association with the examined weather conditions of the districts of London, Aberdeen and Rome are shown in table 5.3 and table 5.31. In each of these three cities, the Figures demonstrated that energy demands are expected to be covered to sustain the hot water demand in the bathroom. The Figure 5.13 shows the amount of solar energy transferred to the system and its corresponding impact on energy savings as compared to the reference configuration. In Aberdeen, the configuration yields a reduced amount of energy savings of 15.1% as compared to the reference configuration and in Rome, the configuration provides 54% increased savings as compared to the reference system. Based on this Figure, it is evident that the incremental savings can vary drastically depending on the location due to amount to radiation available.

Furthermore, the impact of location on system efficiency was examined for all the climates, Table 5.3 shows that the system performance in Aberdeen provides less efficiency gain as compared to the reference system and Rome provide good efficiency gains as compared to the reference system with the largest incremental increased efficiency occurring in Rome.

Additionally, the Figure 5.12 and table 5.3 shows climate plays a large role in the magnitude of the incremental energy savings, however, it is clear that the locations of Rome yield the highest incremental savings, largely due to their relatively significant incident solar radiation. The extent of energy production yielded through solar collector and energy consumed in Rome are higher than in London while lesser in Aberdeen. This is due to several reasons. The first is a higher energy production from the same size of solar collector due to a higher solar irradiance. The second is that the solar collector energy production better matches the annual energy demand. Finally, the third is a lower OFF time in the system because of freezing limitations.

In the light of this, parametric study demonstrated that high energy savings and system performance is a function of location, load profiles and control which can offer a reduced level of energy consumption and rates of carbon emissions which in turn combat global warming and climate change. Furthermore, the designed system simulation is validated in the following sub-sections.

5.4 Validation

5.4.1 Components Validation

In this section, the internal validation of the modelled system in this chapter is presented. To carry out a validation, each component is fed a group of test parameters to calculate component performance. The prediction is then compared with the same information provided by another method or model.

5.4.2 Solar Collector

The solar collector model is validated by comparing model output against field trial studies done by Ayompe (2015). The parameters used for validation and the predicted results are summarized in Table 5.4. As can be seen, the parameters of the solar collector model were set to match the ones used in by the field trial studies. The predictions by both simulation and field trial are well matched with minimum discrepancy.

A comparison of the key parameters calculated by both the computer model and field trial studies done by (Ayompe, 2015).

Table 5. 5: Component parameter

Parameter/Input of solar collectors	Unit	Polysun	Field trial by (Ayompe, 2015).
Numbers in series	-	2	2
Total gross area	m^2	4	4
Total aperture area	m^2	3.6	3.95
Heat transfer medium		Propylene mixture	Propylene mixture
Maximum flow rate	l/hr	144	194
Collector slope		45	45
Total Energy yield	kWh	1920	1984
Total energy delivered	kWh	1721	1639

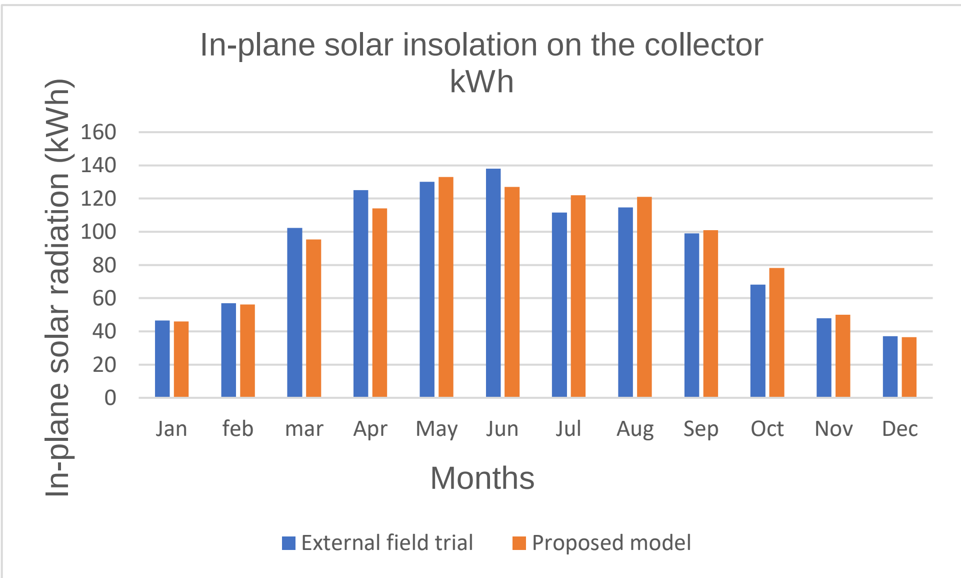


Figure 5. 15: In-plane solar radiation

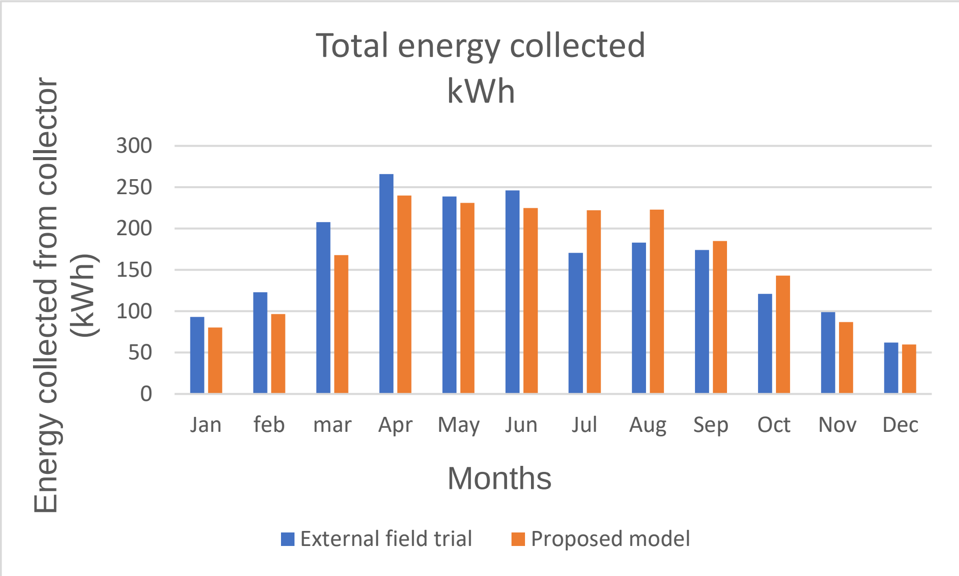


Figure 5. 16: Total energy collected.

As can be seen from Figure 5.15 and Figure 5.16, that the modelled values follow the same trend as the field trial values. The values of solar collector field yield simulated with Polysun and the field trial do not differ significantly. For the in-plane solar radiation result of external field trial result gives an average of 5.2% higher radiation mostly during the winter months whiles while the proposed model output gives a higher average of 3.2% during the summer and autumn compared to the result of field trial. The differences between the values of the solar thermal energy produced occur due to the monthly variations of the efficiency of the solar thermal system and the varied difference in the aperture area and flow rate of the collector fluid. These differences are manufacture specific.

5.4.3 System Validation

To perform a system validation, Polysun model configuration results for these studies are compared to results from Ayompe, 2015. The model developed in this research performs simulations using a one-hour resolution, the outputs are also averaged to monthly values to compare results. The performance of a solar assisted domestic hot water heating system for a three-person family. The water usage time-series defined by the low hot water consumption profile 300 litres is used with an auxiliary heater which was used to top-up the tank temperature to 60^{o} C whenever hot water is used. The input parameters are summarized in Table-5.5 and the model output are described here are shown in Figure-5.17 to Figure-5.20.

Table 5. 6: System parameters

System Parameters	Units	Description
Collector	-	2 flat plate collectors
Hot water tank volume	M^3	300
Heat exchanger effectiveness	%	85
Pipes	mm	15
Load profiles	L	200
Desired load temperatures	^{o}C	60
Initial load temperatures	^{o}C	30
Auxiliary heater (boiler) power	kW	10

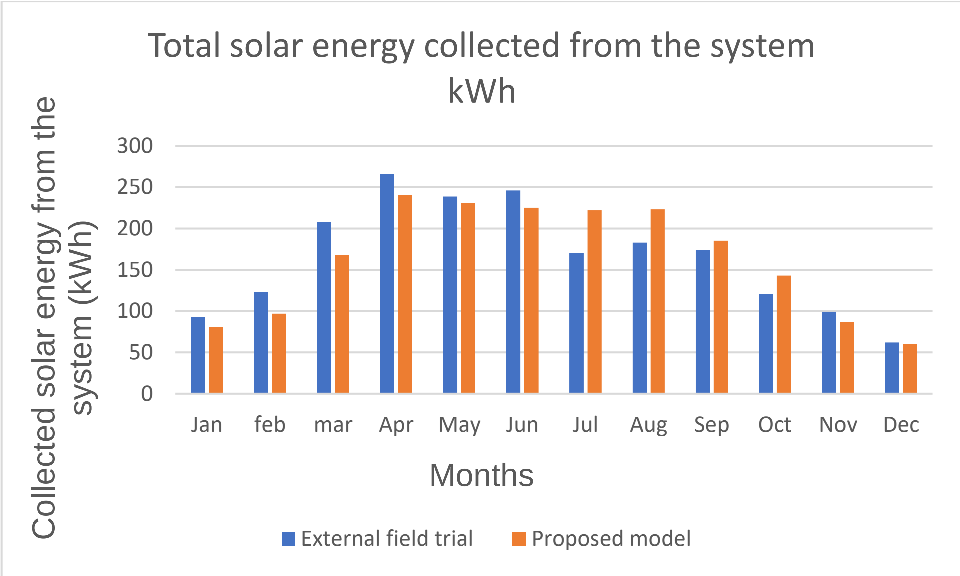


Figure 5. 17: Total energy collected

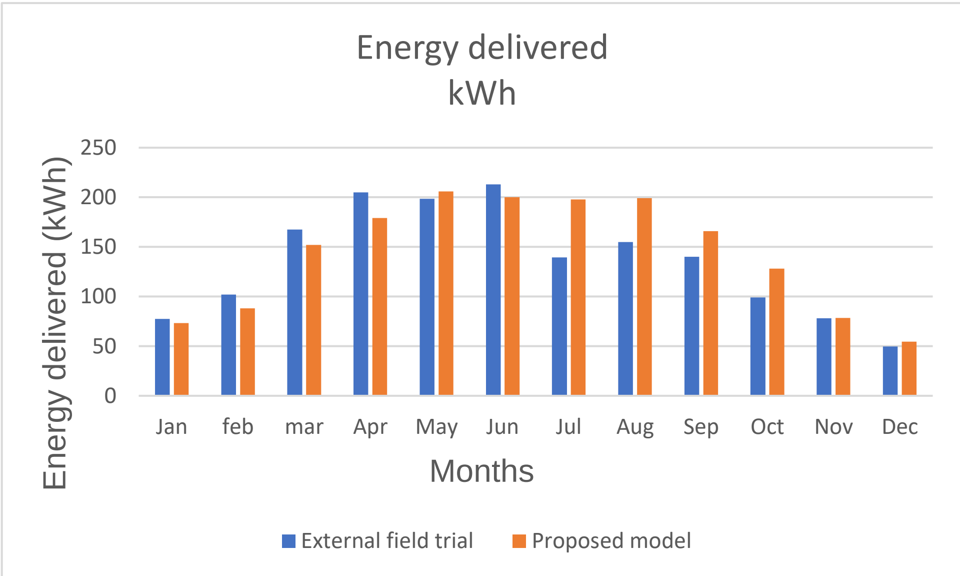


Figure 5. 18: Energy delivered.

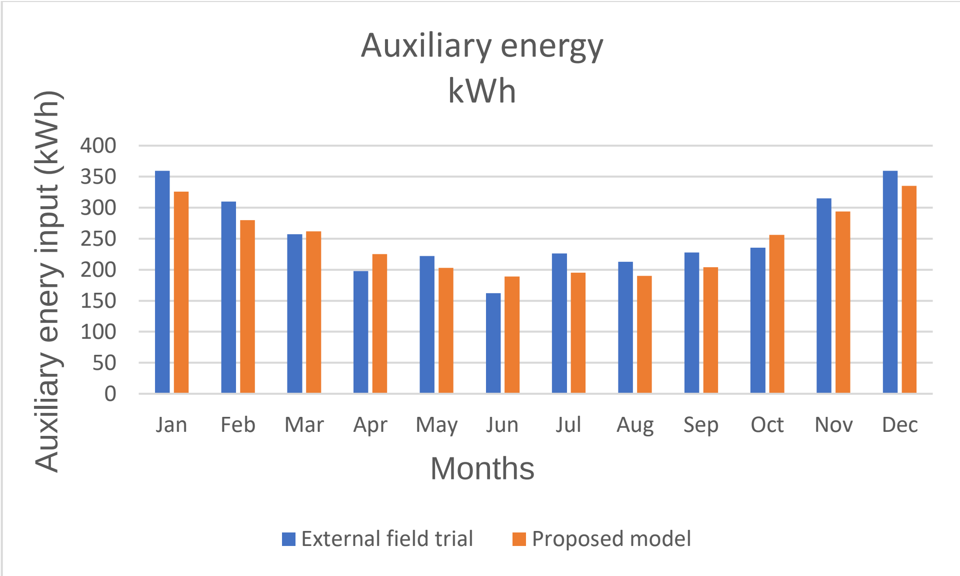


Figure 5. 19: Auxiliary energy

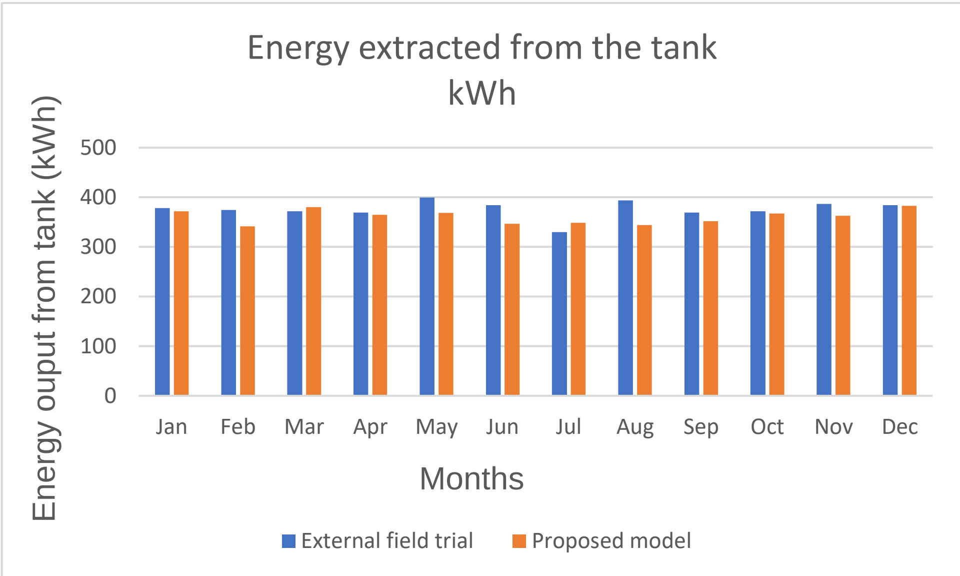


Figure 5. 20: Energy extracted from the tank.

As shown in Figures above, the correlation between the model and field result on a monthly basis is good. There is good agreement for auxiliary energy input with 3.14% error difference, (Figure 5.19), collected solar energy with 4.13% error difference, (Figure 5.17), delivered energy with 4.94% error difference, (Figure 5.18) and Energy extracted from the tank with 2.67% error difference (Figure 5.20).

5.4.4 Auxiliary Energy Analysis

Here, the auxiliary energy input is the overall conventional energy input which accounts for the effects of heat usage without the solar energy of the domestic hot water tank. Also, only some collected solar energy is actually delivered to the load (delivered solar energy); the rest of it becomes the solar pre-heating tank's residual energy causing the final tank temperature to be higher than the initial temperature; furthermore, the daily delivered energy doesn't include any thermal loss through the storage tank to the environment.

As can be seen Figure 5.19, the model predicts lower values compared to the field trial results mostly in the winter months with an average difference of 3.14%. The results show that the field trial auxiliary heating system works more generally throughout the year compared to the proposed model. This means that the polysun model uses more solar energy and required less of auxiliary heating. The discrepancy is due to a better system efficiency from the polysun model, and this is because, the polysun model provides more hot water from the solar collector resulting to less auxiliary heat source required to heat the water.

5.4.5 Energy Delivered Analysis

The energy delivered to the system in Figure 5. 21 shows that more energy is delivered in the winter months by the external field trial results, while more energy is delivered in the summer and autum by the polysun model.

The discrepancy is due to the temperature of the delivered hot water from the tank that is recorded hourly time series in Polysun and one minutes time series in the field trial. The set temperature of the model and the field trial for the domestic hot water tank's set point is at 60 ˚C. While, the field trial developed by Ayomipe, 2015 shows that the outputs of the delivered hot water temperature is on the minute basis, which means when the system calls for hot water, the cold make up water enters the system and causes the domestic hot water tank temperature to drop immediately when the tank temperature decreases below the controller dead-band setting, the auxiliary heater is turned on. In most cases, it is impossible for the system to bring the hot water temperature back to the set point (60 ˚C) within one minute. This causes a small temperature difference in the actual delivered load resulting in a smaller value for delivered energy as compared to Polysun model results. The energy delivered from the polysun results is consistent with the component modelling in Figure 5. 22.

5.5 Design of a Smart Control Strategy for Hot Water Bathroom Unit

The analyses performed in this chapter have demonstrated that the use of on-off controllers (thermostat) in the reference models designed in Polysun software are not well suited to achieve the desired outcome. Although the on-off controllers are simple to use, inexpensive and digital output are only two states. The main drawbacks are the controlled parameter which will continuously switch around the setpoint and if the hysteresis is not correctly set, the deviation from the setpoint could be quite significant. It also has problems of overshooting in a complex dynamic or nonlinear system.

To overcome this problem, this study has preferred to design and use of FLC (fuzzy logic controls) systems to control hot water usage in the bathroom. It is smart control strategy that can be employed for a bathroom hot water heating instead of the on-off hot water controller. Fuzzy logic control works fine with most classes of non-linear system that has variability and uncertainty, this kind of control is well suited and appropriate for controlling water heating system for bathroom usage which shows non-linearity between water flowrate and water temperature.

Their performance is evaluated based on the results of computer simulations. In controlling the input and output flow of the system, the controller should read the temperature and the flowrate at every sampling period. To design a simulation of this system, MATALB software is used. Fuzzy logic controller is designed using fuzzy logic toolkit of MATALB and simulations are performed in Simulink.

5.5.1 Control Objectives

The main idea behind the control system is to give a temperature and flowrate set point to the controllers, by opening and closing the hot- and cold-water valves and should attain the set temperature and pressure as quick as possible. The core objective is to minimize the energy consumption for heating hot water without influencing the user's comfort. This can be achieved by maximizing the use of available energy coupled with fuzzy logic system.

