Department of Mechanical and Aerospace Engineering

Investigating the Energy Demand Reduction Potential of Wastewater Heat Recovery Systems in the United Kingdom's Domestic Sector.

Author: Suzanna Graham

Supervisor: Dr Daniel Cóstola

A thesis submitted in partial fulfilment for the requirement of the degree:

Master of Science

Sustainable Engineering: Renewable Energy Systems and the Environment

2021

Copyright Declaration

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: Suzanna Graham

Date: 23/08/2021

Abstract

Renewable energy technologies and the implementation of improved building standards such as PassivHaus have been at the forefront of the UKs strategy to reduce energy consumption and carbon emissions in the built environment. As buildings become more airtight and insulated, space heating demand becomes a less prominent percentage of the overall energy demand associated with the built environment with a reduction from 59% to 13%. On the other hand, the percentage of energy demand associated with DHW will increase from 23% to 49%. This thesis investigated WWHRS in the UK through numerical analysis to determine if significant energy and carbon savings are possible. Data associated with WWHRS was acquired from manufacturers websites who currently provide this technology and temperature data for incoming cold water was found in the SAP calculation methodology whilst temperatures for water streams associated with the end-use appliances were acquired through analysis of literature.

The benefits of introducing WWHR to the wastewater streams from showers, baths, taps, dishwashers, and washing machines were studied in a domestic property in the UK with an occupancy of 4 people. The volume of water used for each end-use was calculated along with the heat content of the water going down the drain and the amount of heat that could be recovered from the drain using heat exchangers.

The main findings of this thesis show that almost 62% of the heat lost through the drains can be recovered by installing WWHRS on all end-use appliance's studies. This leads to an 18.2% reduction in energy consumption for DHW in the 4-bedroom dwelling studied and could reduce carbon emissions from 4-bedroom homes in the UK by 1.1 tonnes per year.

Acknowledgements

Firstly, I would like to extend my thanks to my supervisor, Dr Daniel Cóstola, who offered his expertise and guidance at regular meetings throughout this project and whose encouragement and assistance kept me on track and moving forwards.

I would also like to thank the lecturers within the Mechanical and Aerospace Engineering department for providing me with the knowledge required to undertake this thesis.

Lastly, I would like to thank my parents and friends who have offered their continuous support and encouragement throughout my academic career.

Table of Contents

List of Figures

List of Tables

Nomenclature

Symbol	Description	Units
UF	Utilisation Factor	
UK	United Kingdom	
GHG	Greenhouse gas	$MtCO_2e$
CO_2	Carbon Dioxide	
SAP	Standard Assessment Procedure	
WWHRS	Wastewater Heat Recovery System	
DHW	Domestic hot water	
WWHR	Wastewater heat recovery	
PV	Photovoltaic	
CGS	Clean Growth Strategy	
CO_2	Carbon Dioxide	
MHRV	Mechanical Heat Recovery Ventilation	
PCDB	Product Characteristics Database	
WRAS	Water Regulations Advisory Scheme	
RHI	Renewable Heat Incentive	

1.0 Introduction

1.1 Problem Definition

The Climate Change Act, passed in 2008, commits the United Kingdom (UK) to achieve an 80% reduction in greenhouse gas (GHG) emissions by 2050 from the levels observed in 1990. However, in 2019 the act was amended with the UK now increasing its commitment to achieve 100% reduction in GHG emissions by 2050 with a 78% GHG reduction aiming to be achieved by 2035. Presently the UK is on track to meet its target of a 37% reduction in emissions by 2022 as outlined in the third carbon budget. However, greater measures will need to be implemented if the fourth and fifth carbon budget targets are going to be met (Dray, 2021). The UK government has also set targets through the Clean Growth Strategy (CGS) to improve energy efficiency of businesses, homes, and industry. New energy efficiency targets for UK domestic homes were set in 2021 which state that by 2025 the residential sector should be reducing its Carbon Dioxide (CO_2) production by 75-80% when compared to current levels (ODYSSEE, 2021). With a total of 41.3Mtoe in 2019, the domestic sector is accountable for 29.1% of the UKs final energy consumption (*Figure 1*) with gas representing 64.4% of the total fuel consumed (*Figure 2*) within this sector (gov, 2020).

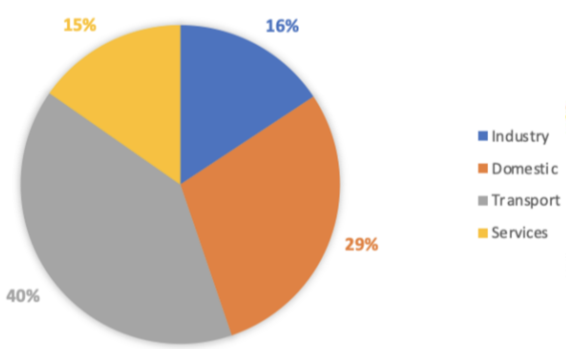


Figure 1: % of energy consumption per sector.

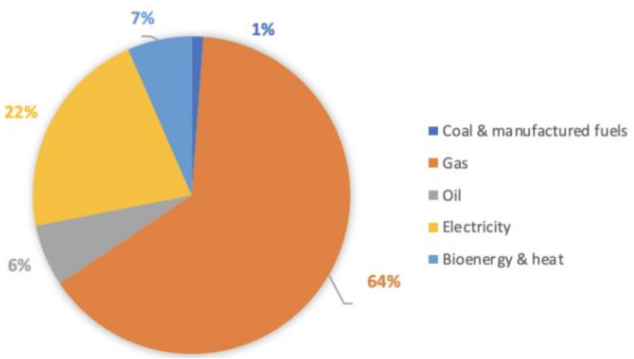


Figure 2: Fuel consumption of domestic sector.

In the UK domestic sector, domestic hot water (DHW) accounted for 17.6% of the share of final energy consumption in 2019 (*Figure 3*), second only to space heating (66.2%) (Statista, 2021). With improvements to building standards such as PassivHaus as well as improved insulation and air tightness of the building envelope it is expected that space heating demand will decrease over time therefore, DHW plays an increasingly important role in energy demand reduction.

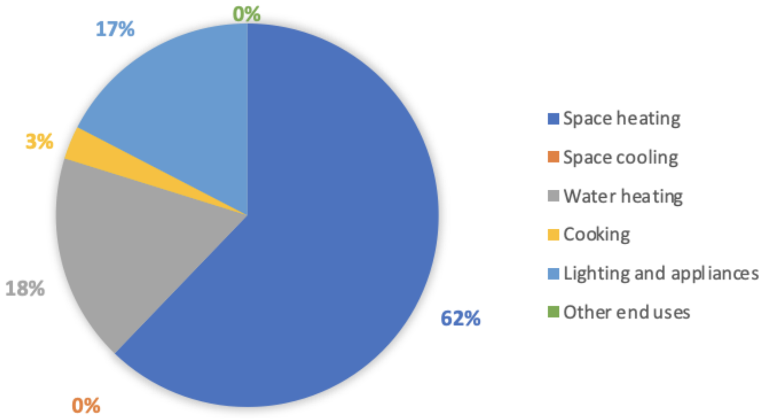


Figure 3: Share of final energy consumption in the residential sector by end use 2019 (Statista, 2021).

Data gathered by the Energy Savings Trust from over 86,000 homes in the UK found that 50% of hot water energy demand is used by showers and an estimated 85-90% of this heat energy is lost from the building envelope once it goes down the drain. In households built to comply with the PassivHaus standard, DHW accounts for a much greater percentage of the overall energy consumption at 48.9% which potentially results in 20.8% of the total energy used in these homes being lost through the drain purely from showers (Recoup, 2017).

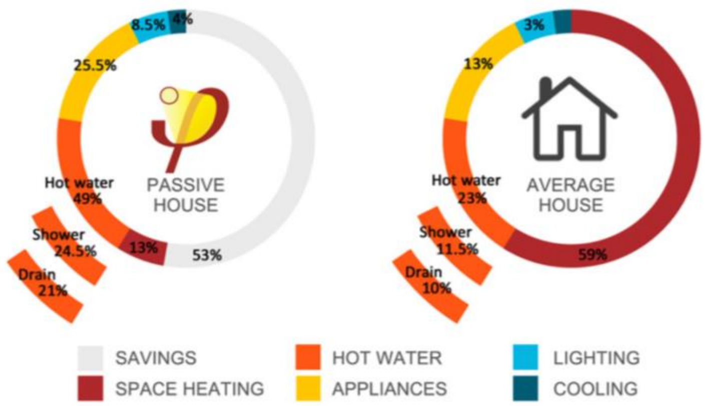


Figure 4: Energy consumption and losses in a passive house vs. an average house.

Recovering heat from the various wastewater streams in a building is one of the options to reduce energy consumption related to DHW. Wastewater heat recovery systems (WWHRS) are designed to capture the heat being lost through the drain and recycle it back into the buildings hot water system. Unlike mechanical heat recovery ventilation (MHRV), WWHRS have no moving or mechanical parts and therefore require no planned maintenance or end-user interaction. They are also capable of efficiencies around 70% (Recoup, 2017). The thermodynamic potential of wastewater heat recovery has been studied in literature, finding significant energy savings.

In literature, most studies are focused on the energy savings associated with heat recovery from shower wastewater streams and the cost savings that can be achieved by recovering the wasted heat. Many studies also investigate the heat recovery potential in combination with heat pumps. However, these studies are mainly undertaken outwith the UK and literature relevant to the UK is sparse. The UK has a different climate and different building standards to the countries studied in the literature, as well as having optimistic energy targets to reach. It is important to examine the impacts that WWHRS would have on UK household energy demand and how the technology could benefit the UK in achieving its climate goals. It is also of interest to investigate energy savings from all greywater wastewater streams in the household and not only that from showers to give an indication of the total amount of heat recoverable in a standard domestic dwelling.

1.2 Aim

This thesis aims to investigate the potential energy savings that can be achieved in the UKs domestic housing sector through the implementation of wastewater heat recovery (WWHR) using heat exchangers and whether utilisation of this technology will aid in UKs journey to net-zero carbon.

1.3 Objectives

1. Develop an understanding of how energy in the UK is currently used within the built environment and where the UK intends to be in the coming years in relation to carbon emission reduction and the strategies currently being used to get there.
2. Gain an understanding on the energy used to heat water in the domestic housing sector, and how much heat is lost after reaching its end-use by undertaking further research into DHW.
3. Investigate a variety of WWHRS currently on the market in the UK, comparing the effect that the varying efficiencies have on heat recovery potential.
4. Determine the reduction in carbon emissions that can be achieved by implementing WWHR technology in the UK and discuss how this impacts the UK in its journey to net-zero carbon.

1.4 Summarised Methodology

This sub-section gives an overview of the methodology undertaken to achieve the aim set out by this thesis.

Initially, data will be gathered on different WWHRS to identify their efficiency and utilisation factor (UF), along with data given by UK Government approved Standard Assessment Procedure (SAP) on incoming cold-water temperatures and behavioural factors of end-use appliances. This data will be used to calculate water consumption, heat content of draining water, and heat recovered by the WWHRS for each end-use appliance using the SAP calculation methodology which is outlined in detail in chapter 3. These results will be gathered for several different WWHRS to compare the heat recovery potential of each technology.

Following this, a comparative analysis will be performed showing which end-use appliance boasts the greatest heat recovery potential and the energy savings achieved in relation to current data on DHW consumption in domestic dwellings in the UK.

A UK wide analysis will then be undertaken on the reduction of carbon emissions resulting from the installation of WWHRS in all UK households and the impacts this would have on the UKs dependency on fossil fuels.

1.5 Thesis Structure

Chapter 1 (Current): This first chapter introduces the background of the subject and the reasoning behind carrying out this thesis. The aim and objectives are also presented within chapter 1, along with a summarised methodology of the study.

Chapter 2: Chapter 2 comprises a literature review to identify similar areas of research, ensuring no identical investigations have been performed previously, and gain an understanding of the elements studied within this research. For this thesis it was necessary to gain knowledge on the UKs current energy use and the technologies utilised to reduce this. In particular, DHW is researched and methods of wastewater heat recovery using heat exchangers, including technologies that are currently available in the UK market.

Chapter 3: Chapter 3 details the methods used to carry out the study as well as the data and sources utilised.

Chapter 4: Chapter 4 presents the results of the study. Analysis of the findings is presented in this chapter, emphasising the heat recovery achieved from various end-use appliances and how this impacts the overall energy demand of DHW. A discussion is undertaken on the findings of the study and how the utilisation of WWHRS will aid in reducing the UKs dependency on fossil fuels relative to other technologies such as solar photovoltaics (PV) and wind turbines. Benefits of this technology in a wider context such as implementation of WWHRS into building standards such as PassivHaus is also discussed.

Chapter 5: Chapter 6 draws on the conclusions and key findings of the study. Any areas for further research are identified as well as the limitations of the study.

2.0 Literature Review

This literature review will critically evaluate existing research on the United Kingdom's residential energy sector and the trends which have inspired the uptake in renewable and clean energy technologies and go on to analyse and compare previous studies of wastewater heat recovery within domestic housing.

