March 2019

An Assessment of the Influence of Local Conditions on the Economic and Environmental Sustainability of Drain Water Heat Recovery Systems

Anusha Ravichandran
University of South Florida, anushauvs@gmail.com

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An Assessment of the Influence of Local Conditions on the Economic and Environmental Sustainability of Drain Water Heat Recovery Systems

by

Anusha Ravichandran

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Environmental Engineering Department of Civil and Environmental Engineering College of Engineering University of South Florida

Major Professor: Qiong Zhang, Ph.D.
Sylvia Wilson Thomas, Ph.D.
Nancy Diaz-Elsayed, Ph.D.

Date of Approval:
March 12, 2019

Keywords: resource recovery, waste heat utilization, impacts of climate change, effects of population density

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DEDICATION

This thesis is dedicated to my parents who encouraged me to pursue my master’s degree half way across the globe. I wouldn’t have been here without the sacrifices you both have made for me. This work is also dedicated to my family and friends who stood by me through all my lows during the entire process of completing my thesis.
ACKNOWLEDGEMENTS

I would like to thank my advisor, Dr. Qiong Zhang, for her constant support and guidance throughout the thesis. The questions you had asked during the weekly meetings helped me move forward and find solutions to the problems in my research. I would also like to thank Dr. Nancy Diaz-Elsayed for spending time with me every week for the past four terms through which I worked on my thesis. Your valuable suggestions and assistance guided me towards the right direction and played an important role in me successfully completing this thesis. I am grateful to Dr. Sylvia Wilson Thomas for being on my thesis committee. Also, I thank the Modelling and Assessment of Sustainable Systems (MASS) research group for providing suggestions to improve my study.

This material is based upon work supported by the National Science Foundation Faculty Early Career Development (CAREER) grant of the United States (No. 1454559). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.
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ABSTRACT

Increasing resource demand and decreasing supplies necessitate a paradigm shift in wastewater management from treatment to resource recovery. As the economic and environmental performance of wastewater-based resource recovery systems is location-specific (e.g., terrain slope influences hydro-energy recovery), a holistic view of their sustainability requires a comprehensive analysis on the effect of the local conditions on these systems. Although the internal factors affecting such systems (e.g., water quality and end use) are well studied, there is limited literature on the effect of external factors such as topography, climate and population density. This study evaluated the role of climate and population density on the sustainability of drain water heat recovery systems (DWHRS) for regions across North America.

A MATLAB-based model was developed to compute life cycle energy consumption and net present value (NPV) of the DWHRS. Life cycle assessment (LCA) was performed to estimate carbon footprint, eutrophication potential and ecotoxicity. Energy recovered from the DWHRS was found to vary inversely with ambient temperature. For instance, 113% more energy is recovered in New York City as compared to Tampa, Florida. Regions with hot climates (e.g., Florida) are estimated to have a 5-6-year payback period, while colder regions like New York have a 1-2-year payback period. The DWHRS showed more economic benefits with increasing population density; NPV was −$125 for a one-person household and $513 for a three-person household over a 20-year lifespan in Tampa. The LCA reveals that the DWHRS performs better from an environmental standpoint than systems with no heat recovery. For example, in Tampa,
heat recovery is estimated to reduce greenhouse gas emissions by 295% (3.97 g CO₂ eq/ litre of water heated to 60 °C). The results were also compared with that of district heating in Canada. The DWHRS has about 3 times shorter payback period than the district heating system; however, the district heating system performs better than the DWHRS in all environmental impact categories except three indicators – non carcinogenics, eutrophication, ecotoxicity.

The model can be utilized to evaluate the sustainability of the DWHRS for specific locations and help consumers decide whether to invest in the DWHRS. Overall, this study provides a platform to evaluate the feasibility of wastewater-based resource recovery systems through sustainability assessment.
CHAPTER 1: INTRODUCTION