5.5.2 Simulation Model for FLC

The simulation for FLC control was simulated in Simulink-MATLAB and simulation results have been obtained for FLC system block diagram. The initial setting for the cold and hot water circulation in the bathroom system i.e., for shower, taps, sinks and toilet were randomly chosen with temperature from 1^{o}C to +50^{o}C. With the current settings input from the user, the target potable water temperature and flowrate must initiate adjustment to the potable water going to the tap, shower and sink using the valves to attain optimum water temperature and flow quickly with only few changes. The FLC is responsible for managing the water heating to serve and satisfy user requirements i.e., the water temperature at each instant, for hot water demand and the level of comfort by regulating the flow rate and the user desired temperature concurrently. The bathroom hot water system uses the Mamdani's fuzzy inference system; this system expects the output membership functions to be fuzzy sets. Following the fuzzification, there is a set of fuzzy for each output that requires a de-fuzzification. Mostly, it is more effective to use single spike membership function as output than to use a distributed fuzzy set. This can be regarded as pre-fuzzified fuzzy set as it boosts the effectiveness of the defuzzification method due to computational simplicity it needs by the more general Mamdani method.

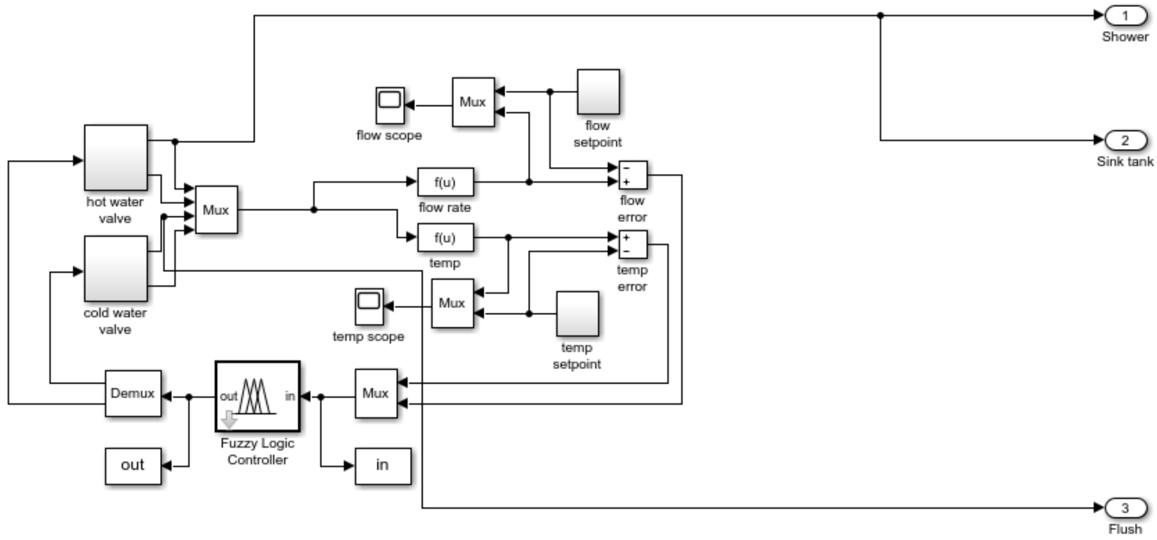


Figure 5.21: Simulink Model

The Simulink block diagram of the hot water distribution system in the bathroom is shown in Figure 5.21. There are four subsystems in this model such as, flow set point, temperature set point, cold water valve and hot water valve. The flow set point subsystem consists of signal generator that generates the flow rate variation. The input signal supplied by the signal generator is square wave type with amplitude of 0.2 and natural frequency of 0.3 rad/sec. The temperature set point subsystem consists of signal generator that generates the temperature variations. The input signal is supplied with the amplitude 4 and natural frequency 2143 rad/sec. The cold-water valve system and the hot water valve system receive signals from the fuzzy logic controller (FLC). For this system, the user controls the flow rate and temperature in the bathroom fixtures by adjusting hot and cold-water valves. Since there are two inputs for the fuzzy system, the model concatenates the input signals using a Mux block. The output of the Mux block is connected to the input of the Fuzzy Logic Controller block. Similarly, the two output signals are obtained using a Demux block connected to the controller.

5.5.3 Membership Function

A membership function (MF) is a curve that defines how the value of a fuzzy variable in a certain region is mapped to a membership value (or degree of membership) between 0 and 1. The fuzzy membership functions are required for the input and output variables for defining linguistic rules that controls the relationship between them.

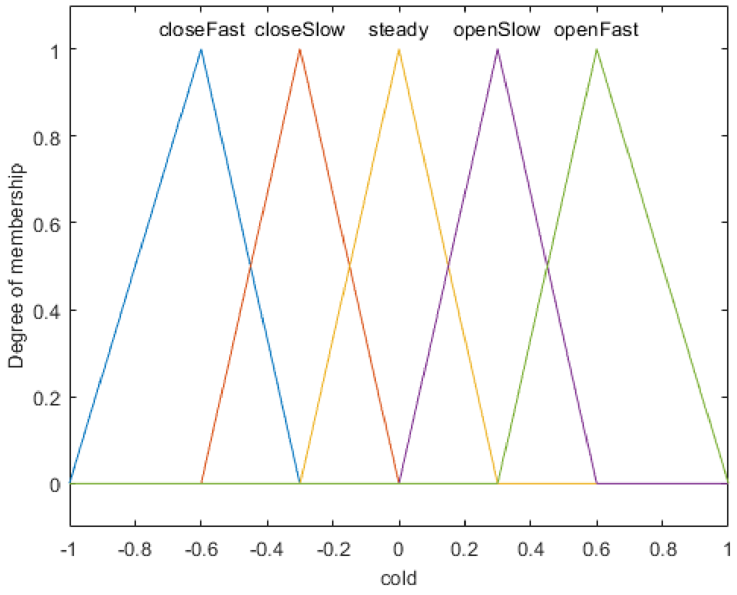


Figure 5.22: Membership functions of output 1

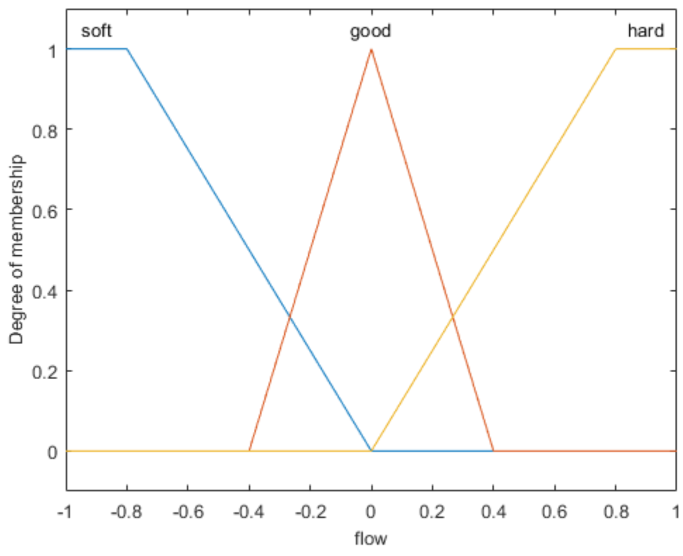


Figure 5.23: Membership functions of input variable 1

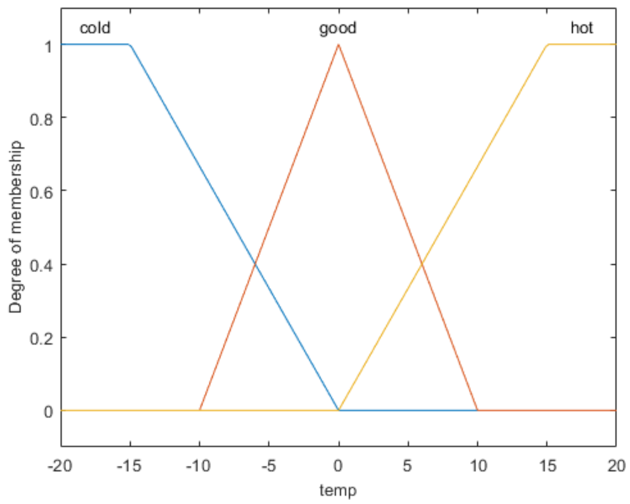


Figure 5. 24: Input variable 2

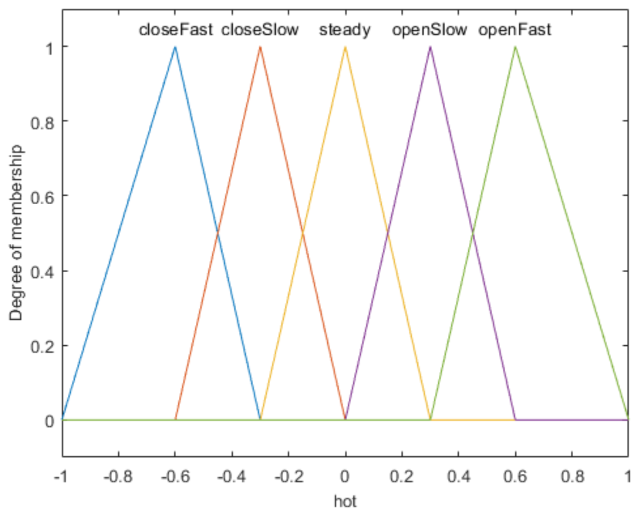


Figure 5. 25: Output variable 2

The fuzzy controller for bathroom system switches between two input controllers (namely, temperature and flow controllers) and produces two required outputs (cold and hot). This output will control the valve opening. The fuzzy inference system is shown in Figure 5.26 below.

There are nine rules defined in the fuzzy logic controller. The rules used are shown in Figure 5.26.

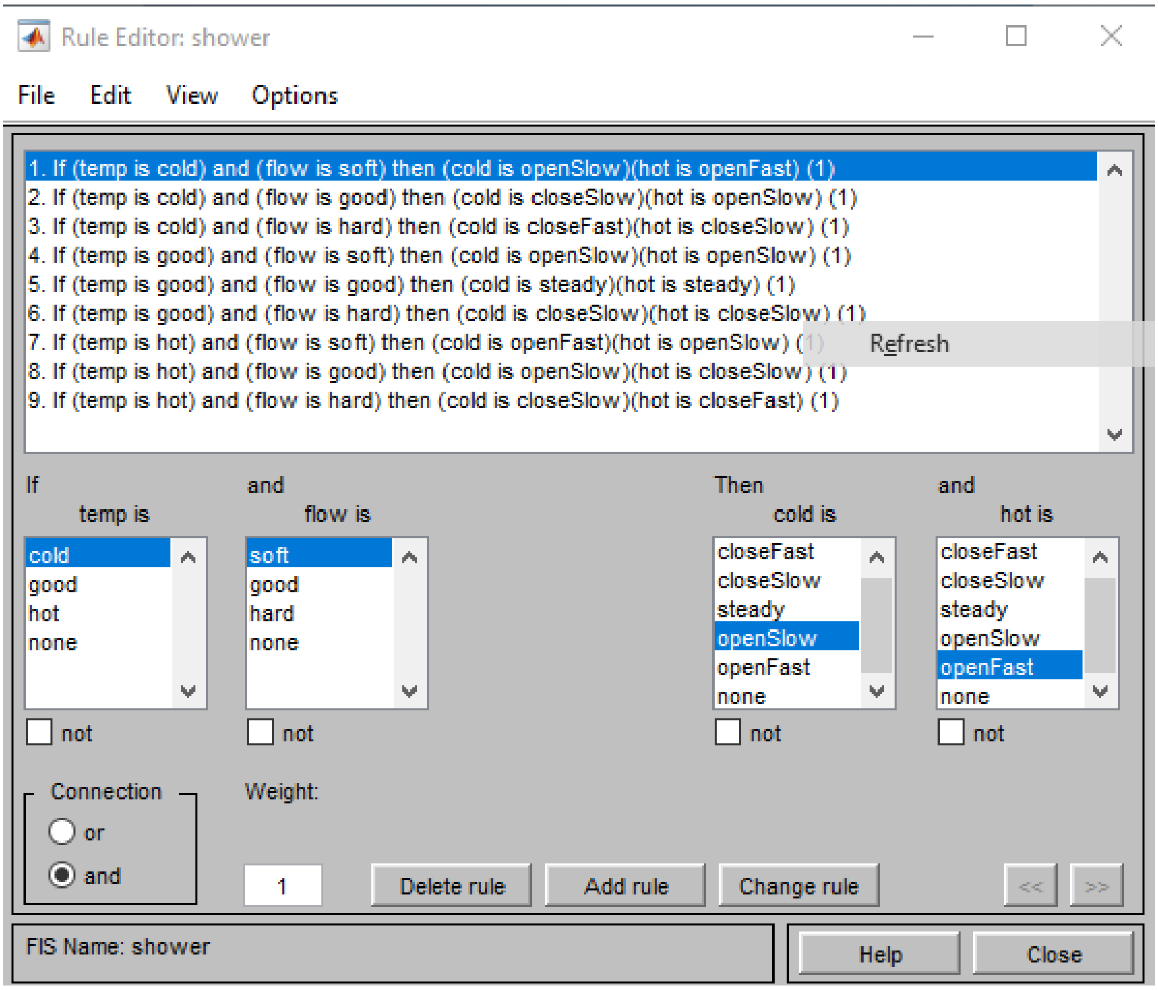


Figure 5. 26: Rule editor

The rule editor is developed using graphical rule interface and its based-on input and output variables that is defined with the FIS editor, this allows the automatic creation of rule statements.

5.6 Results and Discussion

Two input and one output system were simulated using fuzzy logic toolbox in MATLAB. Three fuzzy levels are considered for each of the two inputs and nine levels for the output parameter. Rule base consisting of nine rules will be activated to follow-up the user desired temperature and flowrate to be achieved. The rule viewer is used to get the crisp defuzzied values for the corresponding crisp inputs given. It shows the fuzzification and defuzzification process.

Simulations were conducted to assess the efficiency of using FLC to reduce energy and potable water usage in the bathroom application using the membership functions and set of fuzzy rules as described in the preceding section in Figure 5.22 – Figure 5.25. Accordingly, the simulation for the temperature and pressure flow control is accomplished by the fuzzy control execution, and the attained test is grounded upon the signal of step responses as shown in Figure 5.27 and 5.28. As revealed from simulations, the FLC method can offer appropriate parameters for the Fuzzy controller and the selected system yield can be realized. As a result, the anticipated control possesses appropriate execution on stability with no error of steadiness and having little overshot. It also possesses fast speed response and competent control of the parameters of FLC once required.

As revealed in Figure 5.27 and 5.28, the system yield is resolved at the set-point having a state that is steady and stable. The outcome demonstrates that, the fuzzy control can keep changing the parameters of control to improve the performance control. The controller stabilizes shows transient at the user desired temperature and flowrate

The system output control simulation is displayed in Figure 5.27 and 5.28. It demonstrates that, settling time and rising time shows that the control can rapidly reply to the input signal with quick rising rate as appeared in Figure 5.27 and 5.28. There is little overshot in this control procedure other than the quick response speed. Moreover, the steady state is stable when the control procedure settles. This implies that the anticipated control has suitable on stability, control accuracy, avoiding overshot and having fast response speed.

The advantage of using FLC for this study benefits the water heater in providing much better efficiency irrespective of the manufacturer’s rating and subsequently reduces the energy usage by a more accurate calculation of the power to reach and stabilize at target temperature than to depend on binary principles i.e., hot or cold. The FLC also determines or predicts the quantity of energy needed to reach the desired temperature, hence, causes the energy demand to proportionally reduce once the temperature desired is reached. Since the FL controllers produces finer graduations between discrete values of temperature between the discrete temperature values, the water heater is not expected to undershoot or overshoot as shown in Figure 5.27 and

Figure 5.28 when making +/- modification towards the temperature targeted along what product manufacturers call the "heat rise curve". This greater precision means the heater consumes less energy.