2.1 Buildings and Energy in the United Kingdom

Worldwide, the built environment accounts for a large proportion of energy consumption. 40% of energy use in the European Union (EU) can be traced back to buildings (Cao et al., 2016) and this energy use is one of the main factors contributing to the release of CO_2 into the atmosphere. In 2019, energy consumption in the UK was 142Mtoe. A decrease of 0.9% when compared to 2018 (Department for Business, Energy & Industrial Strategy, 2020). Total energy consumption is categorised into industry, transport, domestic, and services (including agriculture) sectors. To breakdown the energy consumption per sector in the UK, the domestic and services sectors to account for over 40% of energy consumption for the year of 2019 which is second only to transport (Department for Business, Energy & Industrial Strategy, 2020).

The result of the domestic and services sectors being accountable for over 40% of the total final energy consumption is that they are responsible for approximately one third of CO_2 emissions (Martinez A., 2014). The construction and operational phases of the built environment have a significant impact to the carbon emissions in the UK, showing an increasing trend each year (Azzouz et al., 2017) and taking into consideration that almost 87% of buildings projected to be standing in 2050 are already built (UK GBC, 2016), a large emphasis in the future will be in relation to retrofitting current buildings and improving energy efficiency during the operational phase. According to Druckman & Jackson (2008), 30% of the UKs energy use and 27% of total CO_2 emissions in 2004 was the responsibility of the domestic sector. In 2019, domestic energy consumption was responsible for 29% of total energy consumption in the UK, a decrease of 1% from 2004 (Department for Business, Energy & Industrial Strategy, 2020).

Over 80% of UK domestic final energy consumption is related to space and water heating which is provided primarily by gas (National Statistics, 2017). The remaining 20% is used for cooking, lighting, and electrical appliances.

Electricity drawn from the grid in the UK has a varying amount of emissions per hour due to production from different generation technologies which each have varying emission factors. Renewable technologies, particularly wind turbines, are able to power a high percentage of the total generation therefore lowering the emission factor associated with electricity however, as renewable power generation is dependent on several variables such as weather conditions, when these conditions are not optimal, and the percentage of electricity generation from renewables is low, the majority of the total generation comes from fossil fuel fired power plants therefore increasing the emission factor. In recent years, the CO_2 emission factor for electricity from the grid in the UK has been falling (Department for Business, Energy & Industrial Strategy, 2020).

On the other hand, heating is mainly provided using fossil fuel generated power and is arguably one of the most difficult areas to decarbonise in the UKs energy sector. With heating being the single largest use of energy in the UK, 86% of demand for heating being met using gas boilers connected to the natural gas network has to change (Chaudry et al., 2015). The extensive gas network and the low upfront costs of gas boilers are part of the reason that renewable technologies have struggled to penetrate the heating industry. However, with the UK aiming for net zero carbon emissions by 2050 it is imperative that heat related CO_2 emissions are reduced to near zero. Domestic heating demand accounts for over 60% of the total annual heating demand and in 2009, accounted for 47% of heat related emissions. It is estimated that by 2030 the UK will have achieved a 30% reduction in emissions from domestic buildings (Chaudry et al., 2015).

The UK has adopted a legally binding commitment to reduce GHG emissions by 80% by 2050, with significant progress necessary by 2030. There is a general consensus that achieving this will be difficult with the structure of the current residential heating sector and will require extensive change to current infrastructure. The government introduced schemes such as the renewable heat incentive (RHI) in attempt to encourage people to make the transition to renewable heating technologies and bridge the clear disconnect between the ambitious emission reduction goals required to meet climate goals and the low uptake of renewable and clean heating practices (Eyre & Baruah, 2015). These schemes, encouraging the uptake in renewable technologies such as heat pumps and combined heat and power (CHP), as well as energy recovery technology, and globally recognised standards such as Passive House are the main solutions in overcoming this issue (Ramadan et al., 2016).

2.2 Energy in the United Kingdom Residential Sector

Reducing emissions by 80% by 2050 requires a reduction in the demand on energy which is increasing due to the expansion of industry, depletion of fuel resource, and a growing population. The efforts to overcome this crisis have classified solutions into three main categories: renewable energy resources, improvement in energy management, and the development of energy recovery technologies (Ramadan et al., 2016).

2.2.1 Electricity

Figure 5 below shows the electricity generated by fuel type for the year of 2019. Around 45.5% of electricity generation was a result of burning fossil fuels. The remaining 54.5% was generated by clean technology such as renewables and nuclear.

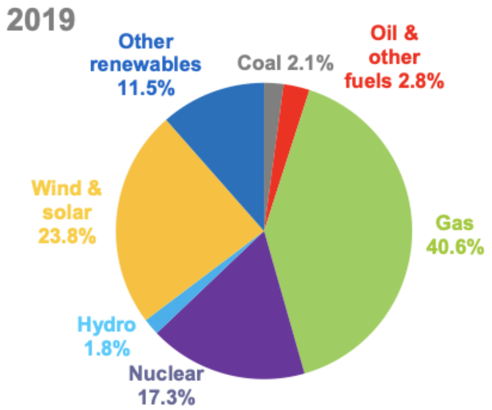


Figure 5: Electricity generated by fuel type (gov, 2020)

Electricity generation from burning coal has been falling steadily since the 1990s with a 97% reduction from the 229.8TWh generated in 1990 to only 6.9TWh in 2019. A 6.5% increase in renewable energy capacity in 2019 saw renewables increasing their share in electricity generation by 4% from 33.1% in 2018 to 37.1% in 2019 (gov, 2020). David JC MacKay indicates in '*Sustainable Energy – Without the Hot Air'* that as well as a large portion of the UKs land being required to be given to renewable energy technologies, energy demand must be reduced to lower the amount of land required for renewable energy and increase the publics acceptance of harnessing clean energy.

2.2.2 Cooling

A study was published by BRE in 2017 addressing energy use by air conditioning in the UK. Over the span of two years, the study concluded that air conditioning and cooling is accountable for up to 10% of all the electricity use in the UK. It found the majority of this energy use was around London and the Southeast of the UK, likely due to the high number of offices and retail space present in this part of the country (icax, 2017). In the UK there is very little demand for cooling in the domestic sector. The report also concludes that cooling in offices used around kWh/m^2 per year, with 65% of offices having air conditioning installed as well as 30% of retail spaces having air conditioning. It has been recommended for the Government to update their product policy model to estimate peak and monthly demand to manage air conditioning units more efficiently (CIBSE, 2016).

2.2.3 Heating

One of the biggest challenges faces in the movement to a clean energy future is the decarbonisation of heat. Of all energy consumed in the UK, almost half of this is used to provide heat with almost 60% of this heat being utilised for space and water heating. 70% of heat energy in the UK comes from burning gas and the remaining 30% is a mixture of electric heating and non-gas fuels such as oil and bioenergy. Some of the main options for decarbonising heat include improved energy efficiency, electrification of heating through the use of heat pumps, and hydrogen networks. Improving the energy efficiency of buildings means retrofitting existing buildings with higher standard materials such as cavity wall insulation, double/triple glazing, and smart sensors to minimise the heat that is able to escape through the building fabric and ensuring new build homes are following high standards set for their performance. Reducing the base heating demand from buildings will be imperative in the successful decarbonisation of heat (ofgem, 2016).

2.2.4 Domestic Hot Water

Hot water consumption is a significant proportion of domestic energy consumption with the UK consuming approximately 4kWh per day based on 2.4 occupants using 80 litres of hot water at 55°C (BRE: Domestic Annual Heat Pump System Efficiency (DAHPSE) - Estimator - BETA, 2019). It is estimated that 14% to 30% of all energy consumed in UK dwellings is to heat water with this proportion likely to increase to as high as 49% as the demand for space heating lessens to achieve demand reduction targets (Marini et al., 2021).

In residential buildings with non-recirculating distribution there is estimated to be distribution losses of 10% to 40% of the total annual energy consumption for hot water production. Insulating the pipe network has a significant impact in potential energy savings. In some cases, insulating the entire distribution system could achieve up to 30% of the energy savings (Marini et al., 2021). A study carried out by Clarke et al. (2009) using energy models to optimise hot water system design and pipe insulation showed that substantial reduction of emissions, heat loss, and hot water consumption was possible.

2.2.5 Renewable Energy for Domestic Hot Water

Renewable energy has been actively researched and developed worldwide since the oil crises in the early 1970s. These technologies can produce useable energy through the conversion of natural occurrences such as sunlight, wind, the tides, and the heat of the Earth (Dincer, 2000). In the UK, geothermal energy has good potential due to the land being rich in heat producing granites that produce heat through the decay of small amounts of radioactive isotopes (Paulillo et al., 2020). Without significant change to policy, the UK will remain in a natural gas-based heating system. As of present, the implementation of heat pumps powered by low carbon electricity is the preferred alternative of UK policy makers (Eyre & Baruah, 2015).

A yearlong trial undertaken by Harrogate Borough Council between 2005 and 2006 saw the installation of Ground Source Heat Pumps (GSHPs) in 8 elderly peoples' homes. The trial reported a 64% reduction in CO_2 emissions as well as reducing their space and water heating bills from 12% of their income to 3.8%, helping them out of fuel poverty (Singh et al., 2010). Rosenow et al. (2018) estimates that 36% of total energy savings will be achieved through heat pumps and heat networks, suggesting investment in these heating technologies will be necessary to achieve the reduction in energy consumption and carbon emissions that the UK requires.

It is possible for heat pumps to be used as a heat source for DHW, although the increased water flow temperatures required can negatively impact their efficiency in comparison to space heating with standard units. To increase efficiency, high temperature units are available using appropriate refrigerants. Other heat pump systems can be comprised of separate components allowing for the provision on both space heating and DHW. These systems typically include complimentary purpose designed ancillaries such as hot water cylinders and controls (CIBSE, 2021 pp1-27 – 1-28).

Sunlight can be harnessed in the form of solar energy for a variety of purposes including space heating and DHW (Alrikabi, 2014). A study carried out by Biaou & Bernier (2008) in Montréal where various methods of producing DHW in zero net energy homes were investigated. The study determined hot water production with solar thermal collectors to be best solution for the climate with a reduction in DHW energy consumption from 4222kWh to 1537kWh.

2.2.6 Heat Recovery for Domestic Hot Water

Energy recovery has several variations with the most developed being the recovery of heat. Heat recovery Is defined as the process of recovering energy from a stream at a high temperature to a low temperature stream that is effective and economical to run (Mardiana-Idayu & Riffat, 2012). It has also been defined by Schurcliff (1988) as any device that removes in terms of extracts, recovers, or salvages heat or mass from one air stream and transfers it to another air stream.

Heat recovery covers a range of domains which include industrial applications such as heat recovery from industrial machines and combustion engines, and building applications such as ventilation and wastewater. Mechanical Ventilation Heat Recovery (MVHR), as shown in *Figure 6*, uses the heat from extracted air by passing it through a heat exchanger with fresh cold air and in turn reduces the heating load on the building.

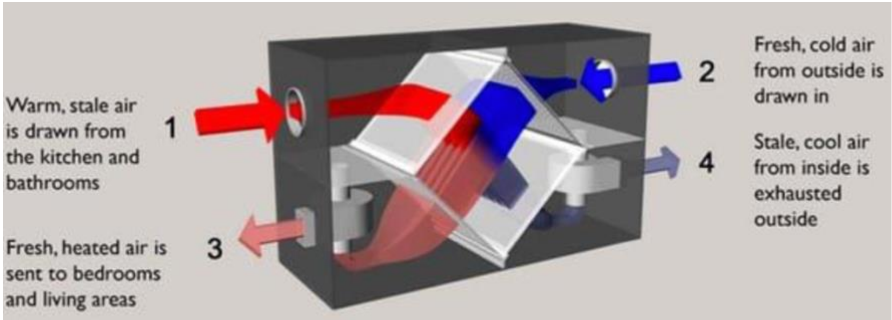


Figure 6: How a heat recovery ventilator works (Ermen system, n.d.)

The most common MVHR technologies are plate heat exchangers (*Figure 7)* due to their low cost and easy maintenance. They allow the supply and exhaust air streams to exchange heat without any cross contamination.

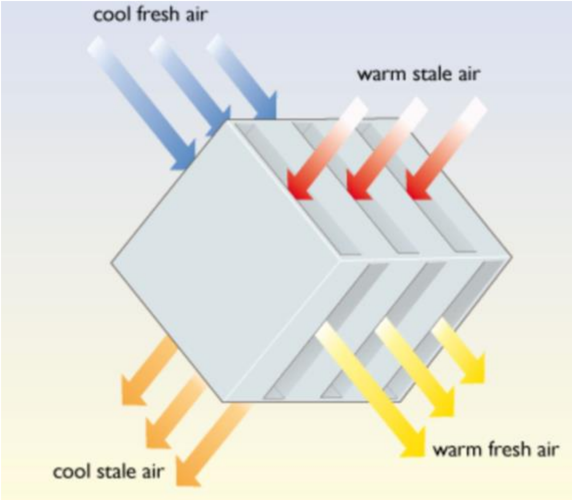


Figure 7: Plate heat exchanger (Open.Learn, n.d.)