1.1 Introduction

The global population has been rapidly increasing over the past few decades with a population of about 7.6 billion people in 2017. The population is projected to increase by 29 percent over the next three decades (United Nations Department of Economic and Social Affairs Population Division 2017). As population escalates, more resources are being consumed. Due to this growth in resource consumption, coupled with the limited availability of resources on this earth, there arises a situation of resource crisis (Coyle and Simmons 2014). Hence, researchers are constantly in search for new sources to bridge the gap between the supply and demand. Currently, wastewater is considered as a renewable source as it is a carrier of several resources, namely, water, various forms of energy, nutrients like Nitrogen and Phosphorus in the biosolids, organic carbon and trace elements like Copper, Zinc, Nickel, Chromium, Cadmium, Arsenic, Lead, etc., (Henze and Comeau 2008). To cope with the increasing demand for resources and decreasing supplies, a paradigm shift in wastewater management from treatment to resource recovery and reuse is essential. Energy contained in wastewater can be harnessed in several forms such as heat energy, hydro energy, chemical/bioenergy and kinetic energy from flowing water (Frijns et al. 2013). Also, energy can be recovered across various scales of wastewater systems – small, medium and large scales.
Heat can be recovered from domestic wastewater at the small scale within residential houses, at the medium scale from sewers or at the large scale at wastewater treatment plants (WWTPs) (Frijns et al. 2013). The recovered heat is used for heating the incoming cold water in residential houses, space heating in buildings, and drying sludge in WWTPs (Elias-Maxil et al. 2014). There are several factors that affect the amount of energy recovered from the system such as water characteristics, system design and configuration and the usage patterns of the system (Cipolla and Maglionico 2014; Słyś and Kordana 2014). Additionally, wastewater-based resource recovery systems are highly dependent on the local conditions of a place; for example, the amount of hydro energy recovered depends on the difference in elevation along the direction of water flow (Bousquet et al. 2017). Another example in this vein is the influence of the topography of a region on the capital, operation and maintenance cost of direct potable water reuse systems (Guo and Englehardt 2015).

This study evaluates the influence of location-specific conditions (climate and population density) on the heat recovery from drain water in residential houses based on five criteria – net present value (NPV), the amount of energy recovered, carbon footprint, eutrophication potential and ecotoxicity.

1.2 Rationale

About seventeen percent of the total water consumed in a residential household in the US is for showering (Mayer et al. 1999). Water heating for the above purpose constitutes about 14% of the total electricity consumption (US Energy Information Administration 2018a). About 80 to 90% of this heat is wasted when the water is transported from the point of generation to the
WWTP through the sewers (Henderson and Hewitt 2001). This waste heat can be recovered as thermal energy using a heat exchanger and utilized to preheat the incoming cold water to the electric water heater as there is simultaneous waste heat generation and hot water required during a shower (Bertrand et al. 2017). Moreover, it has been shown that recovering the heat within the house immediately after use allows for exploitation of higher wastewater temperatures than recovering heat lower in the wastewater flow (Meggers and Leibundgut 2011). But existing studies focus only on the economic assessment of heat recovery from large and medium scale wastewater-based systems (Culha et al. 2015; Hepbasli et al. 2014; Schmid 2008). Hence, studies evaluating the potential of heat recovery on a small scale in residential houses is required. Furthermore, to better understand the benefits of the heat recovery system, it is essential to analyze the economic and environmental sustainability of the system.

The influence of factors such as water flow rate, length of the heat exchanger and shower time, that are directly associated with the heat recovery system, on the economic performance of the system have been extensively analyzed (Bertrand et al. 2017; Henderson and Hewitt 2001; Słyś and Kordana 2014; Zaloum et al. 2007b). However, wastewater-based resource recovery systems are highly location specific, i.e., the economic and environmental performance of these systems and the efficiency of resource recovery depend on the characteristics of the place in which the system is situated (Bousquet et al. 2017; Guo and Englehardt 2015). Climatic conditions (e.g., ambient temperature, solar radiation, wind speed) and population density are some of the local conditions that impact the sustainability of the heat recovery systems. Therefore, this study aims to perform a comprehensive analysis on the influence of local conditions on the economic and
environmental sustainability of drain water heat recovery systems (DWHRS), thus providing a holistic view on the sustainability of these systems.

1.3 Research Objectives

The main objectives of this study are as follows:

- Evaluate the influence of local conditions (e.g., climate and population density) on the amount of energy recovered from the system, and on the economic and environmental sustainability of the DWHRS.

- Compare the small-scale system with heat recovery from drain water to the large-scale heat recovery system used for district heating.
CHAPTER 2: LITERATURE REVIEW

In this chapter, domestic wastewater-based thermal energy recovery systems across various scales have been reviewed. The different methods of heat recovery and the end use of the recovered heat for small-, medium- and large-scale wastewater-based systems are discussed. The performance of a DWHRS along with the various types of heat exchangers and the various configurations are scrutinized. Also, the factors affecting the economic and environmental sustainability of the heat recovery systems are presented. Existing literature evaluating the sustainability of heat recovery systems are studied and the research gap that is bridged by this study has been highlighted.