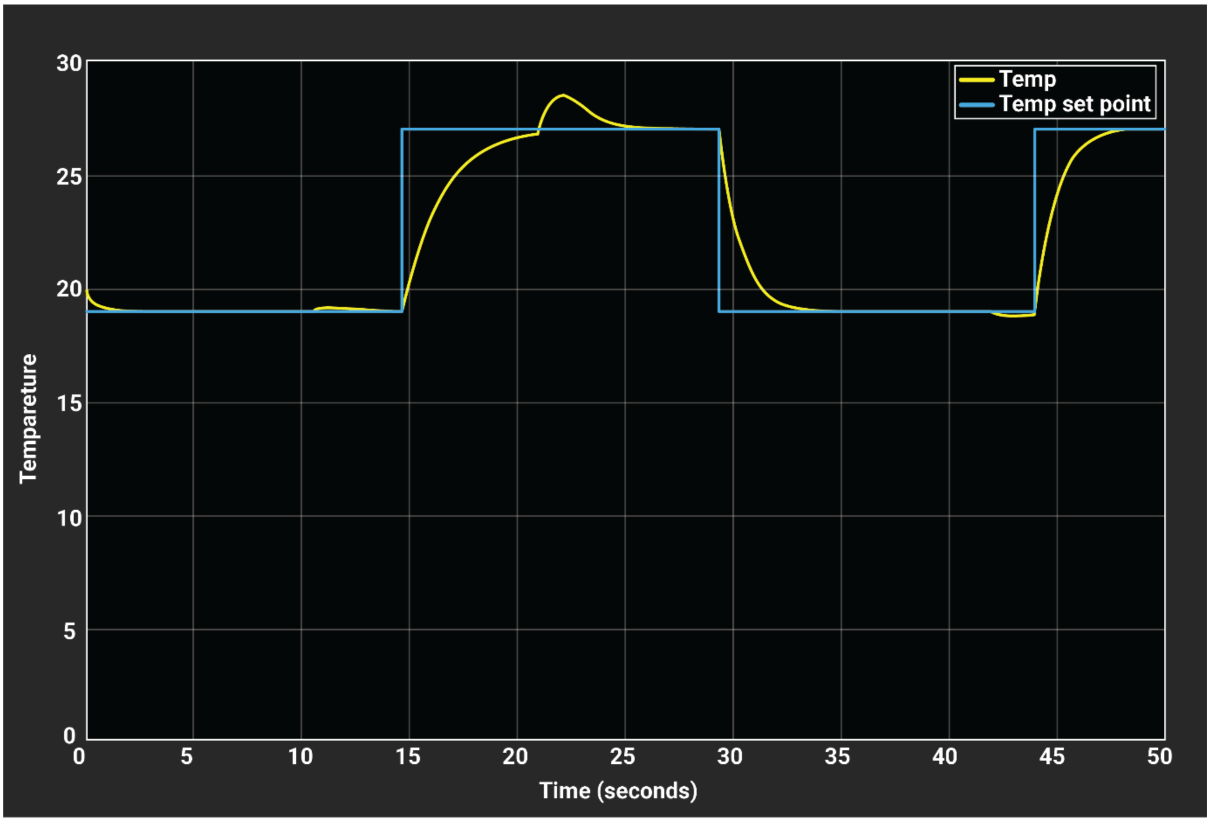


Figure 5. 27: Step responses for temperature simulation

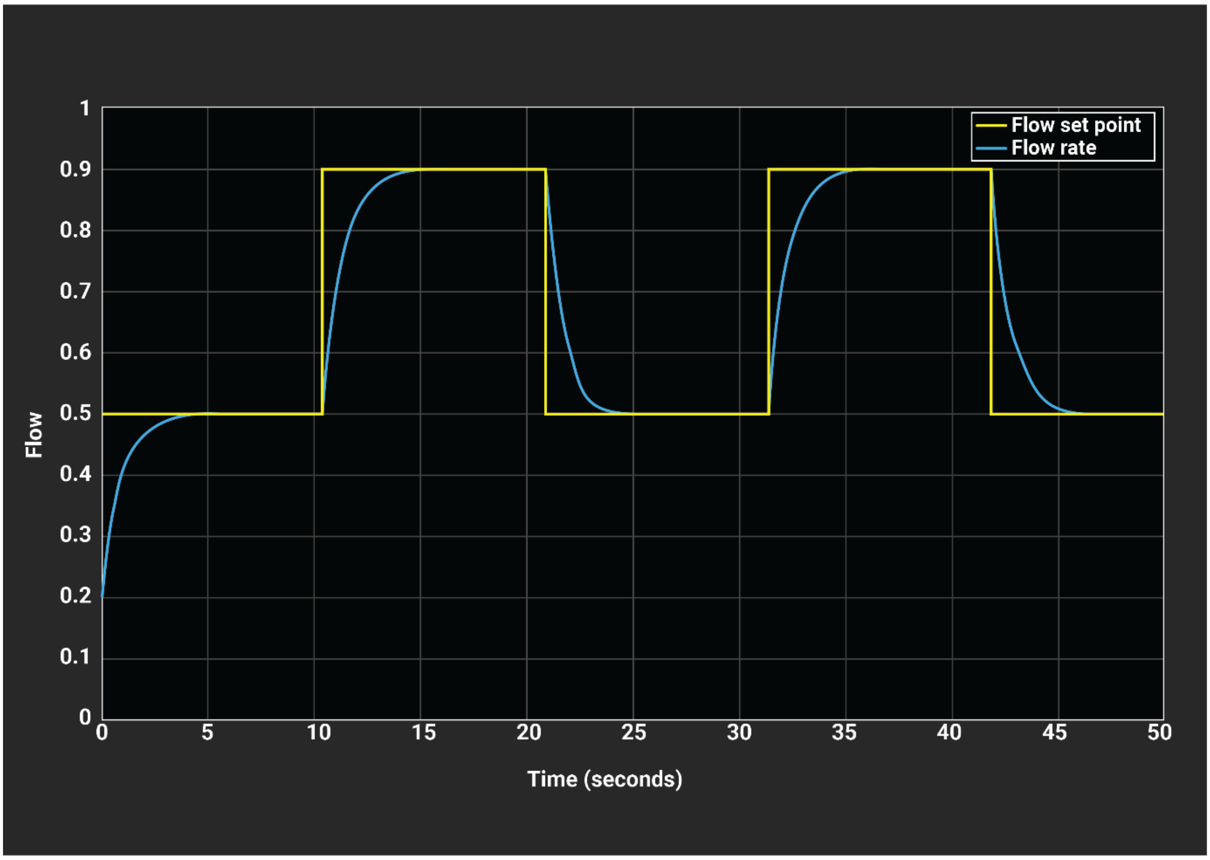


Figure 5.28: Step responses for flowrate simulation

5.7 Summary

In conclusion, simulations are executed to analyse the proposed solar bathroom and the smart hot water controllers. The results of the simulations are deliberated upon to evaluate the solar bathroom and the system controllers' executions on the indexes together with time constant, overshot, stability and response speed. Additionally, the controller design potential for controlling bathroom comfort is deliberated which is grounded upon the results of the simulations.

The implementation of smart technologies or energy-saving measures in bathroom systems benefits greatly from a holistic modelling approach, as systemic interactions increase the performance of the overall system. Results from this study shows the importance of holistic approaches for investigations of the water-energy nexus in the bathroom. Indeed, the most striking results of this study relate to the interdependency of the sus-systems relative to the performance of the bathroom.

In line with the basis of conceptual modelling in the previous chapter, the components of the system are simulated in the Polysun software, and the results unveiled that the system could provide the required yearly energy yield without compromise. Consequently, the simulation results of solar bathroom uncover the importance of using renewable as a source of clean energy in bathroom hot water systems and the particular contribution it makes to the level of energy consumption and carbon emission. The system significantly demonstrates the importance of using solar energy as alternatives to fossil fuel to provide adequate hot water for bathroom systems, vis-à-vis combatting global warming and climate change, and hereby promoting sustainable development.

Also, considering that most bathroom hot water are controlled by using a static setting on the thermostat or on the water heater during certain times i.e., using binary principle to control water temperature is energy inefficient and leads to user dissatisfaction. The FLC controlled strategy implemented in this study is a smart control technique which was applied and simulated successfully for based water temperature and water flow rate control. Several studies have shown that using thermostat (on-off) controls for regulating non-linear systems i.e., for controlling the variability and non-linearity of water temperature and its flow rate have many drawbacks and errors when any variation and non-linearity arises. Smart controls like FLC works perfectly well under these conditions and can be effortlessly designed and executed. This study presents and shows that a smart fuzzy logic control is efficient in its operation and can lead to a great reduction of energy consumption and subsequently leads to reduction of carbon emission and energy cost.

Therefore, the solar hot water bathroom and the smart bathroom control system presented the strong sustainability of the overall system - the social sustainability of the wellbeing and comfort of inhabitants, which is, in turn, technically influenced by the environmental sustainability of the system. As a result, there is development, steadiness and productivity of the system for greener solutions to the world’s energy requirements. The next chapter of this study assesses the economic impact of the solar bathroom system by way of revealing the financial profitability (NPV, IRR, ARR and the payback period) of the system.

Chapter Six

6.0 The System Economic Assessment

6.1 Introduction

This chapter unfolds the economic assessment of the solar bathroom unit. The analysis of the system in the previous chapter demonstrated appropriate functionality with maximum predictability and stability. Also, the analysis outcome established that solar bathroom system can cover the proposed unit demand through the system sufficiency of electricity consumption. The proposed system exhibits an appropriate feasibility measure through producing sufficient solar energy while reducing the rate of energy consumption and carbon emissions, which can tackle climate change. This study subsequently unleashed the economic dynamics of the system, which is the financial profitability of the solar bathroom unit via analysing and calculating the accounting rate of return, net present value, payback period and the internal rate of return of the proposed system. Also, the advantages and drawbacks of each financial assessment indicators are subsequently considered for proper assessment of the system.

6.2 Concept of Profitability

The meaning of profitability is the capability to create profit from the entire business pursuits of a firm, company, enterprise, organization or a system. It demonstrates by what means the productivity of the administration may produce profit through utilising the entirely possessions accessible in the marketplace. Research studies by Harward and Upton (1961), suggest that productivity or efficiency is the capability of a specified asset to make a return as a result of its utilisation.

Nevertheless, the expression represented as ‘Efficiency’ is not tantamount to the expression characterised as ‘Profitability’. Profitability is basically an efficiency index; and is subsequently viewed as efficiency measure and administration lead to better efficiency. Albeit profitability is a vital standard for determining the efficiency, the profitability extent is unable to be confiscated as a concluding efficiency proof. Occasionally, acceptable profits can symbolise inefficiency and on the contrary, a suitable efficiency degree can go together with profit absence. Also, the net profit basically discloses an acceptable steadiness amongst the received values and given value. Although, operational productivity change is among the influences upon which an enterprise profitability mainly relies upon. Hence, it can be presumed that profit is not fundamentally the key mutable upon which the foundation of an organization financial and operational productivity may be equated. For the reason to quantify the efficiency of assets utilised and to quantify the efficiency of operation, the analysis of profitability is contemplated as one of the best methods.

6.3 Profit and Profitability

From time to time, the expression represented as ‘Profitability’ and ‘Profit’ are interchangeably utilised. However, there is a dissimilarity amongst the two. Profitability is a comparative notion while profit is a complete word. Albeit both are meticulously connected and equally symbiotic, possessing different business roles. Profitability alludes to the venture efficiency of operation, whereas profit alludes to the entire revenue produced via the venture all through the stated time. For it is the capability of a venture to produce profit on sales and to acquire adequate profit on the investment and personnel utilised in operation of the business.

The research studies by Weston and Brigham (1978) accurately stated, “to the financial management profit is the test of efficiency and a measure of control, to the owners a measure of the worth of their investment, to the creditors the margin of safety, to the government a measure of taxable capacity and a basis of legislative action and to the country profit is an index of economic progress, national income generated and the rise in the standard of living”, whereas profitability is the profit result and that is to say, no profit operates in the direction of profitability. Organisations possessing profit of equivalent quantity may differ in standings of profitability. For this reason, research studies by Kulshrestha (2015) have accurately specified that, “Profit in two separate business concern may be identical, yet, many a times, it usually happens that their profitability varies when measured in terms of size of the investment”.

6.4 Analysis of Profitability

Discretely from the long-term and short-term creditors, management and owners likewise amuse in the reliability of the solar air-conditioning which can be sustained through profitability assessment. The profitability assessment is basically of two categories. The ones depicting profitability in connection to investment and the ones exhibiting profitability in connection to sales. In conjunction, both assessments designate the system's total operation effectiveness. For the reason to appraise profitability of the proposed system, the analysis is carried out from the point of view of management/ owner of the system. The management/ owner of the proposed system is certainly enthusiastic to measure the solar bathroom efficiency of operation. Correspondingly, the owners capitalise their resources in the anticipation of sensible yields. The solar bathroom unit operating efficiency and its capability to guarantee satisfactory yields relies eventually upon the profits produced through the system.

Report by Renewable Energy Hub (2021) unfolded that the average yearly energy of solar system components for a bathroom system is 4,848 kWh per year. According to Renewable Energy Hub (2021), the average costs of solar bathroom unit is £4800 which includes all the system components and installation cost. Research studies suggest by Oye et al. (2020a) that cost of the system installation is determined according to the following grounds:

- The equipment costs which are basically ascertained through its category.
- Costs are contingent upon the specific place and the category of building involved.
- It also relies upon the level of salary in the engineering domains in the specific environment.

Nevertheless, the estimated solar bathroom unit average installation costs are employed. In this study, all values are calculated in pound sterling for accuracy and consistency in the assessment of financial profitability. Consequently, the costs of maintenance specified consist of the system adjustment and periodical check. Twenty years is the lifespan of the system components as specified by the manufacturer and the proposed costs of the system average maintenance is £100 per year. The annual renewable heat incentive (RHI) for the solar thermal system is 21.49p.

For bathroom profitability assessment, the following assumptions have been made

- The efficiency of the collector reduces by 0.5% annually. Abu-Bakar et al. (2014a).
- The annual maintenance cost increases by 3% annually. (Cherrington et al. 2013: Abu-Bakar et al. 2014b).
- The standard gas conversion rate is 0.049/kWh. (Duffie and William 2012).
- The RHI is 21.49 for the renewable system and paid for a 7-year duration with 4% inflation annually for the 7 years period. (Abu-Bakar et al. 2014a: Energy Saving Trust 2021).

In this study, profitability of the proposed system has been carried out by means of calculating the accounting rate of return, payback period, net present value and the internal rate of return as discussed and analysed in the following subsections.

6.4.1 Accounting Rate of Return (ARR)

Accounting rate of return studies commenced by Harcourt (1965), Vatter (1966) and Solomon (1966) respectively, and sustained through the studies of Kay (1976, 1978), Peasnell (1982), Franks and Hodges (1984), Kay and Mayer (1986), Edwards et al., (1987), Brief and Lawson (1992), Brief (1996), Brief (1999), Al-Ani, (2015) and so on. The key purpose was also to study the connection amongst the internal rate of return and the accounting rate of return or to practice the valuation process of accounting rate of return. For the elementary framework was given in both cases through an economic model and the model of accounting was subsequently suitable into the context of economic procedures.

The accounting rate of return strategy for investment of capital evaluation seems to go under various appearances, with a large number of definitions utilized as the reason for its estimation. Studies suggest that there is no solitary acknowledged calculation for the accounting rate of return (ARR), and there is impressive perplexity in the professional and academic literature with respect to which technique for calculation requires to be received. Thus, the board may choose either of the formula that suits them most. Reference is formed to the accounting rate of return without offering an exact definition to its meaning or calculation. Correlations are form on the fundamental suspicion that; one is contrasting similar with similar. This, as a rule, is a bogus presumption. In spite of the fact that a differentiation is form between the accounting rate of return dependent upon average investment and initial investment, there is no commonly acknowledged premise figures calculation to be utilized for whichever interest in or the return received from a project. The accounting rate of return is as well usually alluded to the return on investment (ROI), return on capital employed (ROCE) and average rate of return (ARR). It is likewise recognised as simple rate of return, unadjusted rate of return, book rate of return, return on book value and average book rate of return. Much of the time, the expressions are utilized synonymously, even though they infer unobtrusive contrasts in calculation. Despite the fact that the accounting rate of return, in whatsoever arrangement, experiences genuine deficiencies (it depends on an accumulation and not a cashflow idea; it considers not the way profits may change yearly and subsequently demonstrate an uneven example - it disregards the time estimation of funds flow and possibly not appropriate for contrasting ventures and diverse life expectancies), investigation demonstrates that it keeps-on being utilized in the USA and UK for capital project appraisal. Purposes behind its utilization have been specified as effortlessness and simplicity of calculation, prompt understandability, and its utilization of gathering accounting measures through which administrators are much of the time assessed and compensated. For it offers a possibility for control through creative accounting. Beneath the 'underlying' technique, the returns from an undertaking are communicated as a level of the underlying expense. The returns are expressed after deterioration and subsequently displays reality - in an oversimplified way, the rate of return that is relied upon to be accomplished over that which is required to recoup the underlying investment expense. In any case, a way of thinking that develops the recommendation as the investment of capital will be discounted over the valuable existence of the task, at that point, the investment figure should be considered. For this would bring about an 'average' figure of investment in its utmost fundamental structure of one-portion of the original cost. Under either approach, the income from the project would continue as before.

In this study, the formula for accounting rate of return is specified in the equation (6.1) below:

$$ARR = \frac{Average\ Annual\ Profit}{Initial\ Investment} \times 100 \ldots\ldots\ldots\ldots\ldots. \qquad 6.1$$

$$Average\ Annual\ Profit = Revenue - Annual\ Maintenance\ Cost$$

$$Average\ Annual\ Profit = 8500.00 - 100.00 = 8400.00$$

$$ARR_{20} = \frac{8400.00}{4800.00} \times 100 = 175\% \qquad \ldots\ldots\ldots\ldots\ldots..6.2$$

The solar bathroom unit initial investment is £4800.00 while the first annual maintenance cost is £100.00 with 3% annual increment and in twenty years of the system operation, the maintenance costs is £2687.09. Also, the solar bathroom unit investment which includes the maintenance cost in twenty years of operation is £7487.09. This is the addition of the initial investment and the cost of its maintenance for twenty years. The proposed revenue of the system is £9517.20 (business income from its normal business activities). The average annual profit is £793.1, and it is subsequently obtained from the dividing proposed revenue of the system by the useful life of the system (20 years). The accounting rate of return is obtained by dividing the average annual profit and the system initial investment. As a result, the accounting rate of return (ARR) is 16.5%. For this system, for every pound that is invested, it will receive an average return of 16.50p.

However, there appears to be some advantages and drawbacks of the accounting rate of return as given in Table 6.1

Table 6. 1: Advantages and disadvantages of the accounting rate of return.

Accounting Rate of Return (ARR)	
Advantages	Disadvantages
• It is very easy to calculate and simple to understand like payback period. It considers	• This method ignores time factor. The primary weakness of the average return method

the total profits or savings over the entire period of economic life of the project. • This method recognizes the concept of net earnings. This is a vital factor in the appraisal of an investment proposal. • This method facilitates the comparison of new product project with that of cost reducing project or other projects of competitive nature. • This method gives a clear picture of the profitability of a project. • This method alone considers the accounting concept of profit for calculating rate of return. • This method satisfies the interest of the owners since they are much interested in return on investment.	of selecting alternative uses of funds is that the time value of funds is ignored. • A fair rate of return cannot be determined based on ARR. It is the discretion of the management. • This method does not consider the external factors which are also affecting the profitability of the project. • It does not take the cash inflows into consideration which are more important than the accounting profits. • It ignores the period in which the profits are earned. • This method cannot be applied in a situation when investment in a project to be made in parts.

6.4.2 Net Present Value (NPV)

The Net Present Value is elucidated as the dissimilarity amid cost inflows present value and the outflows of cash present value (Jory et al., 2016). That is to say, the net present value of a project - normally calculated as the initial investment time is the project's cash flow present value from activities and disinvestment less the initial investment amount. For instance, by calculating NPV of the project, the flow of cash occurring at numerous emphases in period are balanced for the estimation time of cash utilizing rate of discount, which is the return smallest rate required for the task to be satisfactory. For the projects possessing positive NPV (or with values in any event equivalent to zero) are satisfactory and projects with negative NPV are unsatisfactory. On the off chance that the project is dismissed - it is dismissed on the grounds that cash flows will likewise be negative. NPV is utilized in budging of capital to investigate the project or investment profitability and it is delicate to the dependability of imminent incomes that the investment, undertaking, project or venture will produce. For example, the net present value equates the value of the pound sterling today to the estimation of that equivalent future pound sterling considering returns and inflation.

In this study, the formula for the net present value is expressed in the equation (6.3) below:

$$NPV = \Sigma \frac{C_i}{(1+r)^n} - Initial\ Investment \quad \dots\dots\dots\dots\dots\ 6.3$$

Where C_i is the cash flow generated per year; r is the rate of inflation and n is the number of years. For higher net present values are advantageous and the rule for precise decision is as follows:

- $NPV > 0$, accept project
- $NPV \leq 0$, reject project

Nevertheless, inflation can upsurge the future revenue of solar bathroom unit. Then, the feasibility of substitute investments reduces the future revenue value and interests of bank deposit may be of assistance in that circumstance. The proposed yearly inflation rate applied in this study is four percent (4%) with the discount rate of five percent (5%). Moreover, to obtain the initial income generated, the average yearly power of the solar system must be multiplied with the feed in-tariff and the export tariff respectively, and subsequently added together. Hence, this can be calculated as follows:

$$Annual\ RHI\ Income\ for\ year\ 1 = (0.2149 \text{ x } 4878) = £1048.28 \dots\dots\dots..6.4$$

As a result, Table 6.2 revealed the operating profit, generated income and cash flows for the next twenty years of the system and each annual calculation are systematically given in Appendix B in this study.

Table 6. 2: The determination of NPV for 20 years.