With energy efficiency becoming a more central focus of system design, tapping into the ability to recover heat from various wastewater streams in a building aids the reduction of energy demand through the use of clean technology (Ramadan et al., 2016). Wastewater heat recovery, as shown in *Figure 8,* uses heat from various DHW streams leaving a building and passes it through a heat exchanger with fresh cold water and in turn reduces the load required for DHW heating in the building.

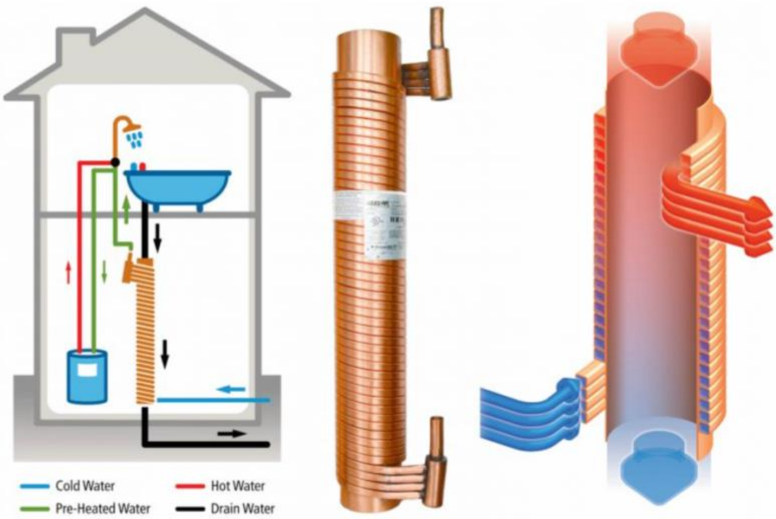


Figure 8: Wastewater heat recovery (Prescott, 2016).

In an early study addressing heat recovery from wastewater where the consumption of energy for water heating is studied in terms of lifestyle of occupants, it was discovered that energy savings of up to 10% can be achieved in some configurations (Smith, 1975). Several works have been carried out since then investigating potential energy savings and emission reductions as a result of heat recovery from wastewater. These studies focus on the numerous streams of wastewater available to recover heat from, including dishwashers, saunas, and shower systems, each reporting positive findings (Ramadan et al., 2016).

2.3 Domestic Hot Water Heat Recovery Systems

One method of reducing the energy consumption related to DHW is to recover the heat from the various wastewater streams leaving the building. Comprising of heat exchangers, the devices currently available in today's market are around 60% efficient meaning that they recover over half of the heat that would be lost down the drain. The recovered heat is then used to warm the incoming cold water which can either be directed straight to the shower or to the water heater. Using the recovered heat to warm the incoming water lessens the heating load required of the boiler and can potentially result in saving on water and gas bills (Sadler, 2019).

2.3.1 Concepts

Wastewater heat recovery systems (WWHRS) are a simple fit and forget technology with no electrical components, pumps, or controllers, and so requiring little maintenance. Currently there are three recognised methods for installation of WWHRS, each impacting the efficiency of the WWHRS differently. The first method sends the preheated cold-water mains (CWM) water to the cold side of the shower and the water heater, the second sends the preheated CWM water to the cold side of the shower only, and the third sends the preheated CWM water to the water heater only.

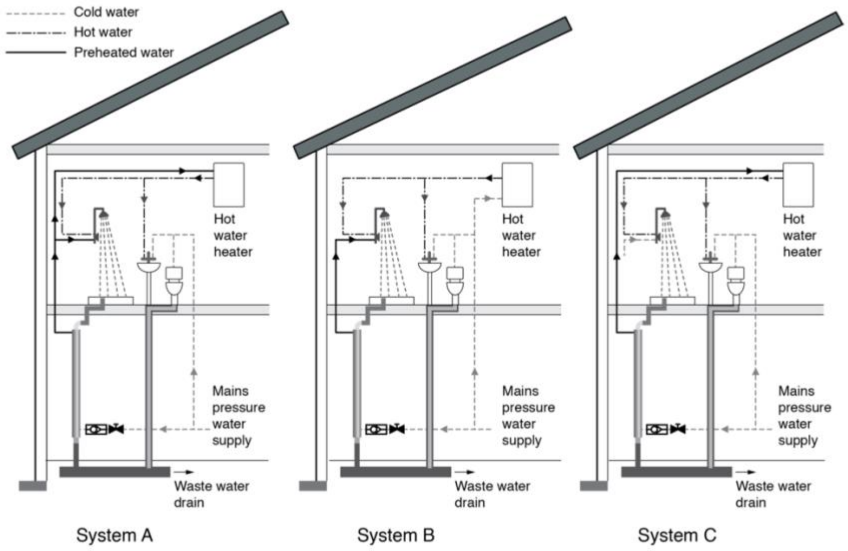


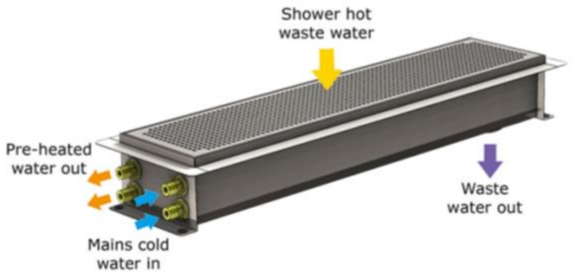
Figure 9: Three methods of WWHR (CIBSE,2021)

Routing the preheated CWM water to the source of DHW can result in significant energy savings due to the heat generator not needing to work as hard to reach the required DHW output temperature. Routing the preheated CWM water to the cold side of the shower adjusts the ratio of generated DHW to CWM water and results in less generated DHW being used per shower. As of present, long vertical copper pipe heat exchangers are the most efficient WWHRS. Wastewater runs counterflow to the incoming mains water in a thin film through the inside of the heat exchanger circulating around the outside to ensure maximum heat exchange. Vertical WWHRS best suit houses and other buildings where the shower is on the first floor or above, and typically have a heat recovery efficiency of 55% - 65% with good cost and energy reduction potential.

Horizontal WWHRS are typically integrated into shower trays or wet room drain channels and are suitable for bungalows or apartments as they can also be installed directly below a bath or shower tray, rather than on the floor below.

2.3.2 Available in Market

There are currently many wastewater heat exchangers available in the market, the most notable of which are by the Recoup brand. Recoup claim to offer "the most advanced and competitive WWHRS available" with numerous products available to suit a variety of building types. For areas and buildings with access issues such as bungalows and ground floor bathrooms, Recoup offer the 'Drain+' range which comprises of three horizontal WWHRS: the 'Drain+ Duo HE', ‘Drain+ Duo’, and ‘Drain+ Compact’. Of the mentioned products, the Drain+ Duo HE boasts an efficiency of up to 57%, dependant on the flow rate, validated by KIWA (global specialist in Testing, Inspection, and Certification), and is the highest in the Drain+ range. It is a double walled heat exchanger with no required maintenance or end-user interaction. The Drain+ Duo requires a shallower installation depth compared to the Drain+ Duo HE and has a lower efficiency of 42%, validated by KIWA. It also is comprised of a double walled heat exchanger and requires virtually no maintenance. The Recoup Drain+ Compact product is ideal for wet rooms and is comprised of a double walled heat exchangers which KIWA validated flow rate dependant efficiencies of up to 40%. All three of the products in the Drain+ range are legionella control risk assessed and SAP listed.



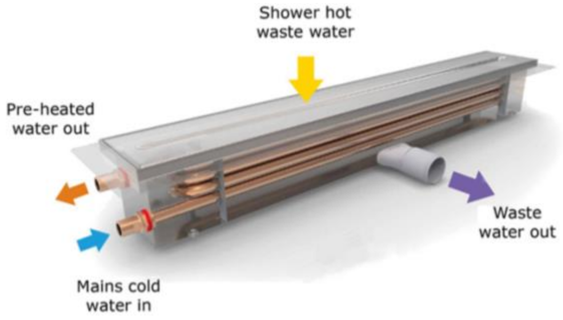


Figure 10: Diagram of the Drain+ Duo HE and Drain+ Duo Figure 11: Diagram of the Drain+ Compact (Recoup, 2017)

Recoup also offer the ‘Easyfit+’ horizontal WWHRS which is a standalone system designed specifically to be installed directly under a standard bath or shower tray making it suitable for retrofitting into an existing system as well as installing into new build properties. KIWA has validated efficiencies of up to 47.5% for the Easyfit+. It is also legionella control risk assessed and SAP listed.

Figure 12: Diagram of the Easyfit+ (Recoup, 2017)

In addition to their range of horizontal heat exchangers, Recoup also offer vertical heat exchangers suitable for above ground floor applications in houses and commercial properties.

Currently they have two products available the first of which is the 'Pipe+ HE'. This vertical WWHRS is a double walled patented heat exchanger and can achieve efficiencies of up to 67% as validated by KIWA and once installed requires zero maintenance and is unable to be seen. Recoup's second vertical WWHRS is the most recent upgrade of the Pipe+ HE and is known as the 'Pipe HEX'. KIWA has validated flow rate dependant efficiencies of up to 68.5% for the Pipe HEX, a 1.5% improvement on the Pipe+ HE. The increased efficiency is thanks to a Turbo Rotator being incorporated into the design. Both WWHRS are legionella control risk assessed and SAP listed in addition to the Pipe HEX being listed in the Product Characteristics Database (PCDB). All Recoup products mentioned are approved by the Water Regulations Advisory Scheme (WRAS).

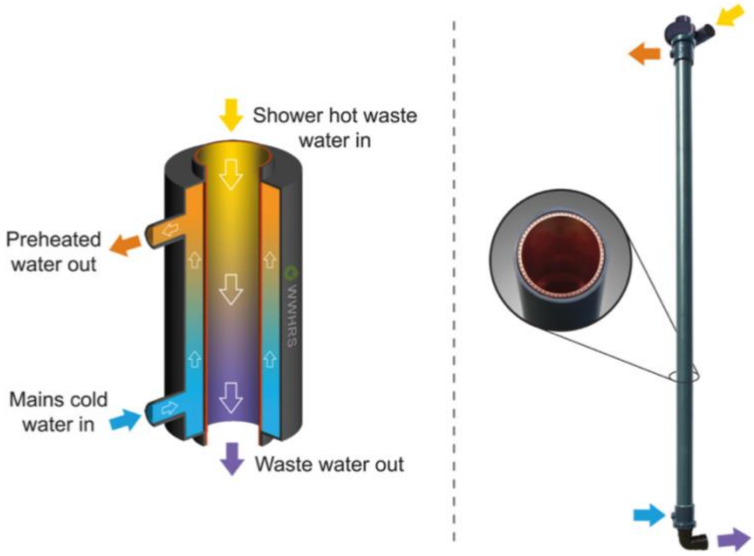


Figure 13: Diagram of the Pipe+ HE (Recoup, 2017)

Other wastewater heat recovery products on the market include the 'Showersave QB1-21' and 'Showersave QB1-21C' shower water heat exchangers aimed at new builds, retrofits, and home extensions. The Showersave products are a double walled copper pipe design and claim to achieve efficiencies of over 60% depending on flow rate. They are WRAS approved, and SAP listed. Another shower water heat recovery product is the 'Cerian Passive Shower' (*Figure 14*) which is a horizontal heat exchanger designed to be installed in new build homes and bathroom renovations. It can be installed without making holes in the floor as a conventional shower tray and claims efficiencies of up to 40%.

Figure 14: Diagram of the Cerian Passive Shower

Heatrae sadia offer both horizontal and vertical solutions to shower water heat recovery. Their Megaflo Vertical shower heat recovery unit comprises of a heat exchanger within a vertical section of copper pipe known as a pipe-in-pipe design which requires no maintenance. This design can be installed in new build homes as well as retrofitted into existing buildings and is WRAS approved. The Megaflo Vertical shower heat recovery unit claims to be up to 63% efficient. Their horizontal shower heat recovery unit is less efficient at 29.4% and can be installed directly under a shower or bath, requiring no regular maintenance. It is SAP listed and WRAS approved.