Annual	Initial Investment (£)	Panel Performance (%)	Annual Solar Output (kWh)	RHI Income (£)	Annual Savings for replacing gas boiler (£)	Annual Maintenance Cost (£)	Operating Profit (£)	Cash Flow (£)
Year 0	4800							
Year 1		100.0	4878.00	1048.28	239.02	100.00	1187.30	1187.30
Year 2		99.5	4853.61	1043.04	237.82	103.00	1229.09	1229.09
Year 3		99.0	4829.22	1037.80	236.63	106.09	1219.30	1275.42
Year 4		98.5	4804.83	1032.55	235.44	109.27	1209.44	1317.05
Year 5		98.0	4780.44	1027.32	234.24	112.55	1199.47	1363.30
Year 6		97.5	4756.05	1022.08	233.05	115.93	1189.40	1411.13
Year 7		97.0	4731.66	1016.84	231.85	119.41	1179.22	1460.58
Year 8		96.5	4707.27		230.66	122.99	116.90	180.54
Year 9		96.0	4682.88		229.46	126.68	111.96	187.35
Year 10		95.5	4658.49		228.27	130.48	106.92	194.42
Year 11		95.0	4634.10		227.07	134.40	101.75	201.64

Year 12		94.5	4609.71		225.88	138.43	96.49	209.30
Year 13		94.0	4585.32		224.68	142.58	91.09	217.14
Year 14		93.5	4560.93		223.49	146.86	85.57	225.27
Year 15		93.0	4536.54		222.29	151.27	79.91	233.66
Year 16		92.5	4512.15		221.09	155.81	74.13	242.36
Year 17		92.0	4487.76		219.90	160.48	68.21	251.39
Year 18		91.5	4463.37		218.71	165.29	62.17	260.74
Year 19		91.0	4438.98		217.51	170.23	55.98	270.41
Year 20		90.5	4414.59		216.31	175.34	49.62	280.39

Likewise, the NPV in equation (6.3) can further be expressed as:

$$\frac{C_i}{(1.05)^1} + \frac{1.04C_i}{(1.05)^2} + \frac{1.04C_2}{(1.05)^3} + \frac{1.04C_3}{(1.05)^4} + \frac{1.04C_4}{(1.05)^5} + \cdots \frac{1.04C_n}{(1.05)^n} \quad \ldots\ldots\ldots 6.5$$

In order to obtain the NPV of the proposed system, it is essential to substitute the yearly cash flow presented in Table 6.2 into equation (6.5). Therefore, the twenty-year net present value at discount of rate 5% (0.05) can be expressed as follows:

$$NPV = \frac{1187.30}{1.05^1} + \frac{1229.09}{1.05^2} + \frac{1275.42}{1.05^3} + \frac{1317.05}{1.05^4} + \frac{1363.30}{1.05^5} + \frac{1411.13}{1.05^6} + \frac{1460.58}{1.05^7} + \frac{180.54}{1.05^8} + \frac{187.35}{1.05^9} + \frac{194.42}{1.05^{10}} + \frac{201.64}{1.05^{11}} + \frac{209.30}{1.05^{12}} + \frac{217.14}{1.05^{13}} + \frac{225.27}{1.05^{14}} + \frac{233.66}{1.05^{15}} + \frac{242.36}{1.05^{16}} + \frac{251.39}{1.05^{17}} + \frac{260.74}{1.05^{18}} + \frac{270.41}{1.05^{19}} + \frac{280.39}{1.05^{20}} - Initial\ Investment$$

$$NPV = 1130.76 + 1114.82 + 1101.40 + 1079.55 + 1068.42 + 1053.08 + 1038.01 + 122.23 + 120.87 + 119.42 + 117.92 + 116.54 + 114.89 + 113.83 + 112.39 + 111.17 + 109.78 + 108.19 + 106.88 + 105.81$$

$$NPV = 9065.96 - 4800 = 4265.96$$

It can be observed that the proposed project yielded a positive value $NPV > 0$, which suggests the project is worth undertaking. However, the net present value appears to have some advantages and drawbacks as presented in Table 6.3 below.

Table 6. 3: Advantages and disadvantages of net present value.

Net Present Value (NPV)	
Advantages	Disadvantages
• It is conceptually superior to other methods. • It does not ignore any period in the project life or any cash flows.	• The NPV calculations unlike IRR method, expects the management to know the true cost of capital.

• It is mindful of the time value of money. • It is easier to apply NPV than IRR. • It prefers early cash flows compared to other methods.	• NPV gives distorted comparisons between projects of unequal size or unequal economic life. In other to overcome this limitation, NPV is used with the profitability index.

6.4.3 Payback Period

The payback period is characterized as the time required to recuperate the underlying interest in a venture from operations. The technique of the payback period for money related examination is applied to evaluate capital undertakings, and to ascertain the yield each year from the beginning of the task until the aggregated revenues are equal to the expense of the venture. At that period, the speculation is pronounced to have been repaid and the time engaged to achieve this payback is referred to the payback period (Ong and Thum, 2013; Al-Ani, 2015). The rule decision of payback expresses that worthy ventures must possess not exactly some extreme payback period assigned by the administrators. Payback is said to accentuate the administration's apprehension with liquidity and the need to limit chance through a fast recuperation of the underlying speculation. It is regularly utilized for little uses which have evident advantages that the utilization of progressively refined capital planning techniques is not essential or advocated (Ong and Thum, 2013). The necessary payback period sets the limit boundary (obstacle rate) for the acceptance of project. It regularly gives the idea that, as a rule which the assurance of the necessary payback period depends on personal evaluations, considering past encounters and the apparent degree of venture hazard. The payback period has demonstrated to be a significant, well known, essential and conventional strategy in the developed countries like the United Kingdom and the United State of America (Pike, 1985; Brigham and Ehrhardt, 2005).

Characteristically, the expected payback period by the owners of a system varies. For example, the account of the research studies by Fotsch (1983) and Ong and Thum (2013), reveal that the United State of America appraisal of average impediment payback period is 2.9 years whereas, research studies by Woods et al., (1985) stipulate from United Kingdom appraisal that, “Of the firms using new technology and also using the payback investment appraisal methods for all their investments, we had 31 observations of the standard payback period: the minimum observed was 1 year and the maximum 5 year, with a mean of 2.9 year". Likewise, Studies by Ong and Thum, (2013) and Al-Ani, (2015) state that the average payback period for customary ventures was 2.83 year, whereas 3.11 year is for projects with new technology. Nevertheless, research studies suggest that projects with shorter payback periods are rank higher than those with longer paybacks. The philosophy behind the projects having a shorter payback period is that they are more liquid and thus less risky, for instance, they permit the establishments to recover their investment more readily, and subsequently, the money may be reinvested in a different project. By means of a quicker payback period, it is unlikely that the conditions of the market, economy, interest rates or supplementary factors that is influencing the proposed venture will change severely. Therefore, three years or less payback period is often encouraged, because it is of the opinion that the project is supposed to be indispensable if the payback period is less than a year. However, this study still applied payback period as a result of the ease of usage and its broadly application regardless of known limitations.

Since the proposed project possesses uneven cash flows, the formula employed for the payback period can be expressed in equation (6.6) as:

$$Payback\ Period = \frac{Initial\ Investment}{Periodic\ Cash\ Flow} \quad \ldots\ldots\ldots.6.6$$

As a result of an uneven cash flow and to determine how much time to recover the original investment, the payback period can further be expressed as:

$$Payback = Years\ before\ full\ recovery + \frac{Unrecovered\ cost\ at\ start\ of\ the\ year}{Cash\ flow\ during\ the\ year} \quad \ldots\ldots\ldots..6.7$$

Furthermore, year 6 (six) is the year before the initial investment is fully recovered; however, to calculate the unrecovered cost at start of the year, the initial investment must be subtracted from the addition of the cash flows by the end of the 6^{th} year. Furthermore, the cash flow during the year is the flow of cash when the project has fully recovered from its initial investment.

$$Unrecovered\ cost\ at\ start\ of\ the\ year$$
$$= Initial\ Investment - Cash\ flows\ by\ the\ end\ of\ year\ 6 \quad \dots\dots\dots\dots.6.8$$

Subsequently, the payback period is expressed and calculated as follows:

$$Payback = 4 + \frac{373.47}{1068.42} \quad \dots\dots\dots\dots..6.9$$

$$Payback\ period = 4.3\ years$$

In this study, the estimated payback period is 4.3 years, and this typically demonstrates that the system will begin to make profit after 4.3 years of operation. In any case, there appears to be some advantages and drawbacks of the payback period as given in Table 6.4 below.

Table 6. 4: Advantages and disadvantages of the payback period.

Payback Period	
Advantages	Disadvantages
• It is widely used and easily understood. • It favours capital projects that return large early cash flows. • It allows a financial manager to cope with risk by examining how long it will take to recoup initial investment. • It addresses capital rationing issues easily. • The ease of use and interpretation permit decentralization of the capital budgeting decision which enhances the chance of only	• It ignores any benefits that occur after the payback period i.e., it does not measure total income. • The time value of money is ignored. • It is difficult to distinguish between projects of different size when initial investment amounts are vastly divergent. • It over-emphasizes short run profitability. • The overall payback periods are shortened by postponing replacement of depreciated

worthwhile items reaching the final budget. • It remains a major supplementary tool in investment analysis.	plant and equipment. This policy may do more harm than good to the production process.

6.4.4 Internal Rate of Return (IRR)

The internal rate of return appears to be the rate of discount frequently utilized in budgeting of capital that forms all cash flows net present value from a particular venture equivalent to zero. This predominately implies that the internal rate of return is subsequently the rate of return that forms the whole imminent cash flows present value and the project last market value equivalents to the value of present market (Stefan, 1999; Rangel et al., 2016; Neil et al., 2018). The higher an investment IRR, the further alluring it is to accept the venture (Neil et al., 2018). Therefore, it is utilized to rank numerous potential ventures or systems an organisation or individual is contemplating. Thusly, the IRR gives a straightforward impediment, through which any venture should stay away from if the capital expense exceeds this rate. Internal rate of return is additionally alluded to the economic rate of return. A straightforward criteria of decision making can be to acknowledge a task if its IRR surpasses the expense of capital and dismissed if the internal rate of return is not exactly the capital cost. In spite of the fact that the utilization of internal rate of return could bring about various complexities, for example, a venture with numerous internal rates of returns or possessing absolutely no internal rate of return whereas, that internal rate of return dismisses the magnitude of the project and accept that incomes are reinvested at a steady rate. According to research studies by Rangel et al., (2016) and Neil et al., (2018), IRR is the other side of NPV, where net present value is a stream of cash flow discounted value, produced from speculation. Internal rate of return calculates the return of break-even rate indicating the rate of discount.

In this study, the internal rate of return is calculated through IRRCalculator.net software programme as research studies reveal that internal rate of return cannot be calculated analytically, it must alternatively be calculated by utilising software programme/ programs like Excel or trial-and-error technique. As a result, the internal rate of return for the economic assessment of the proposed system is 20.69%. That is to say, the assessment outcome demonstrates that at the discount rate of 20.69%, solar bathroom unit investment is worth undertaking. Nevertheless, there also appears to be some advantages and drawbacks of the internal rate of return as presented in Table 6.5 below.

Table 6. 5: Advantages and disadvantages of internal rate of return.

Internal Rate of Return (IRR)	
Advantages	Disadvantages
• It is straight forward and easy to understand. • It recognizes the time value of money. • It uses cash flows.	• It often gives unrealistic rates of return and unless the calculated IRR gives a reasonable rate of reinvestment of future cash flows, it should not be used as a yardstick to accept or reject a project. • It may give different rates of return; it entails more problems than a practitioner may think. • It could be quite misleading if there is no large initial cash outflow.

6.5 Summary

In conclusion, this chapter unfolded the economic assessment of the solar bathroom unit. The accounting rate of return, net present value, payback period and the internal rate of return has been evaluated and the analysis portrayed that the project is worth undertaking. The economic assessment of the solar-based systems demonstrates how significant savings can be achieved through utilising a sustainable and renewable means of technology, the solar bathroom unit technology. Moreover, the financial profitability factors evaluated appears to possess several advantages and drawbacks; this has been taken into consideration in the assessment of the system. Therefore, the solar bathroom system demonstrates to reduce the level of energy consumption, carbon emissions and saves investment costs; however, it also analytically demonstrates to meet the sustainable agenda in this study, which is the economic sustainability of the renewable bathroom unit. Furthermore, the next chapter in turn presents the discussion and result validation of the study.

Chapter Seven

7.0 Discussion and Framework Validation

7.1 Introduction

This chapter offers the discussion and framework validation of the study. It systematically begins with the conceptual issues of sustainability that informed the studies, followed by the sustainable framework assessment and application of sustainability that fundamentally adds to the knowledge base of the system through the theoretically developed framework. This study takes forward some insightful suggestions proposed by researchers and addresses some deficiencies in previous studies. It also examines the implication of the environment, economic and social sustainability which forms the sustainable framework principles of the study. The penultimate section of this chapter presents the outcome of the semi-structured interviews with the system experts, used to externally validate the proposed framework.

7.1.1 Conceptual Issues of Sustainability in the Bathroom

Currently, societies and humankind face sustainability challenges which primarily connects with the capacity to sustain ecosystems, humanity, and societies on the planet. In the future, these challenges are anticipated to turn out to be more substantial. Accomplishing sustainability in the bathroom is consequently one of the most vital objectives in any household since bathroom emit a lot of unsustainable resources to the environment.

The extreme energy and water consumption in a domestic bathroom bring about various hidden sustainability consequences and most especially their combined nexus impact. Some major effects form extreme energy and water consumption that cause challenges with the social, economic and environmental sustainability, for example, degrading water surface because of contaminated surface overflow flushing into the water body, further water abstraction that causes degradation of the water body and high cost of maintenance with possible upgrade of water supply and treatment of waste-water mechanism. Although, for this study, the major purpose of saving water and energy is not only due to the decline in natural resources, water shortages, and rise in demand, but also due to the amount of carbon emission that could be saved in every litre of hot water utilized for bathroom activities.

According to (Families and Households, 2015) reports, the present pressure on the water supply corporation and water treatment coupled with the ongoing problem of water resources scarcity and depending on a newly manufactured systems will only bring out future imminent impact. Since UK population is roughly about 65million with an average of 2.4 individual per house-hold and there are almost 27 million houses (old and new) coupled with a goal of building at least 2million houses every year by the government, this will take the UK government over 100 years to implement a new water-energy saving system in all bathroom units in the UK if the innovation executed in all newly houses are being adopted for the existing house, consequently, retrofitting a domestic bathroom is a significant factor in any novel system for sustainability.

To save water and energy for bathroom applications, the use of smart/intelligent control system is of great importance in any localised system. The smart controls system enables adaptation to the pattern of the end-user and further increases the efficiency of the system, this would be a substantial enhancement to an integrated system in any household dwellings to save both water and energy. Although in a domestic application, bathroom has the most potential to save water and energy, retrofitting a bathroom with an integrated water and energy saving technologies does not involve big makeovers in the bathroom building and will utmost result in being sustainable having maximum and timely influence. The adaptability of smart or intelligent systems in essential in retrofitting bathroom systems to be sustainable.

However, the concerns and issues personified through sustainability are comprehensive and many in bathroom applications. Though, the extensiveness of matters associated to sustainability proposes that a comprehensive and holistic tactic to sustainability is required. Sustainability actions are progressively becoming the businesses and governments agendas and operating strategies.

The sustainability principles (environment, economic and social) are required to be associated if actions are to achieve the fundamental goals of sustainability in the bathroom. As a result of the three bottom line principles of sustainability adapted in this study, the results demonstrate accomplishment in the reduction of energy consumption and carbon emissions with exceptional control performance and user comfort improvement.

7.2 Sustainable Framework Assessment

The sustainability assessment framework is significant for making sustainability functioning and monitoring and measuring progress in the direction of sustainability. Nevertheless, assessing sustainability is challenging, because there is no generally recognised sustainability technique that exists for a system. There are several motives for this, as well as the arduously in quantifying the key pillars of sustainability (Hacatoglu et al., 2016). For instance, albeit ozone depleting substances and greenhouse gases emissions are quantifiable, measuring their social and economic influences is challenging. Likewise, regardless of living standard frequently being quantified as 'gross domestic product per capita'; life quality can perhaps be further important measure of satisfaction, comfort and human well-being. In this regards, assessment of sustainability can also be argumentative (Morse and Fraser 2005). However, several approaches for measuring or assessing sustainability have been established as discussed below:

- Several methods of assessment apply indicators or principles of sustainability, which are characteristically straightforward quantitative substitutions that systematically measure environmental, social and economic factors. The indicators of sustainability are typically integrated, unifying the bottom-line principles namely social environment and economic whereas others are not integrated, quantifying only a single sustainability fragment. This method unifying the bottom-line principles is analytically applied in this study as a result of its suitability and straightforward measuring proxies for the proposed system.

- Indexes of sustainability have been established grounded upon a composite or aggregate of certain indicators of sustainability. A single-value sustainability quantity grounded upon an aggregate index is perhaps valuable for communication and understanding, owing to its straightforwardness.

Nevertheless, the resolve of such indicators requires aggregation, weighting and normalization of data. These stages generally lead to a loss of beneficial information and can be problematic. The measure of a single-value sustainability can cover facts essential connected with the multidimensional nature of sustainability and therefore be deceptive. As a result of this known facts, this study refrained from using such quantifying method for the framework sustainability assessment of the proposed system.

- Research studies by Daly (1990), established sustainable development operational principles. Albeit beneficial, these are restricted to quasi-sustainable use of non-renewable resources and as result, this method is not applied in this study due to their limited usage.

Studies unfolded that a small number of sustainability assessment approaches simultaneously reflect the three bottom-line principles of sustainability namely economic, environment and social. Conversely, several methodology assessments lay emphasis upon only one sustainability area or dimension such as the environment or economic sustainability. Numerous instances are contemplated to demonstrate this as highlighted below:

- Assessment of biophysical methods is suitable for assessing environmental sustainability, through measuring environmental impact and resource use. Nevertheless, they are usually inappropriate for addressing economic and social domains of sustainability.

- Financial assessment can perhaps be applied to environmental and social capital to evaluate sustainability. Nevertheless, financial assessments for non-market services and goods are not well established, inappropriate appraisals and problematic owing to our restricted ecosystems understanding and the resources they offer.

- The index of environmental sustainability positions countries grounded upon numerous environmental indicators aggregate. Nonetheless, these are generally incapable to associate economic growth and environmental sustainability.

7.2.1 Theoretical Concepts of the Proposed Framework

The non-existence of a framework approach is the weakness of numerous existing approaches of assessing sustainability, which considers the system being measured as a whole and typically accounts for the connections amongst its subsystems. This is significant because of attaining a society that is sustainable is a systems problem, where the economic, social and environment are completely interdependent. Integrated human-environmental systems have connections between diverse systems that basically lead to trade-offs; for example, costs reduction can perhaps originate a procedure to have lower efficiency or higher emissions. An approach of non-systems concentrating upon solitary factors can perhaps be regularly understood to be insufficient for holistically assessing sustainability. As earlier noted, for instance, biophysical methods lay emphasis primarily upon environmental sustainability and disregard social and economic dimensions, whereas approaches grounded upon weak sustainability typically lay emphasis upon factors of the economic and disregard the biophysical sustainability domain. Obviously, a system sustainability requires to be assessed with a systems framework method. Analysis of life cycle is generally a fragment of such method, as it recognises the system energy and material inputs and outputs or procedure and utilises this information to assess the effects of economic, social and environmental domain of the system framework. In the light this, the sustainability principles through a sustainable framework can possibly demonstrate accomplishment in the reduction of the level of energy consumption and carbon emissions of renewable-based bathroom while having exceptional smart control performance and inhabitants' comfort improvement in the bathroom.

Nevertheless, in recent years, the principles of sustainability framework have subsequently been applied to some areas. A number of illustrations are given in Table 7.1 below.