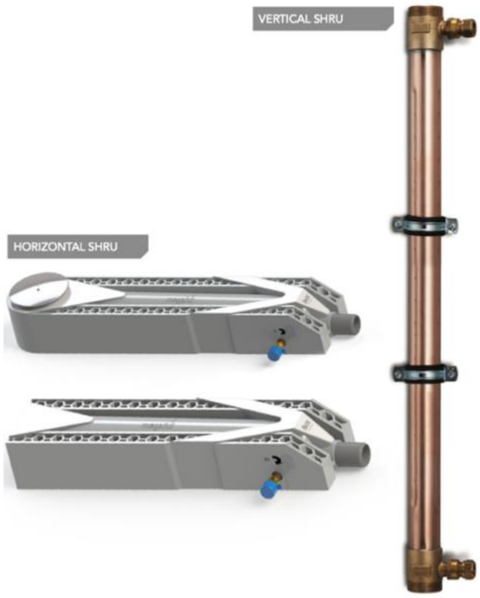


Figure 15: Diagram of the Megaflo vertical and horizontal heat recovery units

2.3.3 Experiments

Existing literature primarily focuses on the energy savings achievable from shower heat exchangers (Eslami-Nejad and Bernier, 2009; Wong et al., 2010; Meggers and Leibundgut, 2011; Guo et al., 2012; McNabola and Shields, 2013; Kordana et al., 2014; Torras et al., 2016; Deng et al., 2016) due to the fact showers account for over half of DHW energy consumption (Elias-Maxil et al., 2014). On a domestic scale many studies have been undertaken either experimentally, theoretically, or using CFD simulation software. Many of these studies claim energy savings of between 30% to 70% (Paduchowska et al., 2019; Dong et al., 2015; Pomianowski et al., 2020). Dong et al., (2015) and Pomianowski et al., (2020) studied the energy saving potential of greywater heat recovery using a heat pump finding 70% and 53% of energy saved respectively which is a large increase when compared to the 30% energy savings determined by Paduchowska et al., (2019) who studied the energy savings from greywater heat recovery systems on their own. Selimli et al., (2019) concluded that heat recovery from a dishwasher greywater stream in Turkey could save 57.1kWh of heat and 21.08kg of CO_2 emissions annually.

The objective of this work is to build on the research of WWHRS in the UK through use of numerical analysis addressing all greywater wastewater streams in a typical household as well as different WWHRS available in the market. Current literature falls short when it comes to the study wastewater heat recovery in the UK with limited papers published in this climate.

2.4 Literature Review Summary

The research in this chapter established the need for the uptake in energy recovery technology to meet the targets set out by the UK government. The current status of energy in the UKs domestic sector was discussed where it can be noted that positive changes were observed. However, with the improvement of building standards resulting in lower space heating demand, DHW become of greater significance in the context of energy consumption. This chapter explained both renewable energy and heat recovery technologies for DHW and the potential impacts these green methods of providing and recycling energy could have when utilised. Previous studies of WWHRS were researched finding very little to be undertaken in the UK but the studies across Europe and Asia found significant energy savings possible from WWHRS. In the following chapter, the methodology used to complete the study of WWHRS in the UK is outlined.

3.0 Methodology

This methodology section will set out the numerical analysis performed on the data to obtain the results of this thesis. A variety of governing equations were used to calculate the total energy savings available from the utilisation of WWHRS in a domestic dwelling in the UK.

For this study, the characteristics of Recoup's Pipe+ HE is analysed as it is the most efficient system currently available in today's market. Performance data from the Product Characteristics Database (PCDB) was obtained for the Pipe+ HE heat exchanger as well as other WWHRS available and temperature data for the incoming cold water was obtained from the Governments Standard Assessment Procedure for Energy Rating of Dwellings. Temperatures of the water reaching the end use appliances were obtained from literature.

The calculation methodology outlined by SAP has been followed to determine monthly water consumption figures, the energy content of the water doing down the drain, and the amount of heat capable of being recovered from the drains by WWHRS each month. It was then possible to determine the energy savings achievable by implementing WWHRS and the carbon emissions associated with the DHW energy consumption with and without the presence of WWHRS.

3.1 Assumptions

The domestic dwelling studied is assumed to have an occupancy of 4 and contain one shower, one bath, a sink in both the kitchen and bathroom, one dishwasher, and one washing machine. For ease of calculation, the dishwasher and washing machine are assumed to have one cycle each per day. It is also assumed that the shower is a thermostatic mixer shower where the water is a mixture of cold feed and water from a combi boiler as per the SAP calculation methodology.

3.2 Showers

The following equations are from the Government's Standard Assessment Procedure for Energy Rating of Dwellings, version 10.0 (2018).

1. Firstly, the number of showers taken per day was calculated using Eq. 3.1. Eq. 3.1. takes into consideration the presence of a bath in the dwelling, with 'N' being the assumed number of occupants.

$$(Eq.3.1.)\ N_{shower} = 0.45N + 0.65$$

2. The flow rate of the shower outlet was determined to be 11 litres/minute as per SAP10 Table J4. The flow rate was multiplied by a value of 6 minutes to calculate the average volume of warm water per shower in litres.

3. Assuming 1 mixer outlet in the dwelling, the volume of warm water per shower was multiplied by the behavioural variation factor 'f_{beh}' for each month, given in Table 4, to calculate the warm water usage per shower for each month '$V_{warm,i}$'.

4. The calculated monthly values were then summed to acquire the total volume of water draining into the WWHRS 'V_{WWS}'.

5. The heat content, 'Q_{WW}', of the water draining into the WWHRS was calculated using Eq. 3.2., assuming the warm water reaches the WWHRS at a temperature of 35°C. 'T_{cold}' is the incoming cold-water temperature for each month and is given in Table 1 and C_p is the specific heat capacity of water (4.18kJ/kg).

$$(Eq.3.2.)\ Q_{WWS} = V_{WWS} \times (35 - T_{cold}) \times C_p \div 3600$$

6. Multiplying the heat content available with the systems heat recovery efficiency and the utilisation factor, the heat recovered by the WWHRS was calculated from Eq. 3.3.

$$(Eq.3.3.)\ S_{S,m} = Q_{WWS} \times \eta_S \times UF_S$$

3.3 Baths

1. The number of baths taken per day was calculated using Eq. 3.4. This equation takes into consideration the presence of a shower in the dwelling, with 'N' being the assumed number of occupants.

$$(Eq. 3.4.)\ N_{bath} = 0.13N + 0.19$$

2. The number of baths per day was multiplied by a volume of 73 litres and the behavioural variation factor for each month of the year (Table 4) to calculate the daily warm water consumption for baths each month (Eq. 3.5.).

$$(Eq. 3.5.)\ V_{warm,bath} = N_{bath} \times 73 \times f_{beh}$$

3. In Eq. 3.6. the daily volume was multiplied by the number of days in the month to calculate the monthly volume of warm water used in baths.

$$(Eq. 3.6.)\ V_{bath,m} = V_{warm,bath} \times n_m$$

7. The calculated monthly values were then summed to acquire the total volume of water draining into the WWHRS 'V_{WWB}'.

8. The heat content, 'Q_{WW}', of the water draining into the WWHRS was calculated using Eq. 3.7., assuming the warm water reaches the WWHRS at a temperature of 35°C. 'T_{cold}' is the incoming cold-water temperature for each month and is given in Table 1 and C_p is the specific heat capacity of water (4.18kJ/kg).

$$(Eq. 3.7.)\ Q_{WWB} = V_{WWB} \times (35 - T_{cold}) \times C_p \div 3600$$

9. Multiplying the heat content available with the systems heat recovery efficiency and the utilisation factor, the heat recovered by the WWHRS was calculated from Eq. 3.8.

$$(Eq. 3.8.)\ S_{B,m} = Q_{WWB} \times \eta_B \times UF_B$$

3.4 Taps (other)

1. Hot water usage for other purposes such as taps was calculated based on the number of occupants (Eq. 3.9.).

$$(Eq. 3.9.)\ V_{d,other,ave} = (9.8 \times N) + 14$$

2. Daily consumption for each month was calculated by multiplying the hot water usage by the monthly variation factor found in Table 2 (Eq. 3.10.)

$$(Eq. 3.10)\ V_{d,other} = V_{d,other,ave} \times f_{beh}$$

3. The calculated monthly values were then summed to acquire the total volume of water draining into the WWHRS 'V_{WWO}'.

4. The heat content, 'Q_{WW}', of the water draining into the WWHRS was calculated using Eq. 3.11., assuming the warm water reaches the WWHRS at a temperature of 35°C. 'T_{cold}' is the incoming cold-water temperature for each month and is given in Table 1 and C_p is the specific heat capacity of water (4.18kJ/kg).

$$(Eq. 3.11.)\ Q_{WWO} = V_{WWO} \times (35 - T_{cold}) \times C_p \div 3600$$

5. Multiplying the heat content available with the systems heat recovery efficiency and the utilisation factor, the heat recovered by the WWHRS was calculated from Eq. 3.12.

$$(Eq. 3.12.)\ S_{O,m} = Q_{WWO} \times \eta_O \times UF_O$$

3.5 Dishwashers

Saker et al. (2015) presented a study which indicates the temperatures and water volumes at the different phases of the washing cycle for an A rated, 12 place dishwasher manufactured by Blomberg/Beko.

Table 1: Dishwasher volume and temperatures (Saker et al., 2015)

Phase	**Wastewater Quantity (kg)**	**Wastewater Temperature (°C)**
Wash	5	65
Cold Rinse	3.5	50
Hot Rinse	4	45

1. The volume of water consumed per day was calculated by multiplying the volume per cycle by the number of days in each month. The calculated monthly values were then summed to acquire the total volume of water draining into the WWHRS ‘V_{WWDW}’.

2. The heat content, ‘Q_{WW}’, of the water draining into the WWHRS was calculated using Eq. 3.13., assuming the warm water reaches the WWHRS at a temperature of 35°C. ‘T_{cold}’ is the incoming cold-water temperature for each month and is given in Table 1 and C_p is the specific heat capacity of water (4.18kJ/kg).

$$(Eq. 3.13.)\ Q_{WWDW} = V_{WWDW} \times (35 - T_{cold}) \times C_p \div 3600$$

3. Multiplying the heat content available with the systems heat recovery efficiency and the utilisation factor, the heat recovered by the WWHRS was calculated from Eq. 3.14.

$$(Eq. 3.14.)\ S_{DW,m} = Q_{WWDW} \times \eta_{DW} \times UF_{DW}$$

These equations were repeated for each phase of the dishwasher cycle.

3.6 Washing machines

The temperature and water quantity profile for wastewater from washing machines has been determined by Saker et al. (2015) where a study of a mid-range, A rated, 7kg washing machine manufactured by Blomberg/Beko was undertaken, determining that, of the 65l of water used, 10l are rejected through the drain at 37(°C).

1. The volume of water consumed per day was calculated by multiplying the volume per cycle by the number of days in each month. The calculated monthly values were then summed to acquire the total volume of water draining into the WWHRS 'V_{WWWM}'.

2. The heat content, 'Q_{WW}', of the water draining into the WWHRS was calculated using Eq. 3.15., assuming the warm water reaches the WWHRS at a temperature of 35°C. 'T_{cold}' is the incoming cold-water temperature for each month and is given in Table 1 and C_p is the specific heat capacity of water (4.18kJ/kg).

$$(Eq. 3.15.)\ Q_{WWWM} = V_{WWWM} \times (35 - T_{cold}) \times C_p \div 3600$$

3. Multiplying the heat content available with the systems heat recovery efficiency and the utilisation factor, the heat recovered by the WWHRS was calculated from Eq. 3.16.

$$(Eq. 3.16.)\ S_{WM,m} = Q_{WWWM} \times \eta_{WM} \times UF_{WM}$$

3.7 Total Energy Savings

1. The heat recovered from each WWHRS was summed to calculate the total savings from WWHRS.

$$(Eq. 3.17.)\ S_m = \sum S_{S,B,O,DW,WM,m}$$

3.8 Water and utility tables

Table 2 Incoming cold-water temperature in ℃ from SAP10

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Header Tank	9.5	10.4	11.5	12.9	15.3	18.4	19.6	18.5	17.2	14.9	12.1	8.9
Mains	7.1	8.2	9.4	13.4	15.3	17.6	18.2	17.3	16.1	13.5	10.3	6.8

Table 3 Monthly factors for hot water use from SAP10

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1.1	1.06	1.02	0.98	0.94	0.9	0.9	0.94	0.98	1.02	1.06	1.1

Table 4 Temperature rises of hot water drawn off from SAP10, in K

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
41.2	41.4	40.1	37.6	36.4	33.9	30.4	33.4	33.5	36.3	39.4	39.9

Table 5 Behavioural factor for showers and baths, f_{beh}, from SAP10

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1.035	1.021	1.007	0.993	0.979	0.965	0.965	0.979	0.993	1.007	1.021	1.035

4.0 Results and Discussion

The results chapter of this thesis has been split into sub-sections with the first reiterating the current energy consumption associated with DHW in domestic dwellings in the UK. The following sub-sections graphically detail the water usage, heat content, and recoverable heat for each wastewater stream within the dwelling, with a further section containing a comparative analysis where the results from the individual wastewater streams were combined to decipher the total amount of heat recoverable in the dwelling and each stream compared as a percentage of the total recoverable heat. Following this, an analysis of energy consumption was undertaken specifying the positive impacts on consumption achieved by the implementation of wastewater heat recovery. Tables describing the result for each end-use appliance can be found in Appendix 1.

4.1 Water Usage of Water Streams

This sub-section visually represents the volume of warm water used by each end use appliance for each month throughout the year. Any assumptions made have been stated previously in chapter 3 of this thesis.

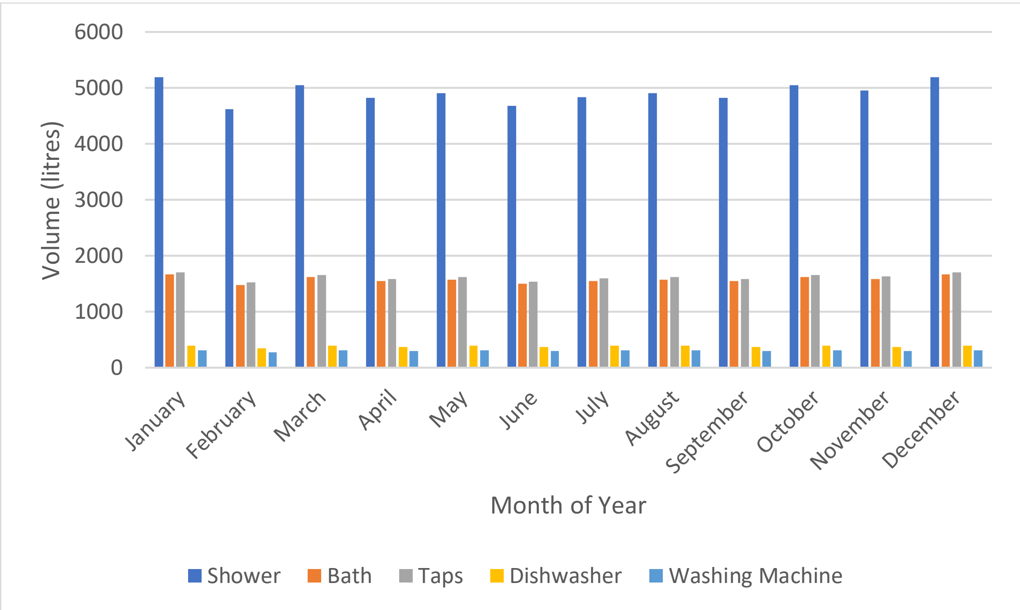


Figure 16: Volume of water used by end-use appliances (litres).

The bar chart shown in *Figure 16* illustrates the volume of warm water used by the end-use appliances over the course of a year based on a domestic dwelling with an occupancy of 4. The water consumed from showers and baths was calculated based on the number of showers and baths taken per day as per the SAP calculation method detailed in chapter 3 of this thesis. This was determined to be 2.45 showers and 0.71 baths. Showers, baths, and taps each consume the greatest volume of warm water in January and December at 5188 litres, 1663 litres, and 1707 litres respectively. The warm water consumption from the washing machine and dishwasher was dependant on how many days were in the month. Therefore, months consisting of 31 days saw the greatest consumption of warm water from these appliances at 388 litres for dishwashers and 310 litres for washing machines. For all appliances February consumed the least amount of warm water due to it being a shorter month. Showers consumed 4623 litres, baths consumed 1482 litres, taps consumed 1521 litres, the dishwasher consumed 350 litres, and the washing machine consumed 280 litres.

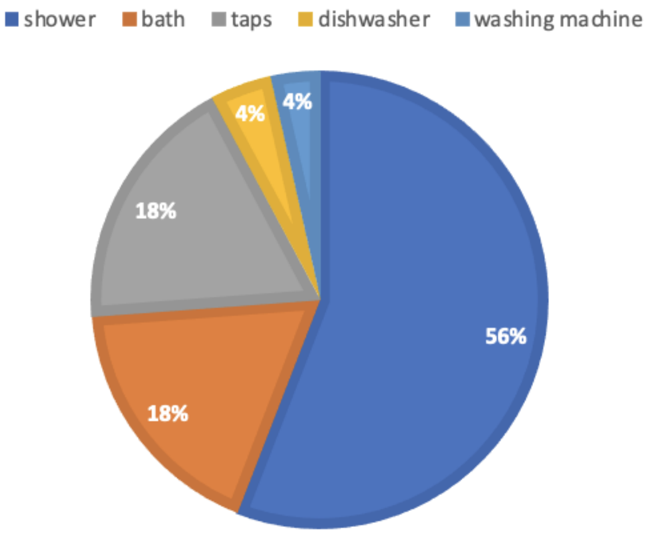


Figure 17: Percentage of total water consumed by each end-use appliance.

Figure 17 above details the percentage of water consumed by each end-use appliance in the dwelling. Showers consume over half of the warm water in the dwelling at 56% which is in line with the 50% that Recoup (2017) claim showers account for in the average UK home. It can be assumed that the value for this dwelling is 6% higher than the average UK home because it has an occupancy of 4 compared to the UK average of 2.4 (ons, 2021). Baths consume more litres of water per use than showers at 73 litres and 66 litres respectively. However, despite this baths are accountable for the 3rd highest percentage of water within the dwelling at 17.9%. The lower frequency of appliance use compared to showers prevents baths from consuming as much water even though the consumption rate per use is higher. Both the dishwasher and washing machine consume the least of the dwellings warm water with the washing machine consuming slightly less at 3.5% of the total compared to the dishwasher at 4.3%.

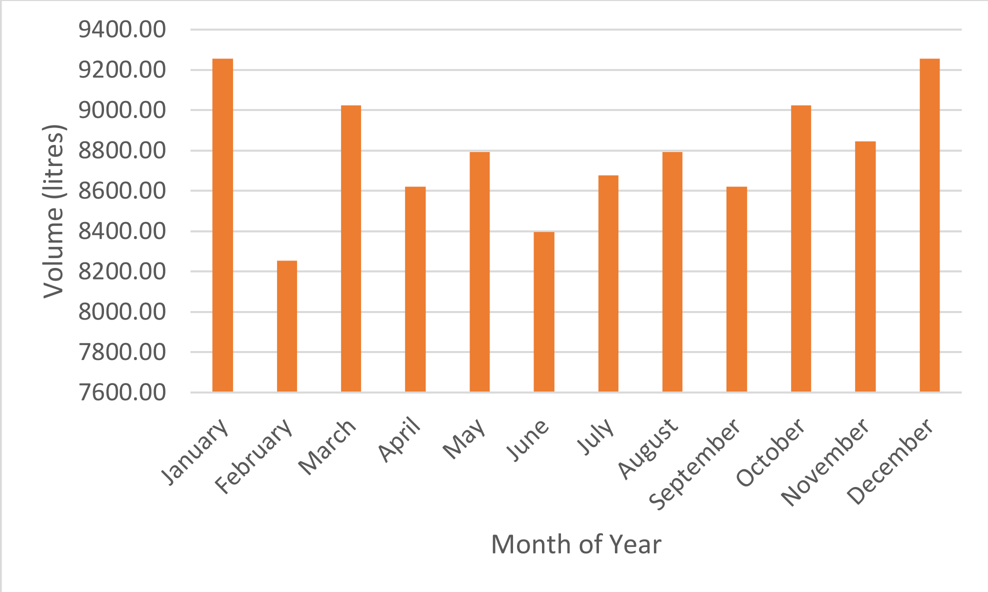


Figure 18: Total volume of warm water used by end-use appliances (l/month).

The total volume of warm water consumed by the household each month is shown in Figure 18. Water consumption is greatest in January and December with 9256 litres being used and lowest in February with 8255 litres being used. In total 105,560 litres of warm water were consumed throughout the year. Statistica (2019) indicates that the average water usage in the UK for a household with 4 occupants is 450 litres a day, calculating 164,250 litres per year. This figure also accounts for appliances such as toilets which were not included in the water volume analysis for the dwelling in question hence the lower volume calculated.

4.2 Heat Recovered by WWHRS

This sub-section visually represents the amount of heat the studied WWHRS can recover from each end-use stream per month.

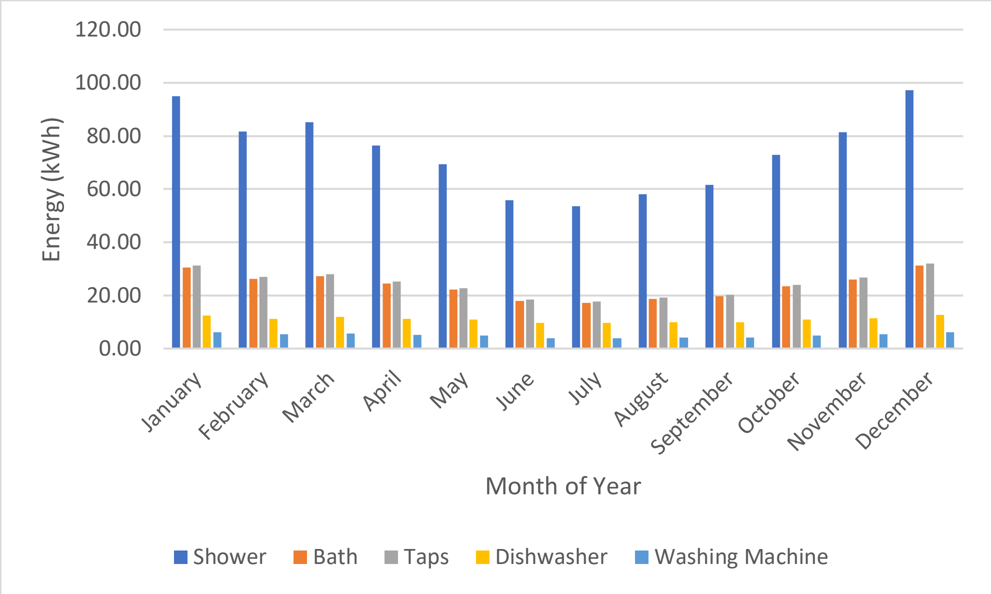


Figure 19: Heat recovered by WWHRS (kWh/month)

Figure 19 illustrates the amount of heat recovered from the water leaving the building through the drain from each appliance. Baths and showers both have behavioural factors associated with them that affect the amount of heat recoverable from the drain. The temperature of the incoming water from the header tank is another variable affecting the heat that was recovered by the WWHRS. Using the methodology outlined in chapter 3, it was calculated that for all appliances the greatest amount of heat was able to be recovered in December. The WWHRS connected to the shower was able to recover 97.2kWh in December whilst baths recovered 31.2kWh, taps recovered 32kWh, the dishwasher system recovered 12.7kWh, and the washing machine system recovered 6.3kWh. July had the least heat recovered across all appliances. The shower WWHRS was able to recover 53.5kWh in July, the bath system recovered 17.1kWh, taps recovered 17.6kWh, the dishwasher system recovered 9.7kWh, and the washing machine system recovered 3.9kWh

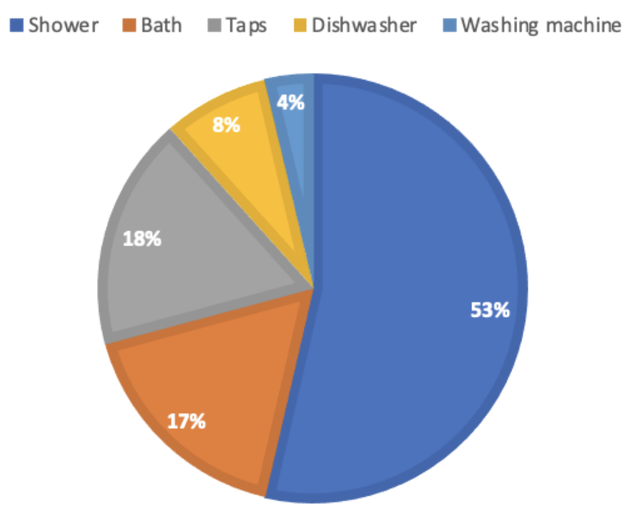


Figure 20: Percentage of total heat recovered by each end-use appliance.

Figure 20 above shows the percentage of the total heat recovered from each end-use appliance. Showers recover over 50% of the total recovered heat at 53%, baths and taps recover 17% and 18% respectively, and the dishwasher and washing machine are responsible for 8% and 4% of the total recovered heat respectively. The trends visible in both the volume of water used by each appliance and the heat recovered from each appliance are similar in nature. The greatest deviance is the percentage of the total heat recovered by the dishwasher system being 8% compared to being 4% of the total water consumed in the dwelling. This can be attributed to the high temperatures experienced during each stage of the dishwasher cycle as well as each stage having a different temperature.

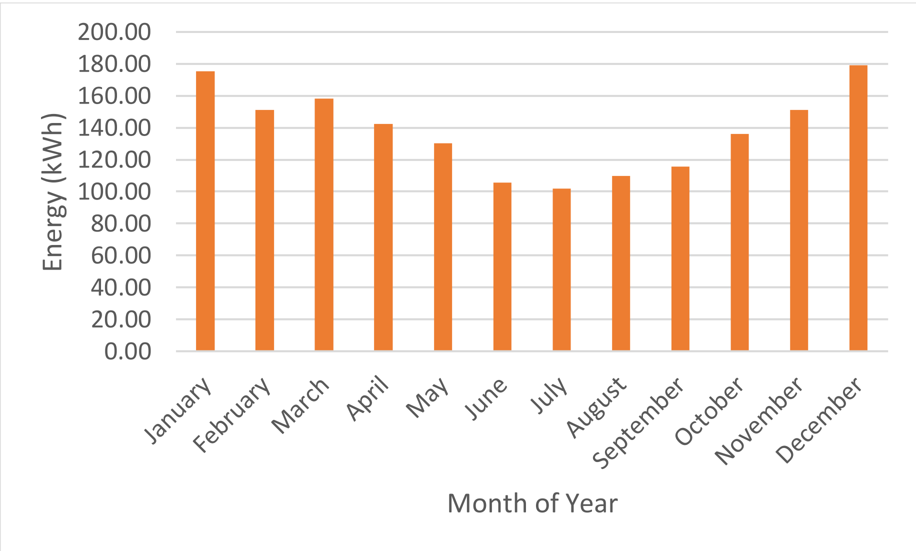


Figure 21: Total heat recovered by end-use appliances

The total heat recovered by the WWHRS in the dwelling is illustrated in the bar chart in *Figure 21*. The WWHRS recovered the greatest amount of heat in December with 179.2kWh being recovered. July had the least heat recovered at 101.8kWh. In total, 1656.5kWh of heat was recovered by the WWHRS in the dwelling.