Table 7. 1: Sustainable framework applications

Authors	Subject areas	Sustainable framework application
Dewulf et al., (2000)	Sustainability of technology	Sustainability of technology via a range of illustrations

Evans et al., (2009)	Sustainability of energy	Sustainability indicators for renewable energy
Gnanapragasam et al., (2011)		Sustainability of a national energy conversion system using hydrogen from solid fuels
Gomez-Echeverri et al., (2012)		Global energy assessment for sustainable routes identification
Nazzal et al., (2013)	Sustainability of manufacturing operations	Sustainability as a tool for manufacturing decision making
Khalid et al., (2015)	Sustainability of infrastructure and buildings	Sustainable building of heating, ventilation, and air-conditioning
Russell-Smith et al., (2015)		Sustainable target value design to improve buildings
Krajacic et al., (2015, 2018)	Sustainability of energy, water and environment systems	Sustainability overview of the topic and description of sample studies
Gomez-Echeverri et al., (2012)	Sustainability of region	Sustainability for the world
Gnanapragasam et al., (2011)		Sustainability for countries
Mansoori et al., (2016)		Sustainability for state
Oye (2018)		Sustainability for districts

Furthermore, this study has highlighted some significant deductions from previous chapters which will strengthen the analysis from the framework developed. These are:

- Smart sustainable development has predominantly been framed in the context of the three-pillar model, that is, the contribution to economic and social development and environmental protection form bathroom viewpoint. Bathroom sustainable development has been highlighted to be oriented along a continuum between the weak and strong sustainability paradigms in chapter two of this study, which differ in assumptions about the substitutability of natural and human-made capital. Renewable energy technologies (solar) can be evaluated within both concepts: the contribution of renewable energy to the development targets of the three-pillar model and the prioritization of goals according to the weak and strong sustainability framework. As such, the sustainable development framework developed will provide useful insight for developers, engineers and policymakers to assess the contribution of renewable energy to sustainable development and to formulate appropriate economic, social and environmental measures.

- One of the key points that emerged from the literature reviews in chapter two and three assessment is that the evaluation of energy system impacts (carbon emissions), renewable technology, smart systems and sustainable development goals has for the most part proceeded in parallel without much interaction. Even as the environmental and economically efficient and socially acceptable transformations of the energy system in the bathroom will require a much closer integration of results from all three of these research areas.
- While the assessment carried out in in literature review has generated several important insights, it also disclosed some of these shortcomings. For example, it highlights the need for holistic modelling of systems, the inclusion of additional boundaries (e.g., environmental) and more complex energy system models within an integrated model framework to improve the representation of bathroom condition and its variability constraints.
- However, the results in chapter five, six and seven in this study also showed evidently that for the multi-dimensional challenge of integrating renewable energy, smart systems, and sustainable development, is possible and can be integrated holistically to generate an output that is efficient, smart and sustainable.
- While the outcome of this study has shown the importance in the promotion of sustainable practices by typically pursuing a balance between environment, economic and social performance in project applications. That is to say, the connection amongst sustainability, renewable energy and smart control for

bathroom becomes clear to reduce the level of energy consumption and rates of carbon emissions. The associated link to social sustainability tackles thermal comfort of bathroom user i.e. bathroom system is of strong environmental significance and subsequently has high economic and social influences. Although, many solutions will or may depend strongly on local and regional cultural conditions, and the approaches and emphases of developing and developed countries or cities may also be different.

Consequently, Figure 7. 1 systematically offers and applied the three pillars of sustainability namely, environment, economic and social as a whole arising from the methodical framework which is in turn presented in this study and subsequently re-established the system to sustainability which necessitate transformation in the system. In other words, it combines both the renewable and smart system as a unique system for the sustainability of the system which in turn improves the human adaptation of the comfort of occupants.

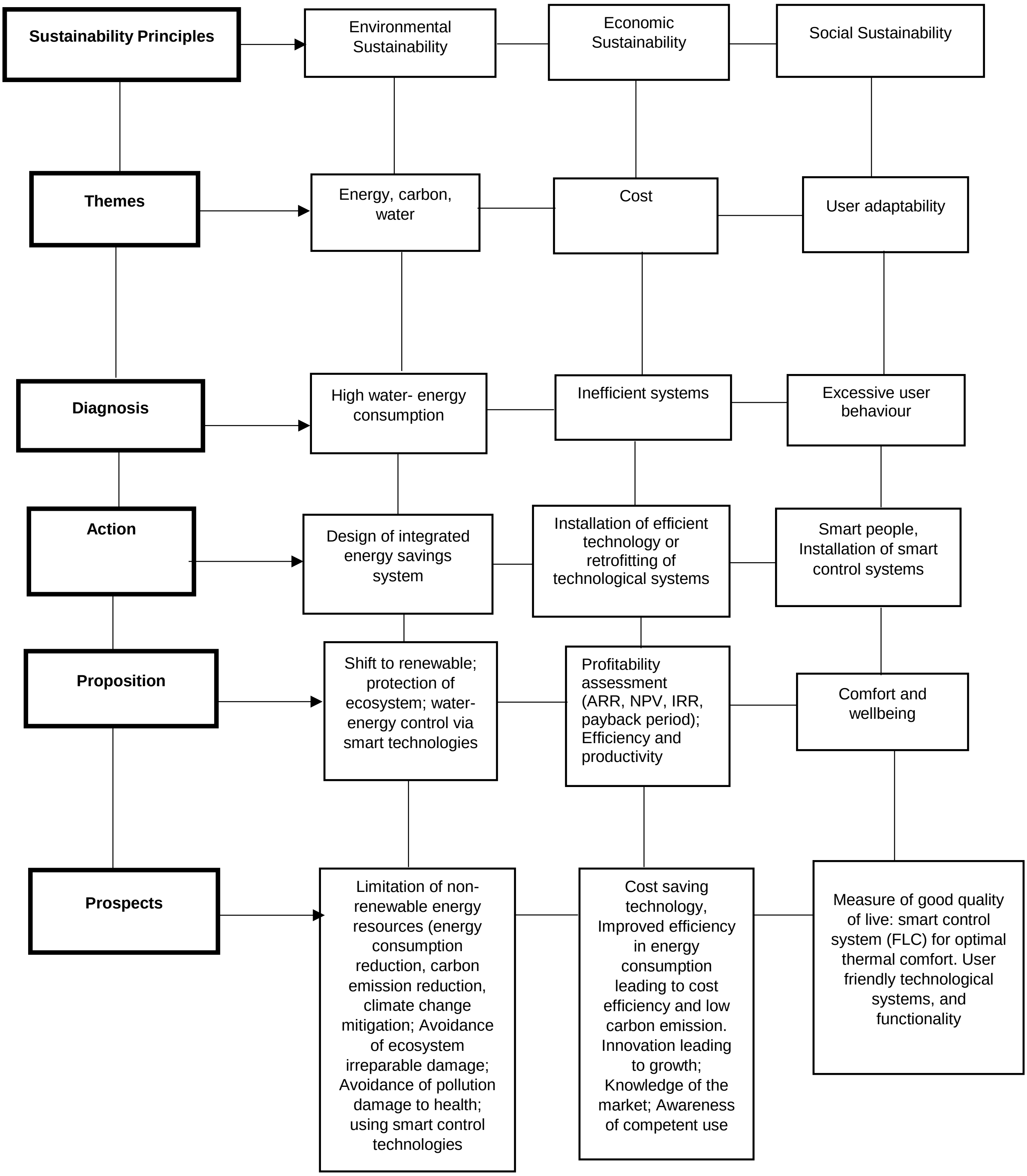


Figure 7. 1: Proposed framework using sustainability principles and indicators.

The framework begins by taking holistic approach to the problem of achieving sustainable and smart bathroom, identifies specific challenges that the bathroom unit must overcome, and finally focuses on the possible opportunities to overcome these identified challenges. The sustainable framework serves to affirm and present the key models as part of the sustainability approach by systematically contributing sustainable solution in a bathroom context. The first column highpoints the triptych in terms of the, environmental, economic and social sustainability. This in turn leads to the key sustainable themes linked to the energy, carbon, water, cost and user adaptability central to smart sustainability principles. Under this lies a further level of analysis focussing on the diagnosis, action and proposition of designers and engineers in securing the sustainability of the bathroom part of an inclusive growth strategy in a wider context.

The literature emphasized that significant variation currently exists in what scholars' target in terms of sustainability approaches to improve the performance in the bathroom from Environmental (emissions reduction), Economic (Cost efficiency) and Social (user inclusion) standpoints. While it has been a generalized approach for researchers to favour an aspect of sustainability model over the others to measure the overall sustainability. This is due to lack of a holistic sustainable framework as this makes it difficult to ascertain if truly bathroom systems are sustainable or not. This will lead to suspicion and distrust in claims.

The holistic sustainable framework developed in this study for achieving bathroom sustainability will work well in the general sense that it will promotes actions towards low energy use, a high degree of renewables and local energy generation and the bathroom can function as a catalyst for the households and several commercial sectors to reduce emissions. This will help to make claims and assertions much more meaningful and comparable, bring greater credibility to the concept of sustainability approaches and thereby increase the opportunity for the approaches to become mainstreamed into a wider context. Without this, the more ambitious target of carbon neutrality might never be possible. The road mapping actions can serve as driving forces for innovation as well. Arbitrating from the framework developed in this study and from the interview validation comments, the route to carbon neutral might come sooner.

Furthermore, the three areas of sustainability can be treated with equality as proposed in this study. The promotion of sustainable practices is to typically pursue a balance between environment, economic and social performance in project applications. That is to say, the connection amongst sustainability, renewable energy and smart control for a bathroom unit becomes clear to reduce the level of energy consumption and rates of carbon emissions. Bathroom is of strong environmental significance and subsequently has high economic and social influences. Therefore, the principles of sustainability namely, environment, economic and social aimed for renewable smart bathroom are theoretically addressed in the following subsections.

7.2.2 The Environmental Sustainability

The subsystems of the environment are social and economic which the basis is and descend of the Earth entire energy and material interactions. The sustainability of humankind suggests guaranteeing the Earth ability to underpin the associated human and activities. Inhabitants and human economies have developed such that activities of anthropogenic currently have long-term and global effects, with numerous consequences. These can perhaps reduce the planet capacity to fundamentally sustain life. However, numerous environmental issues influence sustainability such as the energy consumption and carbon emissions emanating from the use of bathroom systems around the world causing climate change and health effects on inhabitants. There is also loss of biodiversity all over the biosphere, owing to economic growth and other related factors as a result of the constant usage of bathroom system during the year, and this subsequently put threats on environmental sustainability.

The use or removal of deficient resources from the environment and the release of wastes and emissions emanating from the use of bathroom to the land, air and water likewise put sustainability at danger. The pollution emitted by fossil in a conventional bathroom can perhaps also influence the comfort during the utilization of bathroom. Hence, the solar bathroom coupled with the smart/ intelligent system controllers of the system which is subsequently linked with the social sustainability can accomplish such comfortable and healthy bathroom environment quality while tackling the rate of energy consumption, carbon emissions and the resulting climate change effects. The environmental sustainability outcome can demonstrate achievement in the reduction of energy consumption and carbon emissions with exceptional smart hot water control performance and user comfort enhancement. However, the water-energy nexus which is the utmost key significant challenges that affects the sustainable of the bathroom as a result of the rate of energy consumption and carbon emissions is likewise discussed below.

7.2.3 The Water Energy Nexus

The set of water-energy linkages employed in this study is a complex system of components that influence each other directly and indirectly through the greater system in which they operate. Furthermore, these systems are not static but dynamic and nonlinear. The implementation of smart technologies or energy-saving measures in bathroom systems benefits greatly from a holistic modelling approach, as systemic interactions increase the performance of the overall system. Results from this study shows the importance of holistic approaches for investigations of the water-energy nexus in the bathroom. Indeed, the most striking results of this study relate to the interdependency of the sus-systems relative to the performance of the bathroom.

Energy bills and carbon emissions can be cut simply by employing smart control method of water usage: use less, reduce energy bills, and reduce emissions. This is part of the key solution this study search for. The smart bathroom modelling designed in this study have been able to propose a reasonable method to reduce the negative effect of combined water energy nexus with the efficient use of hot water in the bathroom while saving energy and cost.

As a result, this study in addition have likewise proposed a smart hot water control technique that intelligently control hot water usage pattern which in turn also in turn leads to a diminishing level of water-energy consumption and carbon emissions emanating from the use of hot water in the bathroom system.

7.2.4 The Social Sustainability

Social sustainability is a comprehensive notion such as cultural development, wellbeing, health, user behaviour, equity and several other factors. A specific meaning of social sustainability and its contribution is ongoing universally. The development of sustainability rational to comprise a strong social constituent took some time. Initial effort on sustainability is usually concentrated upon either economic sustainability or environmental sustainability while neglecting the social sustainability factors. The importance of the development of both societal and human has been recently realized. The extreme user behaviour associated with hot water use of the bathroom systems is significant since research studies by Yu and Lin (2015) proposed that majority of people spent ten to fifteen minutes of their time especially during shower or bathing. Therefore, the smart control systems for regulating bathroom user pattern is vital in achieving an efficient hot water use in terms of volume, temperature and flow-rate of water. With an appropriate smart control technique of fuzzy logic controller, the hot water usage can be significantly improved. The social sustainability can possibly demonstrate accomplishment in exceptional smart control performance, efficient adaptation bathroom user pattern. Furthermore, the main factor which is the thermal comfort of the bathroom user in social sustainability is discussed below:

7.2.5 Thermal comfort

If the bathroom saves energy and performs very well and does not positively influence the user’s comfort in the bathroom and improve efficiency, then the bathroom is not sustainable. Thermal comfort is key to user satisfaction and productivity and maintaining good thermal comfort is one of the key objectives in the development of the sustainable framework for bathroom. The chapter three of this studies uncovered that the use of traditional flow controls in the bathroom does not provide thermal comfort and could cause burns on the skin, in a bid to increase the hot water flowrate to the user preferred rate, the water volume and temperature also increases which could rise to unsafe degree and cause harm. The environmental parameter (water temperature, and flowrate) which constitute the thermal environment in the bathroom have been controlled in such a way that it will improve the thermal comfort greatly as well as improving the energy efficiency through the use of FL controller.

7.2.6 The Economic Sustainability

An economy that delivers standards of good living, the facilities that individuals need, and occupations is essential for society sustainability. A sustainable society needs continuing economic development somewhat than unbiased economic growth. What happens currently is the economic growth which is frequently measured as growth in gross local product where consumerist economies rely upon economic growth to produce prosperity and occupations. For this reason, studies by Aghbashlo and Rosen (2018), unfolded that the economy functions within a globe possessing limited capacities and resources, over the long term, a constantly growing economy is not perhaps inevitably sustainable. Hence, the universal economy must function more in a stable-state manner, with zero or little development. This fundamentally suggests that the economic assessment of the renewable smart bathroom must be equated as stable-state manner irrespective of the financial profitability analysis outcome in order to promote economic growth and the system benefits to the society since a growing economy is not perhaps certainly sustainable.

The economic sustainability assessment of the solar collector-based systems can possibly demonstrate how significant savings can perhaps be achieved through utilizing a sustainable and renewable means of technology. The economic sustainability opinions are divided into categories of strong and weak sustainability where the ‘strong’ focus more on the environment while the ‘weak’ focused more on the system financial assessment. However, it can perhaps be concluded that, it is beneficial to focus more on the strong sustainability of the solar smart bathroom unit for the overall welfare of the society for constant economic growth.

7.3 Validation

This section clarifies the independent external validation of the sustainable framework developed. In this study, semi-structured interviews with the system experts were conducted to externally validate the sustainable theoretical framework for smart bathroom unit as shown in Appendix G. Semi-structured interviews were conducted with Engineers and sustainable development experts from different organisations to access the feasibility of the developed model for a solar based sustainable smart bathroom unit. Nine representatives from different organisations were approached but only five people consented to take part in the interviews. The five participants consisted as listed in Table 7.2 below.

Table 7. 2: Interviewee profile

Interview Reference	Interviewee professional title
EXV 1	Sustainability Principal Consultant
EXV 2	Senior Mechanical Design Engineer
EXV 3	Sustainable development Manager
EXV 4	Operations Manager
EXV 5	BREEAM Assessor

The interviews were organized with little structure to permit the study to capitalize on the quality of responses assembled and at the same time preventing the difficulties connected with interviewer bias supported by Farrell (2011). Although an interview outline was formulated to guide the interview. This consist of questions and bullet points planned to guide the interviewer throughout the interview process and make sure main theme were not let out. This method was well suitable to make certain that comparable information from the interviewer was collected and the interviews permitted the interviewer to change emphasis if required. The interview was a phone interview and each interview lasted approximately 21 minutes.

To validate the sustainable framework proposed, an independent sample of professionals from the industry were consulted to make certain a balanced opinion of the overall framework developed in this study.

Consequently, an interview plan was developed with three main objectives:

- To access the basis of the sustainable framework developed for the sustainable smart bathroom unit.
- To find out if sustainability sustainable theoretical framework of smart bathroom will be beneficial by tackling the associated excessive user behaviour (high hot water usage) and combatting excessive water-energy usage
- To find out the feasibility of the sustainable theoretical framework for bathroom unit

Most of the professionals agreed after reviewing the sustainable bathroom framework that it would make the bathroom smarter and sustainable. It was agreed by the five participants that the existing methodological system in measuring bathroom and household sustainability had methodological challenges that impacts the water-energy nexus and adds to the rate of energy consumption and carbon emissions, and the proposed system is a commendable development towards improving bathroom sustainability for a sustainable future without compromising satisfaction of its of users. One major disadvantage expressed by two of the participants was that, how the framework can retrofit the bathroom should be considered and the procedure appears to be unconventional and difficult to understand.

Generally, the interviewers agreed with the basis of the developed sustainable theoretical framework for bathroom unit system and applauded its form in the easy-to-understand framework concept. The connection of the three pillars of sustainability namely environmental, economic and social with the bathroom system for an anticipated smart and sustainable future was likewise applauded by the interviewees. Nevertheless, it was suggested unanimously that future studies should perhaps test the result of the sustainable framework developed for smart bathroom in a bid for a clean and sustainable future. One of the interviewees said:

> *"The sustainability of the bathroom is an interesting discourse; this perhaps is a building block in achieving whole house sustainability. The use of solar energy in the bathroom coupled with smart control to regulate water temperature and pressure to the occupant's demands is exciting. Applying this technique on projects can save cost and time". (EXV 3)*

“This is a very broad framework; I can see they cover majorly all the key areas of sustainability and offers more depth in sustainability application than I have seen. It is also systematic in its approach which is a good. I think it should work well as a template for future projects”. (EXV 5)

“The features of sustainability identified within the framework are comprehensive, they will cover most sustainability projects and not only for bathroom”. (EXV 1)

Although, interviewee EXV 1 and EXV 4 did find some potential areas that can improve the framework, with the addition of some bathroom components (heat recovery system) and bathroom fixture (aerated shower head). It was agreed that these will greatly enhance the sustainability of the bathroom since hot-water use is predominant factor in the bathroom.

The interviewee expressed that:

While expert EXV1 advised that the expansion of the framework is needed to include sustainable housing and possibly district though he strongly agreed that at a bathroom level, the framework would work just great. EXV 1 also suggested that in the consideration of any sustainable development, decisions should not only focus on finances but consider other sustainability standards.

Also, EXV 1 suggested that, looking at the framework, I agree with the sustainability side of things, am very much drawn to how the social is linked to the environmental sustainability. With little editing, you can add efficient shower fixture that are now in the market and heat recovery as it can further improve the model.

All respondents mentioned that bathroom systems are generally known for its consumption issues. There is a universal perception about the level of energy consumption and carbon emission associated with the use of bathroom. Surprisingly, nothing really has changed.

Interviewee EXV 2 commented that:

> *The framework is very ok and very thorough.* It depicted the overall sustainability concept of the newly proposed model ranging from its simplicity to its technicality. The logical design of the theoretical framework unravels a reasonable output which can genuinely stand as a future model for achieving sustainability. There is hope for a more sustainable and clean future through the utilisation of the newly developed model. EXV 2

The issue of subjectivity of the framework surfaced during the interview, most of the interviewee reflected on the subjectivity of sustainability framework and agreed that, they are not key obstruction to its execution.

Interviewee EXV 4 commented that:

> *Though some of the content is subjective but it is very practical and can be applied in real world. One of the issues organization face nowadays is putting much attention to the economic sides and satisfaction of the customers without putting much effort to attaining sustainability. It is a good way forward.*

The discussion and opinion on the concept of subjectivity in the framework developed during the interview is consistent with studies from Do Kien Trung, (2019) as it acknowledged that, the existence of subjectivity is a prerequisite for establishing a conceptual framework, a sort of pragmatic guide to the perceived phenomena we conceptualize as “reality”.

It can be surmised from the interviews that sustainability of smart bathroom using framework has not been carried out in sanctioning the sustainability of bathroom. Albeit the respondents are rationally familiar with some aspects of sustainability as they tend to favour an aspect of the sustainability principle over the others. It can be suggested that challenges remain because of non-application of the three bottom line principles of sustainability namely, environment, economic and social. The development of sustainable theoretical framework for smart bathroom as provided in this study and the empirical validation of sustainable smart bathroom will therefore be useful in the sustainability that not only tackles level of energy consumption and carbon emissions, but which also combats climate change and can also reduce cost of operation. Consequently, there appears to be no form of consensus from the interview conducted regarding the outcome of the payback period for the financial profitability assessment of the proposed system.

One of the respondents said:

> *The payback period of the proposed system should not exceed 6 years as most homeowners are not willing to commit resources beyond such period, as system owners are wary about any unforeseen circumstance, related future maintenance cost and returns on investment. EXV 2*

Another respondent mentioned that:

> *Four and half years is a realistic payback period for the proposed system. The system owners should get their return in investment afterwards. Moreover, allowance should be made for annual maintenance and to replace some short-lived equipment. EXV 5*

It was also unanimously suggested that future studies should test the controllers of the proposed system to provide its financial assessment, as well as the overall financial profitability assessment of the proposed system.

Another respondent stated that:

> The payback period can possibly be within the range of four and half years to ten years depending on the investment involved and the capacity of the solar system installed.

Nevertheless, it can be deduced that, it depends on the amount of the initial investment that will provide the desired financial profitability assessment outcome. Since studies by Solar Selections (2019) revealed that solar system is becoming cheaper as 2.5kWh system cost about three times the current price of the system in the last twelve months. The need for further initial investment reduction of the solar hot water system is suggested. This will even be more beneficial for the owners of the system.

7.4 Summary

The aim of this study is to challenge and extend existing knowledge on sustainability related to the smart bathroom systems considering social, environmental and economic dynamics. In line with these, this study has developed a sustainable theoretical framework for smart bathroom which is focused upon conceptual modelling approach that are suitable and fundamentally connected to the scope of this study. The advancement of overall sustainability to pursue balance among environmental, economic and social sustainability for a bathroom is not negotiable, the connection between bathroom and sustainability is strong; cost of designing and construction is of high economic importance and has strong social and environmental effects.

The method this study conducted to external validate the sustainable framework that has been developed in this study were the use of semi structured interviews. Interviews were organised with five professionals from the industry in the United Kingdom with key purpose of assessing and critically evaluating the proposed sustainable framework for smart bathroom. A combination of engineers and sustainable development experts from different organisations to access the feasibility of the developed model for a solar based sustainable smart bathroom unit were selected due to their background in sustainable design and development and experience of working with household energy efficiency and development. The outcome of the interview unveils high level of agreement among the professionals interviewed that the sustainable framework developed will work for its intended purpose and can even be expanded further to accommodate the whole household, this further confirm the validity of this research study and the professional also agreeing the framework is simple, efficient and systematic in its approach within the system proposed for.

Chapter Eight

8.0 Conclusion and Recommendation for Future Studies

8.1 Introduction

This chapter unfolds the overall conclusion of the study. It systematically synopsises the entire study and reviews the stated research objectives. The subsequent section details the main findings from the study and discuss their implications on sustainable theoretical framework. The penultimate section of the chapter subsequently presents the contribution to knowledge of the study and suggests recommendations for future research studies.

8.1.1 Synopsis of the Study

The synopsis offers an overview of the problem statement and how it systematically connects with the objectives of the study. This study addressed each of the objectives which contributed to the knowledge base in diverse ways. The problem statement and research objectives are synopsised in the following section.

8.1.2 Problem Statement

Increased energy consumption and demand, maintenance and upgrade costs and ageing infrastructure, drive the need to improve energy management in order to build up energy efficiency and resilience. Within cities, households deserve particular attention because households are a major building block of cities. Several studies have demonstrated that the heating of water within households dominates energy use of the residential water cycle (Cheng 2002; Arpke and Hutzler 2006).

In the United Kingdom, a great many households are already making savings and making a difference – engaging in water saving behaviour, cutting their bills and conserving resources. But since the average home uses nearly 360 litres of hot water every day, there is still astonishing potential to save water, energy and utility bills through further change. According to Energy Saving Trust in 2014, showers, lavatories, baths and bathroom sinks consume more than two-thirds (68%) of household hot water use. On average, 16% of a household's energy bill relates to heating water for showers, baths and hot water taps. This is on average about £140 a year. As a result, heated water contributes a lot to energy bills, bathroom uses the most hot water in the home, and so it is responsible for the most water-related carbon emissions. The energy used to heat water for devices and appliances emits an average of 875kg of CO_2 per household per year.

Therefore, the challenge that how a combined water and energy saving unit in the bathroom will contribute in sustainability of the houses will remain unresolved. The principles of sustainability namely environment, economic and social which in turn reinforces renewable and smart/intelligent options for more sustainable and energy efficient control systems are the main points in developing a sustainable theoretical framework for delivering sustainable smart bathroom systems that will contribute to overall sustainability of the household. The past issues and current challenges highlight the requirement for detailed analysis of social, environment and economic aspects of smart bathroom systems focused on supporting sustainable future developments.

8.2 Objectives of the Study

The aim of this study is to challenge and extend existing knowledge on sustainability related to the smart bathroom considering social, environmental and economic dynamics. In line with these, this study has developed a sustainable theoretical framework for a smart bathroom which is focused upon conceptual approach that are suitable and fundamentally connected to the scope of the study. The conceptual modelling approach is employed in the modelling of smart bathroom system and the design of the smart bathroom controller. This study also justified and evaluated the basis in existing study. Nevertheless, the research objectives of the study are reviewed, and the main findings are systematically discussed below:

Objective One*:* Conducting comprehensive literature review of sustainable-based smart energy-water saving bathroom unit with holistic approach

Extreme energy and water consumption in a domestic bathroom bring about various hidden sustainability consequences and most especially their combined nexus impact. The UN – Water and Energy sustainability (2014) reports underlined the need to improve sustainability in a business as usual scenario, which may effectively impact the environment and risking the sustenance of social and economic developments. Studies from Water Wise (2014) have also illustrated some major effects form extreme energy and water consumption that cause challenges with the social, economic and environmental sustainability.

However, works from Akadiri et al. (2012), Marco (2013), Anna (2017) and Mourad (2020) have emphasized the concept of a smart and sustainable bathroom. The idea should ideally be capable of efficiently reducing its water and energy it needs and still provide a comfortable experience for its users. Studies from Yi-Mei et al. (2012), Huimin et al. (2015) and Xilian et al. (2021) have discussed on various technologies that have been used to reduce the required energy for bathroom operation using solar thermal technology. Individual components like a solar collector, heat pump, and heat exchanger, tanks etc. are instrumental in achieving the efficient energy savings and carbon emission in the bathroom. While the state of art studies indicated that many of the earlier works on solar water heating is primarily focused exclusively on how each of this components improves solar collector performance, storage tank thermal performance, heat pump and how to manage the hot water usage pattern in reducing energy and carbon emission but they have not indicated on how holistic interaction of subsystems can further improve the system.

Research studies from Water UK (2021) have concluded that more than 66% of the energy utilized for hot water heating applications can be saved using smart technical developments. It was assessed that roughly 90% of the domestic hot water heating functioned inefficiently apparently because it lacked good control systems and thereby costing an extra million in pounds every year. The report from Water UK (2021) concluded laying significant emphases on using an appropriate control system as a requirement to save energy. According to studies from Pomianowski et al. (2020), smart/ intelligent control scheme for improvement of the bathroom performance on energy management is vital to achieve the system overall sustainability goal. Despite the key role of smart system or technology to bring about sustainability in saving water and energy in the bathroom, the smartest piece by all accounts is the user as the bathroom user purposefully picks his/her consumption pattern and activities.

Subsequently, research studies by Hák et al. (2016), Abubakar (2017), Zhai and Chang (2019) suggested that system approach emphasises that discrete technologies are not just upheld by the more extensive technological system, yet in addition by the framework of economic, environment and social standards that reinforces the innovative system. These incorporates existing limitations i.e., economic viewpoints, policies and casual requirements, behavioural and social hindrances Evers (2017). Consequently, this study recommends that one must deliberate upon all the drivers in sustainability when designing transformations to a sustainable bathroom; one also must consider that individual technologies are not only buttressed by the extensive technological system, but the sustainability framework that underpins the technological system. So, it is important to understand the three bottom line principles of sustainability namely, environment, economic and social, and how the renewable and smart/ intelligent approach can contribute to the overall sustainability of the system. This can even offer substantiated insight into sustainable approaches for promoting novelty and concept of smart bathroom for greater sustainability development.

The key to the sustainable-based smart bathroom as a sustainable system (environment, economic and social) is not so much the levels of energy consumption and carbon emission only, but the renewables and smart/ intelligent control it is based on and the theoretical sustainable framework this founds. This is important because without the inclusion of these key components it would not be possible to put forward whether bathrooms sustainable.

Objective Two: Developing and holistic modelling of sustainable-based smart bathroom unit.

With the adoption of conceptual modelling, this study has designed and implement a bathroom unit that is environmentally sustainable and smart. The conceptual modelling of the bathroom unit is meticulously studied and each component of the system which is in accordance with the manufacturer's specifications were described. The actual system components were examined and applied as a basis for the system's description in this study. The holistic designed assumes three flat plate solar collectors, a solar heat exchanger, a pre-heating water storage tank, a main hot water storage tank with natural gas fired water heater, mixing devices and two circulators to collectively improve the overall system efficiency with necessary optimization while achieving substantial energy savings and carbon reductions and tackling global warming climate change. Parametric analysis was also conducted to know how change in variable parameters, location, load and switch-on temperatures will affect the performance of the system designed.

Furthermore, a smart control for the bathroom system is designed to use the fuzzy logic controller, it was used because of its easy adaptability to the bathroom users' pattern. Likewise, its control execution is mostly founded on accurate determination of fuzzy. The main concept behind the control system is to give a water temperature and flow set point to the controllers by opening and closing the hot- and cold-water valves swiftly and attaining user desired temperature as quick as possible while minimizing the energy consumption for heating hot water without influencing the user's comfort.

The simulation for FLC control was done in Simulink-MATLAB software. The initial setting for the cold and hot water circulation in the bathroom system i.e. for shower, taps, sinks and toilet were randomly chosen with temperature from 1 to +50ºC. With the current settings input from the user, the target potable water temperature and flowrate must initiate adjustment to the potable water going to the tap, shower and sink using the valves to attain optimum water temperature and flow quickly with only few changes. The FLC is responsible for managing the water heating to serve and satisfy user requirements and regulating the flow rate which continues until user desired temperature is met i.e., the thermal comfort level.

Objective three: Using computer model to investigate the performance of the solar based bathroom hot water heating systems.

The simulations are systematically carried out on the platform of Polysun and MATLAB Simulink respectively, which is theoretically grounded upon the conceptual modelling and the mathematical modelling of the smart bathroom unit.

The developed model in polysun software was assessed based on energy and environmental performance indices (solar fraction, energy supply or yield, total energy consumption of the system, primary energy savings, system performance and efficiency, reduction of carbon emissions) in order to depict the fundamental ideology of sustainability.

The result shows that the solar collectors produce thermal energy most depending on global solar irradiation and outdoor temperature. The higher the global irradiation level, the better efficiency, and higher thermal performance of collectors. If the temperature is increased, collector heat loss decreases. The total annual energy supplied to the bathroom system is 4,878 kWh. Energy supplied during the winter months is low as it can only provide 20% of the energy required, this means the auxiliary heating system works more during winter. Consequently, the auxiliary heating system is optimised to increase the efficiency of operation and to save significant amount of energy especially during the winter months. In the spring to summer season (April – October), enough useful energy is supplied to the bathroom system with little auxiliary heating from the boiler for energy demand to be covered. The total annual energy consumed by the system is 8,675 kWh. This includes solar energy consumed, auxiliary energy consumed, and energy required to power other components for operation e.g. pumps, boiler, heat exchanger.

The primary energy saved in comparison to a conventional system where the same energy consumptions have to be covered and no renewable energy sources are used. After optimizing the system, the models results shows that the solar thermal systems are still able to save between 50% and 60% of the energy that would have been required annually to heat up the hot water using conventional energy sources, such as gas or electric alone. Most of the savings occurred during the summer months while there was maximum 20% energy savings during the winter months. After optimizing the system, the integrated solar bathroom system completely provided enough energy independently with overall annual solar CO_2 savings of 1,398 kg. This signifies that the energy usage is efficient which enhances the performance of the overall system by making sure the system only uses the required hot water needed in the bathroom.

Parametric study was conducted, and the results shows effects of locations arise because of the differences in solar radiation. Three different climatic locations were analysed, locations with much radiation was found to have better performance over the reference system. The switched-on temperatures of the auxiliary heating system and the volume of hot water use were also a function of the performance of the system.

The parametric study have shown that the use of on-off controllers (thermostat) in the reference models designed in Polysun software are not well suited to achieve the desired outcome due to controlled parameter which will continuously switch around the setpoint and if the hysteresis is not correctly set, the deviation from the setpoint could be quite significant. To overcome this problem, this study has preferred to design and use of FLC (fuzzy logic controls) systems to control hot water usage in the bathroom. The outcome of the FLC design shows that the FLC controller stabilizes and shows transient at the user desired temperature and flowrate. The results also show that FL control has little overshoot, steady state error and stabilizes quickly to the precise user desired flow rate and temperature compare hereby enhancing the efficiency of the reference system.

Objective Four: Assessment of economic impact of the renewable-based system.

In line with the principles of sustainability, the economic assessment of the solar-based system is unfolded in this study. The economic assessment by means of the financial profitability of the solar based bathroom unit namely, the accounting rate of return (ARR), net present value (NPV), payback period and the internal rate of return (IRR) are systematically performed while highlighting the advantages and drawbacks of each financial assessment indicators for proper assessment of the system.

The economic assessment of the solar thermal based system demonstrated that ARR is 16.5%, payback period is 4.3 years, $NPV > 0$ and IRR is 20.69 %. This implies that significant savings can be achieved through utilising a sustainable and renewable means of technology for bathroom application. Each profitability assessment indicators depicted that the project is worth undertaking. Therefore, the solar based bathroom unit designed have demonstrated to reduce the level of energy consumption and carbon emissions and saves investment costs; it however proves to meet the sustainability agenda of the three pillars of sustainability in this study – the economic sustainability of smart/intelligent bathroom system.

Objective Five: Develop and validate the theoretical framework resulting into overall sustainability of the bathroom system.

This study systematically offers and applied the three pillars of sustainability namely; environment, economic and social as a whole arising from the methodical framework which is in turn presented in this study and subsequently re-established the system to sustainability which necessitate transformation in the system. In other words, it combines both the renewable and smart system as a unique system for the sustainability of the system. The framework begins by taking holistic approach to the problem of achieving sustainable and smart bathroom, identifies specific challenges that the bathroom unit must overcome, and finally focuses on the possible opportunities to overcome these identified challenges.

The sustainable framework serves to affirm and present the key models as part of the sustainability approach by systematically contributing sustainable solution in a bathroom context. The first column highpoints the triptych in terms of the, environmental, economic and social sustainability. This in turn leads to the key sustainable themes linked to the energy, carbon, water, cost and user adaptability central to smart sustainability principles. Under this lies a further level of analysis focussing on the diagnosis, action and proposition of designers and engineers in securing the sustainability of the bathroom part of an inclusive growth strategy in a wider context. The holistic sustainable framework developed in this study for achieving bathroom sustainability will work well in the general sense that it will promotes actions towards low energy use, a high degree of renewables and local energy generation and that the bathroom can function as a catalyst for the households and several commercial sectors to reduce emissions. This will help to make claims and assertions much more meaningful and comparable, bring greater credibility to the concept of sustainability approaches and thereby increase the opportunity for the approaches to become mainstreamed into a wider context.

Subsequently, the three areas of sustainability can be treated with equality as proposed by research studies. The promotion of sustainable practices is to typically pursue a balance between environment, economic and social performance in project applications. That is to say, the connection amongst sustainability, renewable energy and smart control for a bathroom unit becomes clear to reduce the level of energy consumption and rates of carbon emissions. Bathroom is of strong environmental significance and subsequently has high economic and social influences. Therefore, the principles of sustainability namely, environment, economic and social aimed for renewable smart bathroom are theoretically addressed in the following subsections.

Furthermore, the technique this study conducted to external validate the sustainable framework that has been developed in this study were the use of semi structured interviews. Interviews were organised with five professionals from the industry in the United Kingdom with key purpose of assessing and critically evaluating the proposed sustainable framework for smart bathroom. The outcome of the interview unveils high level of agreement among the professionals interviewed that the sustainable framework developed will work for its intended purpose and can even be expanded further to accommodate the whole household, this further confirm the validity of this research study and the professional also agreeing the framework is simple, efficient and systematic in its approach within the system proposed for.

8.3 Academic Significance

In the feasibility study for the development of sustainable framework for smart solar hot water energy bathroom unit for this research work, it was necessary to construct a conceptual framework to enable this research to map out the state-of-art in terms of how to achieve sustainability balance from three standpoints, namely: the environmental, economic and social sustainability. Although from the literature review, several frameworks has been mapped out in the area of sustainability for districts, sustainability as a tool for manufacturing decision making and for sustainable developments projects according studies from Nazzal et al., (2013), Russell-Smith et al., (2015), Krajacic et al., (2015, 2018) and Deakin et al 2015, this collective body of evidence failed entirely to established a sustainability approaches that simultaneously reflect the three bottom-line principles of sustainability namely economic, environment and social for households with emphasis on water-energy nexus. Conversely, several methodology assessments lay emphasis upon only one sustainability area or dimension such as the environment or economic sustainability.

The environmental sustainability requires economic sustainability, and social sustainability relies on environmental sustainability. Like wisely, the three areas of sustainability can be treated with equality as proposed by this study. The promotion of sustainable practices is to typically pursue a balance between environment, economic and social performance in project applications. That is to say, the connection amongst sustainability, renewable energy and smart control for bathroom becomes clear to reduce the level of energy consumption and rates of carbon emissions while the associated link to social sustainability tackles thermal comfort of bathroom user; bathroom system is of strong environmental significance and subsequently has high economic and social influences. Therefore, the principles of sustainability namely, environment, economic and social aimed for renewable smart bathroom are theoretically addressed in the following subsections.