4.3 Heat Content of Draining Water vs. Heat Recovered by WWHRS.

The following sub-section details the comparison between the heat content of the water going down the drain to the amount of heat recovered from that water by the WWHRS.

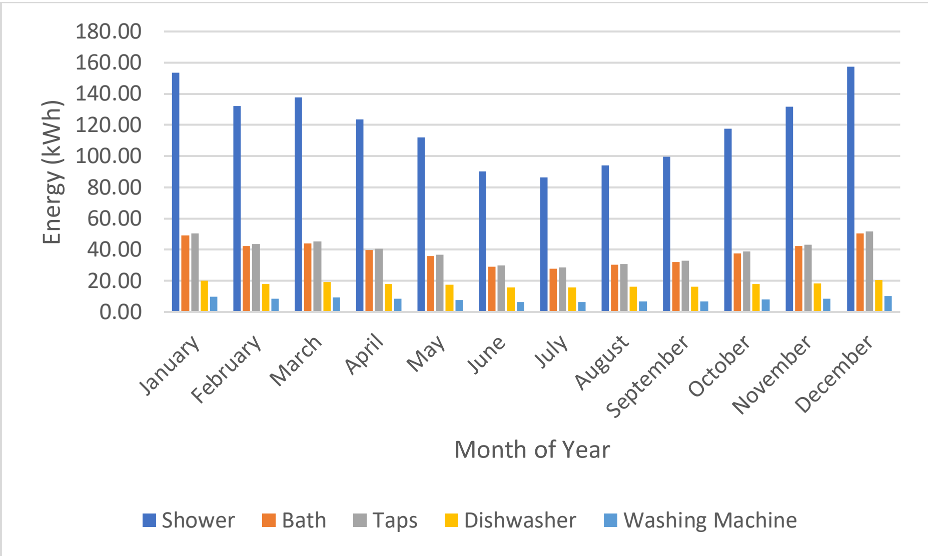


Figure 22: Heat content of draining water (kWh/month).

The bar chart in *Figure 22* shows the heat content of the draining water from each end use appliance. As can be expected, due to the large volume of water associated with showers, the draining water from this end-use is the greatest in comparison to the other appliances. The heat content of water going down the drain was highest in December for all appliances with the shower wastewater containing 157.2kWh, bath wastewater containing 50.4kWh, tap wastewater containing 51.7kWh, the wastewater from the dishwasher containing 20.5kWh, and the wastewater from the washing machine containing 10.1kWh. These figures have been compared against the figures calculated for heat recovered by the WWHRS in *Figure 23*. In total, the water draining from the end-use appliances in the dwelling contains 2679.6kWh of heat energy whilst the WWHRS in the dwelling recovers a total of 1656.5kWh of heat. This indicates that 61.8% of the heat in water draining from the dwelling was able to be recovered using WWHRS.

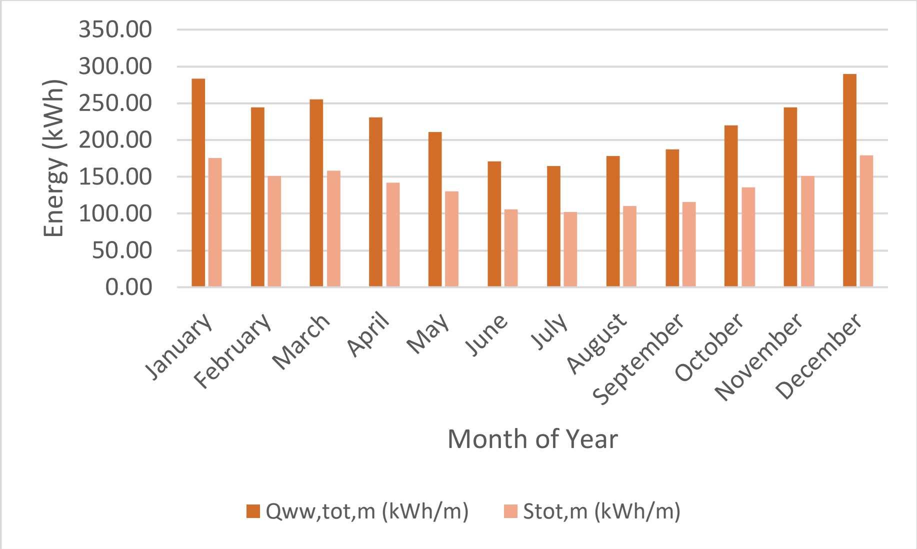


Figure 23: Heat content of draining water vs. heat recovered by WWHRS (kWh/month).

4.4 Comparison of WWHRS in the current market

This sub-section briefly details a comparison of the heat recovery potential of various WWHRS listed in the PCDB. For this analysis only the shower end-use was considered.

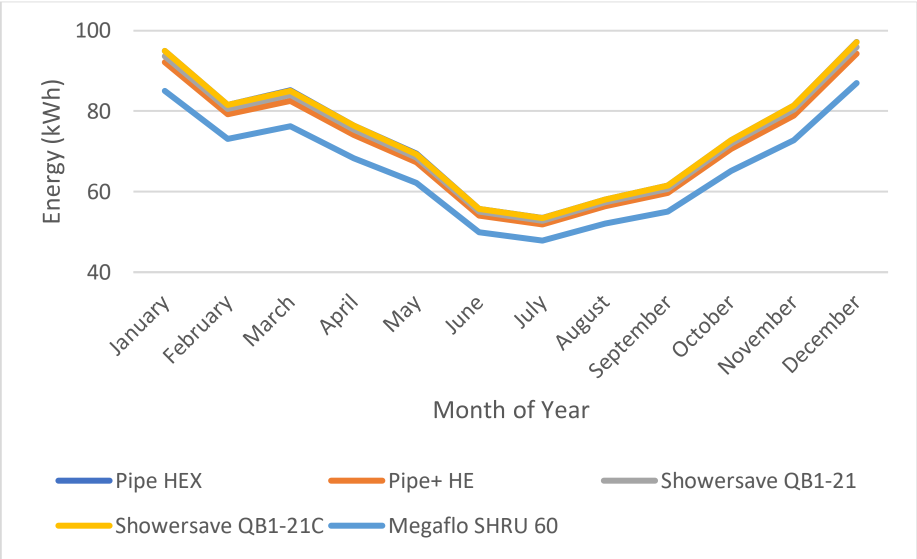


Figure 24: Energy recovered by different WWHRS available in the market (kWh/month).

Table 6: Energy recovered by different WWHRS available in the market (kWh/month).

Month	Pipe HEX	Pipe+ HE	Showersave QB1-21	Showersave QB1-21C	Megaflo SHRU 60
January	94.96	92.11	93.71	94.91	84.98
February	81.63	79.17	80.55	81.58	73.05
March	85.15	82.59	84.03	85.10	76.20
April	76.41	74.12	75.41	76.37	68.38
May	69.39	67.31	68.48	69.36	62.10
June	55.78	54.10	55.05	55.75	49.92
July	53.47	51.86	52.77	53.44	47.85
August	58.12	56.38	57.36	58.09	52.01
September	61.55	59.70	60.74	61.51	55.08
October	72.83	70.64	71.87	72.79	65.17
November	81.41	78.97	80.34	81.37	72.86
December	97.20	94.28	95.92	97.14	86.98

Both *Figure 24* and *Table 6* above show the heat recovered from the draining water produced by the shower by each WWHRS. The calculations took into consideration the varying UF and efficiency for the technologies (*Table 7*).

Table 7: Efficiency and Utilisation Factor of WWHRS

	Pipe HEX	Pipe+ HE	Showersave QB1-21	Showersave QB1-21C	Megaflo SHRU 60
Efficiency	0.636	0.615	0.627	0.635	0.568
Utilisation Factor	0.972	0.975	0.973	0.973	0.974

Recoup's Pipe HEX and Showersave's QB1-21C were capable of recovering the most heat from the shower drain water at 887.9kWh and 887.4kWh respectively for the year. Showersave's QB1-21 could recover 872.6kWh of heat throughout the year and Recoup's Pipe+ HE could recover 861.2kWh. The Megaflo SHRU 60 had noticeably less heat recovery capabilities with the potential to recover 794.6kWh of heat from the shower wastewater in the studied dwelling.

4.5 Improvements to Energy Consumption

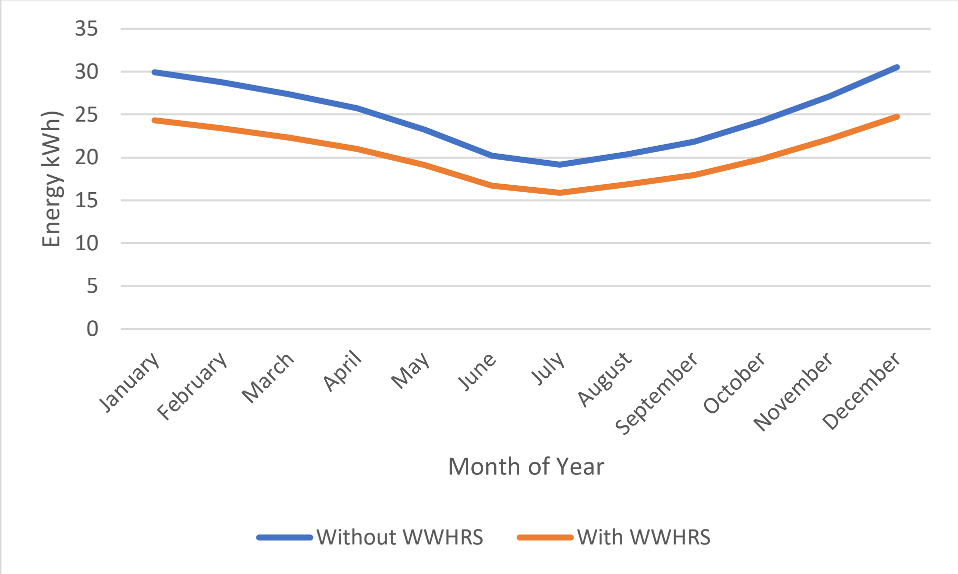


Figure 25: Energy required to heat water with and without WWHRS (kWh/day).

The line graph in *Figure 25* above shows the daily energy required to heat up the water used in the dwelling. In total, 298.7kWh are required daily to heat the water when no WWHRS is in place compared to 244.2kWh when a WWHRS is present in the dwelling. This is an improvement in energy consumption of 18.2% annually.

4.6 Carbon Analysis

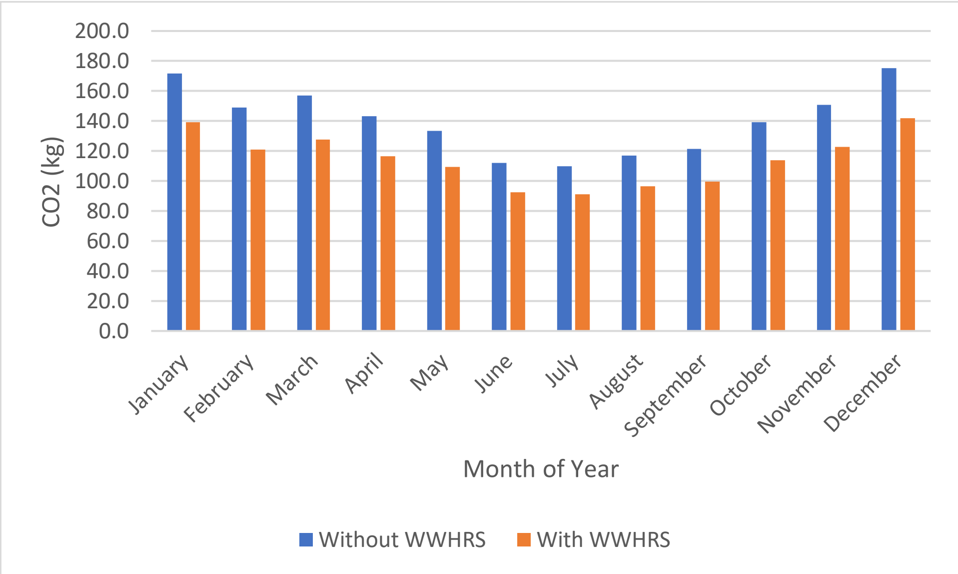


Figure 26: CO2 emissions per month in kg, with and without WWHRS

The amount of CO_2 emissions released with and without the presence of a WWHRS can be seen in *Figure 26* above. At an emission rate of 0.185kg/kWh (carbonindependant, 2021), CO_2 emissions are highest in December when energy consumption for DHW is at its highest, and lowest in July when there is less energy demand for hot water. Without a WWHRS in the household 175.1kg/day of CO_2 is emitted throughout December compared to 141.9kg/day when a WWHRS is installed. In July 109.9kg/day of CO_2 is emitted without a WWHRS compared to 91kg/day when heat recovery is present. Over the year, if there is no WWHRS in the household DHW is responsible for 1.7 tonnes of CO_2 emissions compared to 1.4 tonnes when there is a WWHRS (*Figure 27*). Ro (2020) state that DHW accounts for 6% of all CO_2 emissions in the UK, with older homes emitting 0.96 tonnes and new build homes emitting 0.93 tonnes. As this would be assumed to be an average across all homes in the UK, the higher amount calculated in this study is due to the household having an occupancy of 4 people which makes up only 13% of UK households.

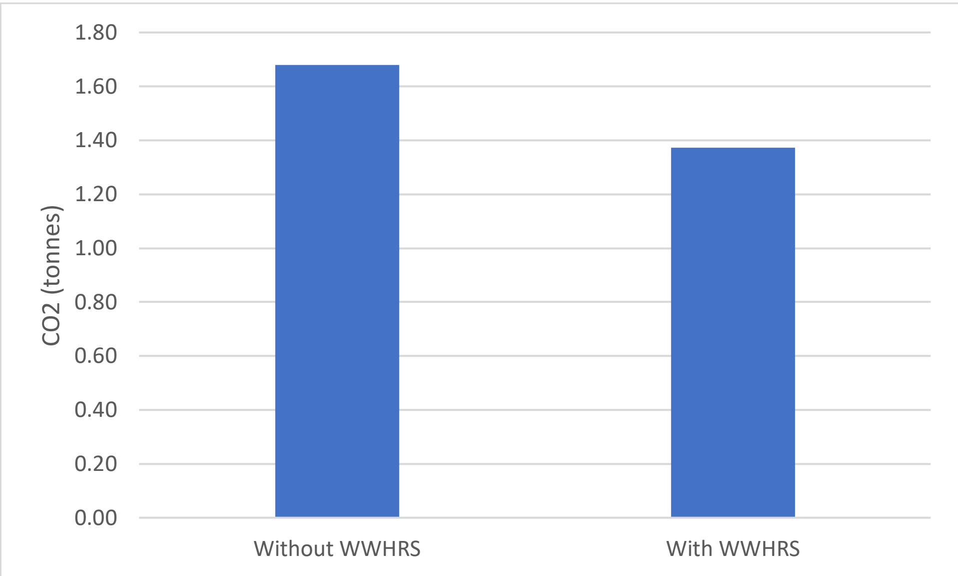


Figure 27: Annual CO2 emissions with and without WWHRS (tonnes).

In 2020 CO_2 emissions in the UK were 326.1 million tonnes (gov, 2020) and with Ro (2020) claiming that DHW accounts for 6% of all CO_2 emissions in the UK this would calculate 19.6 million tonnes of CO_2 emissions stemming from DHW. Dividing this by the 29 million homes in the UK (theccc, 2019) gives an average of 0.68 tonnes per household. As only 13% of UK households have a 4-person occupancy it's to be expected that the CO_2 emissions are higher than UK average. From the monthly emissions calculated in this study, the annual CO_2 emissions across 4-bedroom homes in the UK is 6.3 million tonnes without WWHRS installed compared to 5.2 million tonnes of CO_2 emissions with a WWHRS installed.

5.0 Conclusion

This thesis aimed to present a simple numerical analysis of wastewater heat recovery following the calculation methodology set out by the SAP guidelines with the aim to investigate the potential energy and carbon savings achievable. The objectives of this research were to; explore current energy trends in the UK, particularly within the built environments domestic sector; analyse the heat lost through the building envelope from DHW drainage; investigate and compare WWHRS that are available in today's market; calculate the reduction in energy consumption and carbon emissions achievable from implementing WWHRS in the UKs domestic sector.

Through the review of literature, energy consumption in the UK's domestic housing sector was evaluated. The domestic sector is accountable for a large amount of the country's total energy consumption, second only to transport, in addition to being responsible for a third of CO_2 emissions. With almost 90% of the buildings anticipated to be standing by 2050 already built, large emphasis has been on reducing the energy consumption and carbon footprint related to the operational phase of a building's lifecycle. The uptake in the research and development of renewable energy technologies began in the 1970s in wake of the oil crisis with the aim lessening the worldwide dependency on fossil fuels and in turn reducing carbon emissions. Good progress has been made in the development of wind turbine technology along with heat pumps which have been to credit for over 60% CO_2 reduction in previous studies and have the potential to significantly reduce energy consumption for space and water heating. However, despite government schemes such as the renewable heat incentive (RHI) being offered, public switchover to heat pumps was not as successful as intended by the government likely due to initial cost and people's unwillingness to change. Overall, the UK is making progress in tackling its dependency on fossil fuels but it's clear that the public need encouragement to switch to a cleaner manner of heating their homes and water.

Through numerical analysis, the amount of heat in the water going down the drain from showers, baths, taps, dishwashers, and washing machines was calculated for a domestic dwelling with an occupancy of 4. Using the SAP methodology for WWHRS it was determined that showers would have a frequency of 2.45 per day and baths 0.71 per day. It was assumed that there would be one washing machine cycle and one dishwasher cycle daily. Across all the end-use appliances, 105,559.6 litres of water were consumed yearly with 2679.6kWh of heat escaping the building envelope through the drain each year. Recovering some of this heat using heat exchangers would lessen the demand on the gas network and lower energy consumption and carbon emissions. WWHRS available to buy were investigated and their efficiencies compared with Recoup's Pipe HEX being the most efficient in the market. The SAP calculation methodology was undertaken using the utilisation factor and efficiency of the Pipe HEX system to determine how much heat could be recovered from the draining water. The Pipe HEX system 1656.5kWh of the 2679.6kWh of heat being lost, working out to be 61.8% of the heat being recovered. In total, an 18.2% reduction in energy consumption annually was observed along with a reduction in carbon emissions of 0.38 tonnes per year for one four-bedroom property.

5.1 Limitations

The limitations of this study are presented below including assumptions that were made and the impacts these will have had on the final results.

The calculations within this report are theoretical and provide an insight into the possibilities WWHRS have in the UK in terms of improving carbon emissions and lessening energy demands. Due to restrictions imposed because of the coronavirus pandemic, an experimental study was not able to be undertaken however, this would be advised to validate the conclusions drawn from this thesis.

The calculations to determine the heat recovered by the WWHRS were carried out assuming there would be one dishwasher cycle and one washing machine cycle each day to simplify the calculation. This will have resulted in water consumption and carbon emissions associated with these end-use appliances being slightly higher than reality.

Lastly, one WWHRS was studied for all streams of water. The Pipe HEX system is designed to be used in shower applications, however, for the purpose of this study it was assumed that systems of the same efficiency would be available to recover heat from appliances such as dishwashers and washing machines.

5.2 Future work

Further areas of study that have been identified throughout the course of this research are:

Using a modelling software or carrying out an experimental study of the work detailed within this thesis to validate the findings.

Researching the benefits of integrating a heat pump into the WWHRS to determine whether it is possible to have a DHW system completely independent from fossil fuels.
Carrying out a full cost analysis of the system to establish the payback period and how much it would cost to install these systems across the entire UK.
Investigation of different building types and occupancy levels to create a more robust and accurate understanding of the total carbon reduction and energy consumption across the entire UK.
Evaluation of different pipe materials and the how this would impact the amount of heat recovered from the draining water.

6.0 References

- Alrikabi, N. Kh. M. A. (2014). Renewable Energy Types. *Journal of Clean Energy Technologies*, 61–64. https://doi.org/10.7763/jocet.2014.v2.92

- Assets.publishing.service.gov.uk. 2020. [online] Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/904503/UK_Energy_in_Brief_2020.pdf

- Assets.publishing.service.gov.uk. 2021. [online] Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/972583/2020_Provisional_emissions_statistics_report.pdf

- Azzouz, A., Borchers, M., Moreira, J. & Mavrogianni, A., 2017. Life cycle assessment of energy conservation measures during early stage office building design: A case study in London, UK. Energy and Buildings, Volume 139, pp. 547-568.
- Bengtsson, P., Berghel, J., & Renström, R. (2015). A household dishwasher heated by a heat pump system using an energy storage unit with water as the heat source. *International Journal of Refrigeration*, *49*, 19–27. https://doi.org/10.1016/j.ijrefrig.2014.10.012

- Bertrand, A., Aggoune, R., & Maréchal, F. (2017). In-building waste water heat recovery: An urban-scale method for the characterisation of water streams and the assessment of energy savings and costs. *Applied Energy*, *192*, 110–125. https://doi.org/10.1016/j.apenergy.2017.01.096

- Biaou, A. L., & Bernier, M. A. (2008). Achieving total domestic hot water production with renewable energy. *Building and Environment*, *43*(4), 651–660. https://doi.org/10.1016/j.buildenv.2006.06.032

- Bregroup.com. 2019. *BRE : Domestic Annual Heat Pump System Efficiency (DAHPSE) - Estimator - BETA*. [online] Available at: https://www.bregroup.com/heatpumpefficiency/hot-water-consumption.

- Cao, X., Dai, X. & Liu, J., 2016. Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade. Energy and Buildings, 9, Volume 128, pp. 198-213. B

- Carbonindependent.org. 2021. *Emissions from home energy use*. [online] Available at: <https://www.carbonindependent.org/15.html>

- Chaudry, M., Abeysekera, M., Hosseini, S. H. R., Jenkins, N., & Wu, J. (2015). Uncertainties in decarbonising heat in the UK. *Energy Policy*, *87*, 623–640. https://doi.org/10.1016/j.enpol.2015.07.019

- CIBSE Journal. 2016. *A tenth of UK electricity used for air conditioning*. [online] Available at: <https://www.cibsejournal.com/news/a-tenth-of-uk-electricity-used-for-air-conditioning/>

- Clarke, A., Grant, N., Thornton, J. (2009). Quantifying the energy and carbon effects of water saving. *Elemental Solutions*.
- de Paepe, M., Theuns, E., Lenaers, S., & van Loon, J. (2003). Heat recovery system for dishwashers. *Applied Thermal Engineering*, *23*(6), 743–756. https://doi.org/10.1016/S1359-4311(03)00016-4

- Department for Business, Energy & Industrial Strategy, 2020. *UK Energy in Brief 2020*. London: The National Archives, p.10.

- Dincer, I. (2000). Renewable energy and sustainable development: a crucial review. *Renewable and Sustainable Energy Reviews*, *4*, 157-175. www.elsevier.com/locate/rser

- Dong, J., Zhang, Z., Yao, Y., Jiang, Y., & Lei, B. (2015). Experimental performance evaluation of a novel heat pump water heater assisted with shower drain water. *Applied Energy*, *154*, 842–850. https://doi.org/10.1016/j.apenergy.2015.05.044

- Dray, S., 2021. *Climate change targets: the road to net zero?*. [online] House of Lords Library. Available at: <https://lordslibrary.parliament.uk/climate-change-targets-the-road-to-net-zero/>

- Druckman, A., & Jackson, T. (2008). Household energy consumption in the UK: A highly geographically and socio-economically disaggregated model. *Energy Policy*, *36*(8), 3177–3192. https://doi.org/10.1016/j.enpol.2008.03.021

- Ec.europa.eu. 2021. *Energy consumption in households - Statistics Explained*. [online] Available at: <https://ec.europa.eu/eurostat/statistics-

explained/index.php?title=Energy_consumption_in_households#Energy_consumption_in_households_by_type_of_end-use>

- Elias-Maxil, J., van der Hoek, J.P., Hofman, J., & Rietveld, L. (2014). Energy in the urban water cycle: actions to reduce the total expenditure of fossil fuels with emphasis on heat reclamation from urban water. *Renew Sustain Energy Rev, 30*, 808-820. <http://www.sciencedirect.com/science/article/pii/S1364032113007065>

- Ermen system. n.d. *Ventilation- Mechanical Ventilation Heat Recovery and other products*. [online] Available at: <https://ermensystems.ie/ventilation/>

- Eslami-Nejad, P., & Bernier, M. (2009). Impact of grey water heat recovery on the electrical demand of domestic hot water heaters. *11th International building performance simulation association conference*, Glasgow, Scotland, July 27–30.