8.3.1 From the Environmental Standpoint

There has been extensive work regarding how to improve the performance of solar water heating systems both experimentally and analytically as regards environmental performance in different academic field. A number of studies from (Kulkarni et al., 2008, Hobbi and Siddiqui, 2009, Ayompe, 2015, Gong, 2016, Koke and Kuhr, 2018, Alessandro Franco, 2020) have concentrated on the relationship between performance and design variables. Some examples of the latter are: the storage tank size, the number of tanks, the solar collector area, the collector and heat exchanger flow rates, the hot water load profile, the hot water consumption, the auxiliary water heating device configurations, the cold make-up water replenishment profile, and the heat exchanger configuration. While these authors have majorly concentrated on a system components or parameters at a time for system design or optimization i.e., solar collector, boilers, storage tanks etc. Academic studies from Maria Jakobsons (2015) and Ayompe (2015) have achieve a moderate system efficiency 26% and 31% respectively in terms of the energy savings and carbon emission savings they both search for.

This study reckons that a range of technological challenges are based on the individual components and technologies in the bathroom and concludes that a holistic approach is required for an effective system modelling in the bathroom for better performance. As a result, this study has designed and modelled a solar hot water bathroom from a holistic and integrated perspective which have saved a considerable 50 to 60 percent of energy use with high carbon emission savings. This study have demonstrated that integrated interactions of system components from holistic perspective is significant when considering the concept of solar hot water for use, extracting/collecting solar resource for both water and energy application in the bathroom although, using and optimizing a single technology would be of great advantage nevertheless, the efficiency of a single smart system is constrained to the level of its operation and other system components in the bathroom as evidenced in the work of Maria Jakobsons (2015) and Ayompe (2015). This would not necessarily improve the overall sustainability of the bathroom unit. The concept of energy and water saving using integrated system appears unavoidable to enhance sustainability and focusing on future climate neutrality in bathroom and households while having an appropriate effect on the reduction of natural resources. The concept of the integrated system does not only collectively enhance the efficiency of water and energy nexus but in addition can lessen cost and size of the system components when compared to enhancing or improving each component in the bathroom, subsequently the payback time for an integrated system can be greatly reduce due to the significant incentive provided by the government for the property owner and home developers to adjust to an integrated system. This smart system will simply be smartly controlled to consider the user patterns and to enhance the utmost energy and water saving efficiency.

8.3.2 From Social Standpoint

This study depicted social sustainability as a procedure for making a sustainable and smart bathroom that encourage thermal and environmental comfort, by means of understanding what individuals need from the bathroom they use regularly. This ensures that the cohesion of bathroom users and the ability to work towards common goals (energy and water efficiency) are maintained. Individual needs such as user thermal comfort should also be met. Studies from (Partridge, 2005; Magee et al., 2012; Woodcraft et al., 2012) have mapped out social sustainability framework that help cultural and social life, social comforts, systems for resident commitment and space for individuals and galaxies to grow. The authors have also depicted social sustainability as informal and formal procedures, structures, systems and connections that can effectively bolster the limit of present and future ages to generate liveable and healthy societies. While these state-of-art studies and works from Akadiri et al. (2012) and Mourad (2020) have only discussed social sustainability associated with implementing sustainability in building sector, city and global. None of the studies on the state of art on social sustainability have discussed or mapped out how social sustainability is connected to hot water usage in the bathroom or in the household. This study further tends to capitalize on this gap and designed smart and intelligent energy efficient controller for a bathroom system that is associated with hot water use that can influence environmental parameters and provide thermal comfort for its user. The design also offers an efficient and automatic control of water-flowrate and temperature in the bathroom that is tailored to the user hot water usage pattern that can also save energy in the bathroom system.

8.3.3 From Economic Standpoint

This occurs when development in the bathroom that support economic growth is financially feasible and does not hinder the environmental and social sustainability. Nevertheless, economic sustainability is inseparably connected to both social and environmental sustainability. Studies from Meadows et al., (2004), Gilding (2011), Thomson (2013), Jones et al., (2013) have discussed and that suggested that economies are unlikely to be sustainable if society keeps-on relying upon marvels that hitherto drove development and if natural assets are utilized past the cut-off points and agreed that the use of cost saving technology, reduced running cost with minimum maintenance are paramount. As a result, this study has proposed system components that are cost efficient with good return on investment with minimum payback time of 4.3 years. This study has also modelled a solar hot water smart bathroom with smart systems that saves significant energy that will in turn also reduce cost in-use for the bathroom system.

8.4 Relevance to Practice

The proposed sustainable framework for a smart bathroom unit takes into consideration the three dimensions of sustainable development. It is widely recognised and accepted that sustainability assessment should take into account the three dimensions of sustainable development (Luong et al., 2012). Various key issues and indicators have been taken into consideration in order to ensure effective application of the sustainable framework. The developed sustainable assessment framework guide to encourage clients, designers, contractors and facilities managers to embrace the sustainability agenda from the inception of a project, and to treat sustainability equally as an integral concern throughout rather than as a technological fix that can be bolted on at the end. This framework covers every phase of a bathroom system from the development of a vision for sustainability shared between client and design team, through to good practice in the day-to-day operation of the completed system.

The framework proposed in this study also strive for evaluating how the framework can be utilized in practice to inform investment decisions, providing the researcher with the opportunity to further their research, whilst also further confirming the validity and reliability of the research and, more importantly, the significant contribution it may make in practice. Integrating sustainability in practice implies that the definition and perception of project success take into account the ‘triple bottom line’ of economic, social and environmental benefits as laid out in this study, both in the short term and in the long term. This suggests that the success of the project is assessed based on its sustainable outcome and not only based on financial assessment.

The developed framework highlighted sustainability issues, to act as a starting point for clients and designers, and to provide a range of ideas for consideration. While some principles, like energy conservation, are fundamental, there are many emerging technologies that are undergoing rapid development.

Furthermore, this study has great potential in improving the method in which developers, engineers and designers use in addressing the issue of sustainability in the bathroom and even the household. This will offer designers a systematic approach for achieving sustainability and presents model assisting in making this decision. Each phase of this study can be used in practice.

8.5 Contributions to Knowledge

This study has shown the contribution of renewable energy source and smart control technologies in the bathroom and the significant contribution it makes to the water-energy nexus, levels of energy consumption and carbon emissions. It is attributed to the sustainability of the system and contribution this, in turn, makes to tackle the associated thermal comfort and climate change as part of a sustainability-based strategy. It demonstrates that for this research, renewables and smart control options are the key components for sustainability of a bathroom unit study as it promotes to reduce levels of energy consumption and carbon emission. This study also contributes to knowledge in the following ways:

- Development of a novel framework to the current state-of-the-art through the use of three bottom-line principles of sustainability. The framework developed also reduces the identified gap between theory and practice by facilitating the consideration of sustainable benefit within the feasibility evaluation process, whilst also eliminating several heresies identified in the literature review.
- This study has established a strong quantitative and qualitative links between three dimensions of sustainability. This has made a major contribution to the design of sustainable development and infrastructure by developing a sustainable and smart bathroom framework that have been presented in this study.
- A development of a novel modelling approach to improve the nexus performance of water-energy efficiency and reduction of carbon emission in the bathroom. The result achieved in this study has demonstrated that holistic and integrated interactions of system components are significant when considering

the concept of smart and sustainable bathroom unit in terms of achieving better system performance i.e. energy and carbon emission savings.

- Unfolded a systematic procedure that makes a significant contribution to the sustainability of bathroom study which in turn serves as a future criterion in structuring, selecting, and sustaining a green (environmentally friendly) sustainable-based smart bathroom system that is focused upon supporting sustainable development.
- A novel application of smart fuzzy logic control system to improve the related issues of poor hot water and flow delivery while providing adequate thermal comfort in the bathroom. This shows the importance of interdependency of environment, social and economic sustainability application in the bathroom.
- Demonstrated the use of solar based bathroom system associated with reduction of economic peak loads and related low costs while embracing sustainability, especially in the long term to make future urban suburbs more climate resilient.

8.6 Recommendations for Future Studies

The main work of this study is to challenge and extend existing knowledge on sustainability related to the smart bathroom systems considering social, environmental, and economic principles. In the fulfilment of the research carried out in this PhD thesis, it is beneficial to point out the future recommendation that existed in this work as the following:

- Further research can perhaps consider retrofit options and extend the framework further by way of introducing retrofit options in the environment and social domain of the developed theoretical framework and then assess the overall economic feasibility of the system.
- Future studies can consider other renewable energy technologies such as wind energy, hydropower, geothermal energy, etc., and subsequently integrate such renewable energy into the developed sustainable framework as an alternative source of energy. Thereby, comparing the outcome of solar energy to other renewable energy sources and further extending the developed sustainable

framework. This would provide an even better understanding of carbon emissions and energy performance of sustainable-based bathroom units and household associated with the influence of the developed sustainable-based theoretical framework.

- Further research can subsequently perform the experimental test of the system since the conceptual modelling and the theoretical working analysis of the solar based bathroom unit are unfolded in this study.
- Future studies can perform an experimental test of the developed fuzzy logic control to evaluate the response of the system to flow and temperature change.
- During the validation process, it was discoursed that efficient shower fixtures and heat recovery component should be added. It is therefore any future application of the conceptual framework can consider the potential inclusion of these components.

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Appendices

Appendix A Thermal results (Annual Values) - London District

Thermal results (annual values)

Name	Symbol	Unit	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Solar fraction: fraction of solar er	SFi	%	49.8	24.6	31.4	45.2	60.7	69.1	67.7	70.9	70.4	58.1	44	28.6	18.5
Solar energy to tanks	Ssol	kWh	2,389	96.9	118	194	252	289	281	292	290	230	169	108	68.4
Energy from the heat generator t	Saux	kWh	2,412	298	258	235	163	130	134	120	122	166	215	270	302
Heat removed from tank	Sout	kWh	-3,841.6	-338.5	-309.4	-342.3	-326.4	-330.3	-310.7	-315.9	-313	-300.1	-313.3	-311	-330.7
Solar fraction: fraction of solar er	SFn	%	57.3	26.6	34.5	50.5	66.8	75	73.8	76.8	77.1	65.8	51.6	32.7	20.1
Solar thermal energy to the syste	Qsol	kWh	3,815	122	155	280	396	486	476	505	503	386	271	151	85.6
Heat generator energy to the sys	Qaux	kWh	2,841	337	294	274	197	162	169	152	149	201	254	310	341
Total energy consumption	Quse	kWh	3,822	340	312	345	328	330	308	311	307	294	309	309	330
Total energy demand	Qdem	kWh	4,043	360	330	365	347	348	326	327	322	312	328	328	350
Pump heat to system	Qpar	kWh	24.4	1.8	1.8	2.2	2.1	2.3	2.3	2.3	2.2	2.1	1.9	1.8	1.6
Heat loss to indoor room (includ	Qint	kWh	3,450	179	180	254	311	372	376	395	390	335	282	203	173
Boiler exhaust fumes losses	Qex	kWh	591	68.3	59.9	56.9	41.7	34.6	36.5	32.8	31.8	42.5	53	63.3	69.2
Solar fraction: fraction of irradiati	SFg	%	66.8	37.2	46.7	61.4	75.1	81.6	80.2	82.3	82.3	72.8	61.2	43.4	30.6
Irradiation onto collector area	Esol	kWh	7,916	270	350	604	838	1,028	984	1,018	983	757	558	323	203
Heat generator fuel and electricit	Eaux	kWh	3,938	456	399	379	278	231	243	219	212	283	354	422	461
Electricity consumption of pumps	Epar	kWh	104	7.3	7.3	8.9	9.1	10.1	10.2	10	9.9	9.1	8.4	7.3	6.7
Total fuel and/or electricity consu	Etot	kWh	4,042	463	407	388	287	241	254	229	222	292	362	429	468
Total electricity consumption	Ecs	kWh	104	7.3	7.3	8.9	9.1	10.1	10.2	10	9.9	9.1	8.4	7.3	6.7
Total oil consumption	Eoil	kWh	3,938	456	399	379	278	231	243	219	212	283	354	422	461
Max. reduction in CO2 emissions	StImpe...	kg	1,349	43.3	54.7	99	140	172	168	179	178	136	95.8	53.2	30.3
Primary energy factor	eP		1.18	1.51	1.45	1.26	0.98	0.83	0.93	0.83	0.82	1.11	1.31	1.55	1.57

Solar Fraction to the system (Annual Values) - London District

Solar thermal energy to the system	Qsol	kWh	3,815
Heat generator energy to the system (solar thermal energy no	Qaux	kWh	2,841
Total energy consumption	Quse	kWh	3,822
Energy deficit	Qdef	kWh	224
Total fuel and/or electricity consumption of the system	Etot	kWh	4,042
Total electricity consumption	Ecs	kWh	104
Total oil consumption	Eoil	kWh	3,938
Primary energy factor	eP		1.18

Hot water demand from the system (Annual Values) - London District

Name	Symbol	Unit	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature		°C	57.9	57.8	57.8	57.8	57.7	57.9	57.9	58.2	58.5	58	57.7	57.7	57.8
Minimum value		°C	46.9	48	47.7	47.9	46.9	47.8	47.1	47.1	47.8	47.7	47.8	47.8	47.9
Maximum value		°C	62.4	60	60	60	61.2	61.9	62	62.4	62.3	62.3	60	60	60
Flow rate		l/h	360	360	360	360	360	360	360	360	360	360	360	360	360
Availability	ε	%	95.5	95.6	95.6	95.6	95.5	95.6	95.4	95.6	96	95.3	95	95.2	95.5
Temperature setting		°C	60	60	60	60	60	60	60	60	60	60	60	60	60
Energy deficit	Qdef	kWh	224	19.7	17.8	19.6	19.3	19	18.6	17.2	16.3	17.9	19.7	19.2	19.7
Energy demand	Qdem	kWh	4,043	360	330	365	347	348	326	327	322	312	328	326	350
Energy from/to the system	Quse	kWh	3,822	340	312	345	328	330	308	311	307	294	309	309	330
Volume withdrawal/daily consum		l/d	200	200	200	200	200	200	200	200	200	200	200	200	200

Collector parameters (Annual Values) - London District

Name	Symbol	Unit	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	D
Mean temperature		°C	21.9	10.8	13.1	17.7	23.6	28.9	31.5	32.6	31.5	26.5	20.8	14.3	1
Minimum value		°C	-1.6	-1.6	-0.5	0.9	2.1	6.1	9	10.8	11.2	10	5.9	2.9	
Maximum value		°C	75.5	46.5	51.6	64.7	71.9	74.1	73.3	74.9	75.5	74.7	71.1	57.2	5
Flow rate		l/h	280	280	280	280	280	280	280	280	280	280	280	280	:
Irradiation onto collector area	Esol	kWh	7,916	270	350	604	838	1,028	984	1,018	983	757	558	323	:
Minimum value (Power)		W	0	0	0	0	0	0	0	0	0	0	0	0	
Maximum value (Power)		W	7,487	4,359	5,719	6,751	6,902	7,193	7,246	7,306	7,487	7,300	6,088	5,267	4,:
Collector field yield	Qsol	kWh	3,815	122	155	280	396	486	476	505	503	386	271	151	8
On/Off		%	53	36.3	43.8	51.7	59.9	66.7	71	68.1	63	55.6	47.2	39.3	3
Collector aperture area		m²	7	7	7	7	7	7	7	7	7	7	7	7	
Direct irradiation after IAM		kWh	3,671	147	151	259	417	452	368	450	466	379	298	179	'
Minimum value (Power)		W	0	0	0	0	0	0	0	0	0	0	0	0	
Maximum value (Power)		W	6,464	3,540	4,926	5,765	6,050	5,350	5,398	6,464	6,253	5,748	5,182	3,998	3,!
Collector field yield relating to ap		kWh	546	17.5	22.1	40	56.7	69.5	68.1	72.2	71.9	55.2	38.7	21.5	1
Collector field yield relating to gr		kWh	507	16.2	20.5	37.2	52.6	64.5	63.2	67	66.8	51.2	36	20	1
Maximum temperature		°C	196	196	196	196	196	196	196	196	196	196	196	196	'
Diffuse irradiation after IAM		kWh	3,683	102	173	303	364	502	543	494	451	327	219	119	8
Minimum value (Power)		W	0	0	0	0	0	0	0	0	0	0	0	0	
Maximum value (Power)		W	2,916	1,208	1,798	2,414	2,549	2,810	2,916	2,891	2,696	2,446	2,122	1,445	!
Irradiation onto collector		kWh/m²	1,052	35.7	46.4	80.4	112	137	130	135	131	101	73.9	42.7	2
Minimum value (Power)		W/m²	0	0	0	0	0	0	0	0	0	0	0	0	
Maximum value (Power)		W/m²	1,057	601	787	941	979	1,007	1,013	1,036	1,057	1,026	851	720	!
Temperature during operation		°C	41.2	26.6	28.6	34.5	42.2	45.7	45.7	47.9	47.5	43.7	38.1	30.5	2
Minimum value		°C	16.2	17	16.2	18.5	19.6	21.9	24.1	21.4	25.3	19.5	19.3	17.7	1

Boiler parameters (Annual Values) - London District

Name	Symbol	Unit	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	D
Temperature		°C	34.5	36.7	36.8	36.3	33.8	31.7	33.8	31.3	30.2	34.2	35.9	36.8	3
Minimum value		°C	18	21.3	21.2	20.9	18	18	18.2	18	18	18	20.6	21.2	2
Maximum value		°C	62.5	62.5	62	62.3	62	62.2	62.3	61.9	61.8	62.4	61.9	62.3	6
Flow rate		l/h	500	500	500	500	500	500	500	500	500	500	500	500	[illegible]
Heat loss	Qhl	kWh	507	50.4	45.5	47.9	39.2	34.6	36.2	33.5	31.1	40.1	45.4	48.7	5
Minimum value (Power)		W	0.0001	9	8.6	7.9	0.01	0.0001	0.4	0.001	0.0001	0.003	6.9	8.4	
Maximum value (Power)		W	316	316	314	316	314	315	315	312	311	316	313	313	[illegible]
Exhaust fumes losses	Qex	kWh	591	68.3	59.9	56.9	41.7	34.6	36.5	32.8	31.8	42.5	53	63.3	6
Minimum value (Power)		W	0	0	0	0	0	0	0	0	0	0	0	0	
Maximum value (Power)		W	750	750	750	750	750	750	750	750	750	750	750	750	[illegible]
Fuel and electricity consumption	Eaux	kWh	3,938	456	399	379	278	231	243	219	212	283	354	422	[illegible]
Minimum value (Power)		W	0	0	0	0	0	0	0	0	0	0	0	0	
Maximum value (Power)		W	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,
Energy from/to the system	Qaux	kWh	2,841	337	294	274	197	162	169	152	149	201	254	310	[illegible]
Minimum value (Power)		W	-118.7	-118.7	-117.1	-117.1	-117.3	-117.9	-118.1	-117	-116.9	-117.8	-117.1	-118.1	-11
Maximum value (Power)		W	4,250	4,227	4,227	4,229	4,250	4,250	4,248	4,250	4,250	4,250	4,232	4,228	4,
On/Off		%	9	12.2	11.9	10.2	7.7	6.2	6.8	5.9	5.7	7.9	9.5	11.7	1
CO2 emissions		kg	1,184	137	120	114	83.7	69.4	73.2	65.8	63.7	85.2	106	127	[illegible]
Energy savings solar thermal		kWh	4,489	144	182	329	466	572	560	594	591	454	318	177	[illegible]
Fuel consumption of the back-up	Baux	l	394	45.6	39.9	37.9	27.8	23.1	24.3	21.9	21.2	28.3	35.4	42.2	4
Fuel savings solar thermal		l	449	14.4	18.2	32.9	46.6	57.2	56	59.4	59.1	45.4	31.9	17.7	1
CO2 savings solar thermal		kg	1,349	43.3	54.7	99	140	172	168	179	178	136	95.8	53.2	3
Circuit pressure drop		bar	0.00004	0.00004	0.00004	0.00004	0.00004	0.00004	0.00004	0.00004	0.00004	0.00004	0.00004	0.00004	0.00
Minimum value		bar	0.00003	0.00003	0.00003	0.00003	0.00003	0.00003	0.00003	0.00003	0.00003	0.00003	0.00003	0.00003	0.00