- Eyre, N., & Baruah, P. (2015). Uncertainties in future energy demand in UK residential heating. *Energy Policy*, *87*, 641–653. https://doi.org/10.1016/j.enpol.2014.12.030

- Feist, W., Peper, S. & Görg, M. (2001). *CEPHEUS-Project information No. 36 Final Technical Report.*

- Guo, Y.X., Cai, Y.L., Liang, S.Q., Chen, W. (2012). Experimental study on a shower waste water heat recovery device in buildings. *Applied Mechanical Master, 226-228,* 2402-2406. 10.4028/www.scientific.net/AMM.226-228.2402

- Hoak, D. E., Parker, D. S., Hermelink, A. H., & Hoak, D. (2008). *How Energy Efficient are Modern Dishwashers?*

- Icax.co.uk. 2017. *10% of UK Electricity used for cooling | Decarbonising Cooling | Study on energy use by Air Conditioning | BEIS | low-carbon cooling*. [online] Available at: <https://www.icax.co.uk/Electricity_for_Cooling.html>

- Jeong, S. W., & Lee, D. H. (2014). Drying performance of a dishwasher with internal air circulation. *Korean Journal of Chemical Engineering*, *31*(9), 1518–1521. https://doi.org/10.1007/s11814-014-0194-0

- Kerdan, I., Raslan, R., Ruyssevelt, P., Vaiciulyte, S., & Gálvez, D. (2017). Thermodynamic and exergoeconomic analysis of a non-domestic Passivhaus retrofit. *Building and Environment, 117,* 100-117.
- Khosravi, A., Laukkanen, T., Vuorinen, V., & Syri, S. (2021). Waste heat recovery from a data centre and 5G smart poles for low-temperature district heating network. *Energy*, *218*. https://doi.org/10.1016/j.energy.2020.119468

- Kingspan, "Building Regulations for the Conservation of Fuel and Power.England - existing buildings other than dwellings," 2014.
- Kordana, S., Pochwat, K., Słyś, D., & Starzec, M. (2019). Opportunities and threats of implementing drain water heat recovery units in Poland. *Resources*, *8*(2). https://doi.org/10.3390/resources8020088

- Mardiana-Idayu, A., & Riffat, S. B. (2012). Review on heat recovery technologies for building applications. In *Renewable and Sustainable Energy Reviews* (Vol. 16, Issue 2, pp. 1241–1255). https://doi.org/10.1016/j.rser.2011.09.026

- Marini, D., Buswell, R. A., & Hopfe, C. J. (2021). Development of a dynamic analytical model for estimating waste heat from domestic hot water systems. *Energy and Buildings*, *247*. https://doi.org/10.1016/j.enbuild.2021.111119

- Martínez A., T. I. L. J., 2014. Simulation of Energy Performance of Buildings: A Case Study in Prague. In: Llinares-Millán C. et al. (eds) Construction and Building Research.. Dordrecht: Springer.
- National Statistics (2017) Energy consumption in the UK (ECUK). https://www.gov.uk/government/statistics/energy-consumption-in-the-uk

- Odyssee-mure.eu. 2021. *United Kingdom energy efficiency & Trends policies | United Kingdom profile | ODYSSEE-MURE*. [online] Available at: https://www.odyssee-mure.eu/publications/efficiency-trends-policies-profiles/united-kingdom.html

- Ofgem.gov.uk. 2016. *The decarbonisation of heat*. [online] Available at: <https://www.ofgem.gov.uk/sites/default/files/docs/2016/11/ofgem_future_insights_programme_-_the_decarbonisation_of_heat.pdf>

- Ons.gov.uk. 2020. *Families and households in the UK - Office for National Statistics*. [online] Available at:

https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/families/bulletins/familiesandhouseholds/2020

- OpenLearn. n.d. *Energy in buildings*. [online] Available at: <https://www.open.edu/openlearn/nature-environment/energy-buildings/content-section-2.3.2>

- Paduchowska, J., Abnieńska-Góra, A., & Polarczyk, I. (2019). Energy-saving analysis of grey water heat recovery systems for student dormitory. *E3S Web of Conferences*, *116*. https://doi.org/10.1051/e3sconf/201911600056

- Pakula, C., Stamminger R., (2010). Electricity and water consumption for laundry washing by washing machine worldwide. *Energ Effi*, *3*, 365-382.

- Palensky, P., & Dietrich, D. (2011). Demand side management: Demand response, intelligent energy systems, and smart loads. *IEEE Transactions on Industrial Informatics*, *7*(3), 381–388. https://doi.org/10.1109/TII.2011.2158841

- Paulillo, A., Cotton, L., Law, R., Striolo, A., & Lettieri, P. (2020). Geothermal energy in the UK: The life-cycle environmental impacts of electricity production from the United Downs Deep Geothermal Power project. *Journal of Cleaner Production*, *249*. https://doi.org/10.1016/j.jclepro.2019.119410

- Persson, U., & Werner, S. (2012). District heating in sequential energy supply. *Applied Energy*, *95*, 123–131. https://doi.org/10.1016/j.apenergy.2012.02.021

- Pomianowski, M. Z., Johra, H., Marszal-Pomianowska, A., & Zhang, C. (2020). Sustainable and energy-efficient domestic hot water systems: A review. In *Renewable and Sustainable Energy Reviews* (Vol. 128). Elsevier Ltd. https://doi.org/10.1016/j.rser.2020.109900

- Prescott, A., 2016. *Wise up to water waste heat recovery*. [online] Phamnews.co.uk. Available at: <https://www.phamnews.co.uk/wise-up-to-water-waste-heat-recovery/>

- Ramadan, M., lemenand, T., & Khaled, M. (2016). Recovering heat from hot drain water—Experimental evaluation, parametric analysis and new calculation procedure. *Energy and Buildings*, *128*, 575–582. https://doi.org/10.1016/j.enbuild.2016.07.017

- Recoup. 2017. *WWHRS for Passive Houses*. [online] Available at: <https://recoupwwhrs.co.uk/technical/passive-house/>

- Richter, C.P. (2011). Usage of dishwashers: observation of consumer habits in the domestic environment. *Int J Consum Stud*, *35*, 180-186. http://dx.doi.org/10.1111/j.1470-6431.2010.00973.x>

- Ro, C., 2020. *The hidden impact of your daily water use*. [online] Bbc.com. Available at: <https://www.bbc.com/future/article/20200326-the-hidden-impact-of-your-daily-water-use>

- Rosenow, J., Guertler, P., Sorrell, S., & Eyre, N. (2018). The remaining potential for energy savings in UK households. *Energy Policy*, *121*, 542–552. https://doi.org/10.1016/j.enpol.2018.06.033

- Sadler, A., 2019. *What is a Waste Water Heat Recovery System?*. [online] BuildPass. Available at: https://buildpass.co.uk/blog/what-is-a-waste-water-heat-recovery-system/

- Saker, D., Vahdati, M., Coker, P. J., & Millward, S. (2015). Assessing the benefits of domestic hot fill washing appliances. *Energy and Buildings*, *93*, 282–294. https://doi.org/10.1016/j.enbuild.2015.02.027

- Selimli, S., Karabas, T., Taskin, Y., & Karatas, M. B. (2019). Experimental study of the performance of heat recovery by a fin and tube heat exchange tank attached to the dishwasher greywater line. *Sustainable Energy Technologies and Assessments*, *36*. https://doi.org/10.1016/j.seta.2019.100552

- Shurcliff, W. A. (1988). AIR-TO-AIR HEAT-EXCHANGERS FOR HOUSES THE INCREASING NEED. In *Ann. Rev. Energy* (Vol. 13). www.annualreviews.org

- Singh, H., Muetze, A., & Eames, P. C. (2010). Factors influencing the uptake of heat pump technology by the UK domestic sector. *Renewable Energy*, *35*(4), 873–878. https://doi.org/10.1016/j.renene.2009.10.001

- Spriet, J., & McNabola, A. (2019). Decentralized drain water heat recovery: A probabilistic method for prediction of wastewater and heating system interaction. *Energy and Buildings*, *183*, 684–696. https://doi.org/10.1016/j.enbuild.2018.11.036

- Smith, E. (1975). *RECOVERY AND UT1LISAT1ON OF HEAT FROM DOMESTIC WASTE WATER.*

- Statista. 2019. *Average water usage UK 2020 | Statista*. [online] Available at: <https://www.statista.com/statistics/827278/liters-per-day-household-water-usage-united-kingdom-uk/>

- *The Government's Standard Assessment Procedure for Energy Rating of Dwellings*. (2018). https://doi.org/10.0

- Wallin, J., & Claesson, J. (2014). Investigating the efficiency of a vertical inline drain water heat recovery heat exchanger in a system boosted with a heat pump. *Energy and Buildings*, *80*, 7–16. https://doi.org/10.1016/j.enbuild.2014.05.003

- Wong, L., Mui, K., Guan, Y. (2010). Shower water heat recovery in high-rise residential buildings of Hong Kong. *Applied Energy*, *87(2)*, 703-709. <http://www.sciencedirect.com/science/article/pii/S0306261909003225>

7.0 Appendices

Month	Vwarm,s (l)	Vd,warm,s (l/d)	Vshower,m (l/m)	Qww,s,m (kWh/m)	Ss,m (kWh/m)
January	68.31	167.36	5188.14	153.61	94.96
February	67.39	165.10	4622.68	132.04	81.63
March	66.46	162.83	5047.79	137.73	85.15
April	65.54	160.57	4817.04	123.61	76.41
May	64.61	158.30	4907.43	112.25	69.39
June	63.69	156.04	4681.22	90.23	55.78
July	63.69	156.04	4837.26	86.50	53.47
August	64.61	158.30	4907.43	94.02	58.12
September	65.54	160.57	4817.04	99.56	61.55
October	66.46	162.83	5047.79	117.81	72.83
November	67.39	165.10	4952.87	131.69	81.41
December	68.31	167.36	5188.14	157.23	97.20

Appendix 1: Shower calculation results

Month	Vwarm,bath (l/day)	Vbath,m (l/m)	Qww,b,m (kWh/m)	Sb,m (kWh/m)
January	53.64	1662.97	49.24	30.44
February	52.92	1481.72	42.32	26.16
March	52.19	1617.98	44.15	27.29
April	51.47	1544.02	39.62	24.49
May	50.74	1572.99	35.98	22.24
June	50.02	1500.48	28.92	17.88
July	50.02	1550.49	27.72	17.14
August	50.74	1572.99	30.14	18.63
September	51.47	1544.02	31.91	19.73
October	52.19	1617.98	37.76	23.34
November	52.92	1587.55	42.21	26.10
December	53.64	1662.97	50.40	31.15

Appendix 2: Bath calculation results

Month	Vd,other (l/d)	Vother,m (l/m)	Qww,o,m (kWh/m)	So,m (kWh/m)
January	55.06	1706.92	50.54	31.24
February	54.32	1520.88	43.44	26.86
March	53.57	1660.74	45.32	28.01
April	52.83	1584.83	40.67	25.14
May	52.08	1614.57	36.93	22.83
June	51.34	1540.14	29.69	18.35
July	51.34	1591.48	28.46	17.59
August	52.08	1614.57	30.93	19.12
September	52.83	1584.83	32.75	20.25
October	53.57	1660.74	38.76	23.96
November	54.32	1629.52	43.33	26.78
December	55.06	1706.92	51.73	31.98

Appendix 3: Tap calculation results

Month	Vday,dw (l/d)	Vdw,m (l/m)	Qww,dw,m (kWh/m)	Sdw,m (kWh/m)
January	12.50	387.50	20.20	12.49
February	12.50	350.00	17.88	11.05
March	12.50	387.50	19.30	11.93
April	12.50	375.00	18.07	11.17
May	12.50	387.50	17.59	10.88
June	12.50	375.00	15.68	9.69
July	12.50	387.50	15.66	9.68
August	12.50	387.50	16.15	9.99
September	12.50	375.00	16.20	10.01
October	12.50	387.50	17.77	10.99
November	12.50	375.00	18.42	11.39
December	12.50	387.50	20.47	12.66

Appendix 4: Dishwasher calculation results

Month	Vd,wm (l/d)	Vwm,m (l/m)	Qww,wm,m (kWh/m)	Swm,m (kWh/m)
January	10.00	310.00	9.90	6.12
February	10.00	280.00	8.65	5.35
March	10.00	310.00	9.18	5.67
April	10.00	300.00	8.39	5.19
May	10.00	310.00	7.81	4.83
June	10.00	300.00	6.48	4.01
July	10.00	310.00	6.26	3.87
August	10.00	310.00	6.66	4.12
September	10.00	300.00	6.90	4.26
October	10.00	310.00	7.95	4.92
November	10.00	300.00	8.67	5.36
December	10.00	310.00	10.11	6.25

Appendix 5: Washing machine calculation results

Month	Vd,tot (l/d)	Vtot,m (l/m)	Qww,tot,m (kWh/m)	Stot,m (kWh/m)
January	298.57	9255.53	283.49	175.25
February	294.83	8255.28	244.33	151.04
March	291.10	9024.01	255.68	158.06
April	287.36	8620.89	230.36	142.41
May	283.63	8792.49	210.57	130.17
June	279.89	8396.83	170.99	105.70
July	279.89	8676.73	164.60	101.75
August	283.63	8792.49	177.90	109.98
September	287.36	8620.89	187.32	115.80
October	291.10	9024.01	220.05	136.04
November	294.83	8844.94	244.33	151.04
December	298.57	9255.53	289.94	179.24

Appendix 6: Calculation results for all wastewater steams combined

DEPARTMENT OF MECHANICAL & AEROSPACE ENGINEERING

Student No.