Components parameters - London District

Boiler	**Oil 5kW**	
Power	kW	5
Total efficiency	%	95.1
Energy from/to the system [Qaux]	kWh	2,841
Fuel and electricity consumption [Eaux]	kWh	3,938
Fuel consumption of the back-up boiler [Baux]	l	394
Energy savings solar thermal	kWh	4,488
CO2 savings solar thermal	kg	1,349
Fuel savings solar thermal	l	449
Exhaust fumes losses [Qex]	kWh	591
Collector	**FK2 H4**	
Data Source		ITW
Number of collectors		3
Number of arrays		1
Total gross area	m²	7.53
Total aperture area	m²	6.99
Total absorber area	m²	6.93
Tilt angle (hor.=0°, vert.=90°)	°	30
Orientation (E=+90°, S=0°, W=-90°)	°	0
Collector field yield [Qsol]	kWh	3,815
Irradiation onto collector area [Esol]	kWh	7,916
Collector efficiency [Qsol / Esol]	%	48.2
Direct irradiation after IAM	kWh	3,671

Diffuse irradiation after IAM	kWh	3,683
Hot water demand	**Daily peaks**	
Volume withdrawal/daily consumption	l/d	200
Temperature setting	°C	60
Energy demand [Qdem]	kWh	4,043

Component's parameters - London District

External heat exchanger 1	**4200 W/K**	
Transfer capacity	W/K	4,200

External heat exchanger 2	**small**	
Transfer capacity	W/K	5,000

Pump Solar loop pump	**Eco, medium**	
Circuit pressure drop	bar	1.881
Flow rate	l/h	280
Fuel and electricity consumption [Epar]	kWh	32.5

Pump 5	**Eco, medium**	
Circuit pressure drop	bar	0.001
Flow rate	l/h	280
Fuel and electricity consumption [Epar]	kWh	32.5

Pump 7	**Eco, large**	
Circuit pressure drop	bar	0.004
Flow rate	l/h	500

Fuel and electricity consumption [Epar]	kWh	39.4

Storage tank Pre-heating	**400l potable water**	
Volume	l	400
Height	m	1.35
Material		Stainless steel
Insulation		Rigid PU foam
Thickness of insulation	mm	80
Heat loss [Qhl]	kWh	165
Connection losses	kWh	75.5

Storage tank Backup tank	**400l potable water**	
Volume	l	400
Height	m	1.35
Material		Stainless steel
Insulation		Rigid PU foam
Thickness of insulation	mm	80
Heat loss [Qhl]	kWh	397
Connection losses	kWh	327

Loop

Solar loop		
Fluid mixture		Propylene mixture
Fluid concentration	%	40
Fluid domains volume	l	100.3
Pressure on top of the circuit	bar	4

Components parameters - Rome District

Average outdoor temperature	17.1 °C
Global irradiation, annual sum	1,530 kWh/m²
Diffuse irradiation, annual sum	652 kWh/m²

Component overview (annual values)

Boiler	**Oil 5kW**	
Power	kW	5
Total efficiency	%	9.3
Energy from/to the system [Qaux]	kWh	1,255
Fuel and electricity consumption [Eaux]	kWh	2,126
Fuel consumption of the back-up boiler [Baux]	l	213
Energy savings solar thermal	kWh	7,185
CO_2 savings solar thermal	kg	2,160
Fuel savings solar thermal	l	719
Exhaust fumes losses [Qex]	kWh	319
Collector	**FK2 H4**	
Data Source		ITW
Number of collectors		3
Number of arrays		1
Total gross area	m²	7.53
Total aperture area	m²	6.99
Total absorber area	m²	6.93
Tilt angle (hor.=0°, vert.=90°)	°	30

Orientation (E=+90°, S=0°, W=-90°)	°	0
Collector field yield [Qsol]	kWh	6,107
Irradiation onto collector area [Esol]	kWh	12,138
Collector efficiency [Qsol / Esol]	%	50.3
Direct irradiation after IAM	kWh	6,899
Diffuse irradiation after IAM	kWh	4,462
Hot water demand	**Daily peaks**	
Volume withdrawal/daily consumption	l/d	200
Temperature setting	°C	60
Energy demand [Qdem]	kWh	3,631

Pump Solar loop pump	**Eco, small**	
Circuit pressure drop	bar	1.699
Flow rate	l/h	280
Fuel and electricity consumption [Epar]	kWh	15.3

Storage tank Backup tank	**400l potable water**	
Volume	l	400
Height	m	1.35
Material		Stainless steel
Insulation		Rigid PU foam
Thickness of insulation	mm	80
Heat loss [Qhl]	kWh	438
Connection losses	kWh	421

Storage tank Pre-heating	**400l potable water**	
Volume	l	400

Height	m	1.35
Material		Stainless steel
Insulation		Rigid PU foam
Thickness of insulation	mm	80
Heat loss [Qhl]	kWh	311
Connection losses	kWh	202

Loop

Solar loop		
Fluid mixture		Propylene mixture
Fluid concentration	%	40
Fluid domains volume	l	49.7
Pressure on top of the circuit	bar	4

Components parameters - Aberdeen District

Average outdoor temperature	8.6 °C
Global irradiation, annual sum	882 kWh/m²
Diffuse irradiation, annual sum	515 kWh/m²

Component overview (annual values)

Boiler	**Oil 5kW**	
Power	kW	5
Total efficiency	%	91.1
Energy from/to the system [Qaux]	kWh	4,159
Fuel and electricity consumption [Eaux]	kWh	5,612
Fuel consumption of the back-up boiler [Baux]	L	561
Energy savings solar thermal	kWh	3,943
CO2 savings solar thermal	Kg	1,186
Fuel savings solar thermal	L	394
Exhaust fumes losses [Qex]	kWh	842
Collector	**FK2 H4**	
Data Source		ITW
Number of collectors		3
Number of arrays		1
Total gross area	m²	7.53
Total aperture area	m²	6.99
Total absorber area	m²	6.93
Tilt angle (hor.=0°, vert.=90°)	°	30
Orientation (E=+90°, S=0°, W=-90°)	°	0
Collector field yield [Qsol]	kWh	3,351
Irradiation onto collector area [Esol]	kWh	7,385

Collector efficiency [Qsol / Esol]	%	45.4
Direct irradiation after IAM	kWh	3,319
Diffuse irradiation after IAM	kWh	3,507
Hot water demand	**Daily peaks**	
Volume withdrawal/daily consumption	l/d	200
Temperature setting	°C	60
Energy demand [Qdem]	kWh	4,356

External heat exchanger 1	**6300 W/K**	
Transfer capacity	W/K	6,300

External heat exchanger 2	**17500 W/K**	
Transfer capacity	W/K	17,500

Pump Solar loop pump	**Eco, medium**	
Circuit pressure drop	bar	1.945
Flow rate	l/h	280
Fuel and electricity consumption [Epar]	kWh	30.2

Pump 5	**Eco, medium**	
Circuit pressure drop	bar	0.001
Flow rate	l/h	280
Fuel and electricity consumption [Epar]	kWh	30.2

Pump 7	**Eco, large**	
Circuit pressure drop	bar	0.004
Flow rate	l/h	500
Fuel and electricity consumption [Epar]	kWh	56.1

Storage tank Pre-heating	400l potable water	
Volume	l	400
Height	m	1.35
Material		Stainless steel
Insulation		Rigid PU foam
Thickness of insulation	mm	80
Heat loss [Qhl]	kWh	126
Connection losses	kWh	50.6

Storage tank Backup tank	400l potable water	
Volume	l	400
Height	m	1.35
Material		Stainless steel
Insulation		Rigid PU foam
Thickness of insulation	mm	80
Heat loss [Qhl]	kWh	393
Connection losses	kWh	305

Loop

Solar loop		
Fluid mixture		Propylene mixture
Fluid concentration	%	40
Fluid domains volume	l	168.7
Pressure on top of the circuit	bar	4

Appendix B Economic Calculations

Economic Calculations

$$Annual\ RHI\ Income\ for\ year\ 1 = (0.2149 \text{ x } 4878) = £1048.28$$

Year 1

Income generated from RHI = (0.2149 × 4878) = £1048.28

Income generated from savings = (0.049 × 4878) = 239.02

Total income generated = (1048.28 + 239.02) = 1287.30

Annual maintenance cost = £100.00

Yearly inflation rate is 4% (0.04)

Operating profit = (1048.28 + 239.02) – 100.00

= £1187.30

Year 2

Income generated RHI = (0.2149 × 4853.61) = £1043.04

Income generated from savings = (0.049 × 4853.61) = £237.82

Total income generated = (1043.04 + 237.82) = 1280.86

Total income generated with Yearly inflation rate is 4% (0.04) = 1280.86 + (1280.86 × 0.04) = 1332.09

Annual maintenance cost = £103.00

Operating profit = 1332.09 – 103.00

= £1229.09

Year 3

Income generated RHI = (0.2149 × 4829.22) = £1037.80

Income generated from savings = (0.049 × 4829.22) = £236.63

Total income generated = (1037.80+ 236.63) = 1274.43

Total income generated with Yearly inflation rate is 4% (0.04) = 1274.43+ (1274.43 × 0.04) = 1325.39

Annual maintenance cost = £106.09

Operating profit = 1325.39 – 106.09

= £1219.30

Year 4

Income generated RHI = (0.2149 × 4804.83) = £1032.55

Income generated from savings = (0.049 × 4804.83) = £235.44

Total income generated = (1032.55 + 235.44) = 1267.99

Total income generated with Yearly inflation rate is 4% (0.04) = 1267.99 + (1267.99× 0.04) = 1318.71

Annual maintenance cost = £100.00

Operating profit = 1318.71– 109.27

= £1209.44

Year 5

Income generated RHI = (0.2149 × 4780.44) = £1027.32

Income generated from savings = (0.049 × 4780.44) = £234.24

Total income generated = (1027.32+ 234.24) = 1261.56

Total income generated with Yearly inflation rate is 4% (0.04) = 1261.56 + (1261.56 × 0.04) = 1312.02

Annual maintenance cost = £112.55

Operating profit = 1312.02 – 112.55

= £1199.47

Year 6

Income generated RHI = (0.2149 × 4756.05) = £1022.08

Income generated from savings = (0.049 × 4756.05) = £233.05

Total income generated = (1022.08 + 233.05) = 1255.13

Total income generated with Yearly inflation rate is 4% (0.04) = 1255.13 + (1255.13 × 0.04) = 1305.33

Annual maintenance cost = £115.93

Operating profit = 1305.33 – 115.93

= £1189.40

Year 7

Income generated RHI = (0.2149 × 4731.66) = £1016.84

Income generated from savings = (0.049 × 4731.66) = £231.85

Total income generated = (1016.84 + 231.85) = 1248.69

Total income generated with Yearly inflation rate is 4% (0.04) = 1248.63 + (1248.69 × 0.04) = 1298.63

Annual maintenance cost = £119.41

Operating profit = 1298.63 – 119.41

= £1179.22

Year 8

Income generated from savings = (0.049 × 4707.27) = £230.66

Income generated with Yearly inflation rate is 4% (0.04) = 230.66 + (230.66 × 0.04) = 239.89

Annual maintenance cost = £122.99

Operating profit = 239.89 – 122.99
= £116.90

Year 9

Income generated from savings = (0.049 × 4682.88) = £229.46

Income generated with Yearly inflation rate is 4% (0.04) = 229.46 + (229.46 × 0.04) = 238.64

Annual maintenance cost = £126.68

Operating profit = 238.64 – 126.68
= £111.96

Year 10

Income generated from savings = (0.049 × 4658.49) = £228.27

Income generated with Yearly inflation rate is 4% (0.04) = 228.27 + (228.27 × 0.04) = 237.40

Annual maintenance cost = £130.48

Operating profit = 237.40 – 130.48

= £106.92

Year 11

Income generated from savings = (0.049 × 4634.10) = £227.07

Income generated with Yearly inflation rate is 4% (0.04) = 227.07 + (227.07 × 0.04) = 236.15

Annual maintenance cost = £134.40

Operating profit = 236.15 – 134.40

= £101.75

Year 12

Income generated from savings = (0.049 × 4609.71) = £225.88

Income generated with Yearly inflation rate is 4% (0.04) = 225.88 + (225.88 × 0.04) = 234.92

Annual maintenance cost = £138.43

Operating profit = 234.92 – 138.43

= £96.49

Year 13

Income generated from savings = (0.049 × 4585.32) = £224.68

Income generated with Yearly inflation rate is 4% (0.04) = 224.68 + (224.68 × 0.04) = 233.67

Annual maintenance cost = £142.58

Operating profit = 233.67 – 142.58

= £91.09

Year 14

Income generated from savings = (0.049 × 4560.93) = £223.49

Income generated with Yearly inflation rate is 4% (0.04) = 223.49 + (223.49 × 0.04) = 232.43

Annual maintenance cost = £146.86

Operating profit = 232.43 – 146.86

= £85.57

Year 15

Income generated from savings = (0.049 × 4536.54) = £222.29

Income generated with Yearly inflation rate is 4% (0.04) = 222.29 + (222.29 × 0.04) = 231.18

Annual maintenance cost = £151.27

Operating profit = 231.18 – 151.27

= £79.91

Year 16

Income generated from savings = (0.049 × 4512.15) = £221.09

Income generated with Yearly inflation rate is 4% (0.04) = 221.09 + (221.09 × 0.04) = 229.94

Annual maintenance cost = £155.81

Operating profit = 229.94 – 155.81

= £74.13

Year 17

Income generated from savings = (0.049 × 4487.76) = £219.90

Income generated with Yearly inflation rate is 4% (0.04) = 219.90 + (219.90 × 0.04) = 228.69

Annual maintenance cost = £160.48

Operating profit = 228.69 – 160.48

= £68.21

Year 18

Income generated from savings = (0.049 × 4463.37) = £218.71

Income generated with Yearly inflation rate is 4% (0.04) = 218.71 + (218.71 × 0.04) = 227.46

Annual maintenance cost = £165.29

Operating profit = 227.46 – 165.29

= £62.17

Year 19

Income generated from savings = (0.049 × 4438.98) = £217.51

Income generated with Yearly inflation rate is 4% (0.04) = 217.51 + (217.51 × 0.04) = 226.21

Annual maintenance cost = £170.23

Operating profit = 226.21 – 170.23

= £55.98

Year 20

Income generated from savings = (0.049 × 4414.59) = £216.31

Income generated with Yearly inflation rate is 4% (0.04) = 216.31 + (216.31 × 0.04) = 224.96

Annual maintenance cost = £175.34

Operating profit = 224.96 – 175.34

= £49.62

The yearly cash flow of the system can be systematically calculated as follows:

Year 1

1287.30 – 100.00 = £1187.30

Year 2

1280.86 × $(1.04)^1$ = 1332.09

1332.09 – 103.00= £1229.09

Year 3

1274.43 × $(1.04)^2$ = 1378.42

1378.42 – 103.00 = £1275.42

Year 4

1267.99 × $(1.04)^3$ = 1426.32

1426.32 – 109.27 = £1317.05

Year 5

1261.56 × $(1.04)^4$ = 1475.85

1475.85 – 112.55= £1363.30

Year 6

$1255.13 \times (1.04)^5 = 1527.06$

1527.06 – 115.93 = £1411.13

Year 7

$1248.69 \times (1.04)^6 = 1579.99$

1579.99 – 119.41 = £1460.58

Year 8

$230.66 \times (1.04)^7 = 303.53$

303.53 – 122.99 = £180.54

Year 9

$229.46 \times (1.04)^8 = 314.03$

314.03 – 126.68 = £187.35

Year 10

$228.27 \times (1.04)^9 = 324.90$

324.90 – 130.48 = £194.42

Year 11

$227.07 \times (1.04)^{10} = 336.12$

336.12 – 134.48 = £201.64

Year 12

$225.88 \times (1.04)^{11} = 347.73$

347.73 – 138.43 = £209.30

Year 13

$224.68 \times (1.04)^{12} = 359.72$

359.72 – 142.58 = £217.14

Year 14

$223.49 \times (1.04)^{13} = 372.13$

372.13 – 146.86 = £225.27

Year 15

$222.29 \times (1.04)^{14} = 384.93$

384.93 – 151.27 = £233.66

Year 16

$221.09 \times (1.04)^{15} = 398.17$

398.17 – 155.81 = £242.36

Year 17

$219.90 \times (1.04)^{16} = 411.87$

411.87 – 160.48 = £251.39

Year 18

$218.71 \times (1.04)^{17} = 426.03$

426.03 – 165.29 = £260.74

Year 19

$217.51 \times (1.04)^{18} = 440.64$

440.64 – 170.23 = £270.41

Year 20

$216.31 \times (1.04)^{19} = 455.73$

455.73 – 175.34 = £280.39

Appendix C External Validation

External Validation of Sustainable Smart bathroom unit

Letter of Introduction

Toyosi Oye

PhD Researcher

School of Engineering and the Built Environment

Edinburgh Napier University

Merchiston Campus.

Edinburgh EH10 5DT

19th October 2020

Name of Interviewee

Role of Interviewee in the Industry

Address

Dear Sir/ Madam,

Sustainable Theoretical Framework for a Smart Bathroom Unit

During my PhD research study at Edinburgh Napier University, I have developed a sustainable theoretical framework for smart a smart bathroom using the principles of sustainability namely environment, social and economic.

I would be grateful, if you would grant me permission to interview you (through the telephone or in person) to seek your opinion on the feasibility and performance of the system bathroom models.

The estimated time for the interview will not exceed twenty minutes (20 minutes). I undertake that I will not reveal the identities of the interviewees that participate in these exercises and will observe good and professional ethical conduct throughout the investigation and afterwards. Your participation in this study is completely voluntary. There is no foreseeable risk associated with this investigation. However, if you feel uncomfortable answering my questions, you can withdraw from the interview at any point.

If you wish, I will keep you informed of the progress throughout, and I will be happy to share my findings with you. My thesis will also be available at the University library.

Yours sincerely,

Toyosi Oye

Interview Schedule

Section (I)

1. What will you consider as the major impact of bathroom usage in recent time?

A. Energy consumption

B. Carbon emission

C. Climate change

D. Water consumption

E. All the above

Section (II)

A sustainable theoretical framework has been developed for the smart bathroom unit using the principles of sustainability namely environment, social and economic. The environment and the social address renewable and advanced smart options while the economic addresses the profitability measures of the system.

2. How do you assess the inclusion of sustainability principles in the developed theoretical framework of a smart bathroom unit?

3. Do you think the sustainable theoretical framework of smart bathroom will be beneficial by tackling the associated excessive user behaviour (high hot water usage) and combatting excessive water-energy usage?

4. Which aspect do you think the developed framework can be improved for further sustainability planning of the system?