2.1 Wastewater-Based Thermal Energy Recovery Systems

Thermal energy can be recovered from both industrial and municipal wastewater systems. This study is centered around the municipal wastewater-based heat recovery systems. Thermal energy can be recovered at any point between the wastewater source (point of generation of wastewater) and the endpoint for wastewater (WWTP, septic tanks, etc.). Small-scale recovery systems are situated immediately after the point of generation of wastewater where high wastewater temperatures can be exploited, usually within the household. Medium-scale recovery systems are situated in the sewers where the temperature of wastewater is lower than that at the point of generation due to heat loss along the sewer pipelines. The large-scale
recovery systems are situated at the WWTPs (Elías-Maxil et al. 2014; Frijns et al. 2013; Hepbasli et al. 2014; Meggers and Leibundgut 2011). Thermal energy recovery from wastewater has been shown to reduce the overall energy consumption of the system. A recent study conducted in student hostels in Berlin concluded that heat recovery from wastewater reduces the energy required to heat water by 30% (Alnahhal and Spremberg 2016). Another study estimated a 28% electricity savings in single family houses and a 41% electricity savings in multifamily buildings due to heat recovery from grey water (Bertrand et al. 2017). An experimental and numerical analysis on a DWHRS showed that 34% to 60% of the energy in shower drain water can be recovered (Torras et al. 2016). This type of energy recovery can thus be considered as a potential option to replace a portion of the energy requirements to produce heat for various end uses such as domestic water heating, space heating, snow melting, and sludge drying and other heating requirements at WWTPs.

2.2 Small-Scale Wastewater-Based Thermal Energy Recovery Systems in Residential Houses

In small-scale wastewater-based thermal energy recovery systems, the heat is recovered immediately after the wastewater is generated. Hence, these systems utilize the higher temperatures of wastewater at the point of recovery and have the advantages of exploiting the maximum heat energy contained in the wastewater than at any other recovery point in the sewer network (Meggers and Leibundgut 2011). In a residential house, the water from the outlet of a clothes washer, dishwasher and from the shower drain are generally warmer than the incoming cold water to the house (Bertrand et al. 2017). This difference in temperature between the incoming cold water and drain water demonstrates a potential for heat recovery from these
wastewater streams to preheat the cold water entering the house. Therefore, the end use of the recovered heat in small-scale systems is domestic water heating. Heat exchangers (HXs) are used for recovering heat from wastewater and transferring it to the cold water.

Heat recovery from the shower drain is more common as the volume of shower drain water is much higher when compared to the volume of wastewater generated in the clothes washer and dishwasher (Mayer et al. 1999). Also, during a shower, there is a simultaneous generation of hot wastewater and a requirement for heating water allowing for the immediate use of recovered heat and eliminating the need for a heat storage unit (Elías-Maxil et al. 2014; McNabola and Shields 2013). The heat recovery unit for shower drain water and the various configurations of the system are discussed in Section 2.2.1 and Section 2.2.2, respectively.

2.2.1 Heat Recovery Unit for Shower Drain Water

![Figure 1](image_url) A countercurrent heat exchanger showing the water flow through it, adapted from (Ecoinnovation n.d.).
The heat recovery unit consists of a simple countercurrent HX installed in the shower drain pipe. It does not have any moving parts and has a lifetime of over 30 years (Zaloum et al. 2007b). The HX consists of a straight copper tube over which another copper tube is tightly coiled. The hot wastewater flows through the straight inner tube and the incoming cold-water flows through the coiled outer tube. A countercurrent HX with the water flow directions is shown in Figure 1. When the cold water and hot wastewater are simultaneously passed through their respective copper tubes, the heat from the hot stream is transferred to the cold stream. Thus, the cold water is preheated when entering the electric water heater. (Garmsiri et al. 2017; Leidl and Lubitz 2009).

HXs can be installed either horizontally below the bath tub or vertically by replacing a vertical section of the shower drain pipe. Though the design of both types of HXs is the same, the vertical ones are found to be more efficient than the ones installed in the horizontal orientation. Heat transfer efficiencies of up to 50% were observed in horizontal HXs (McNabola and Shields 2013). Vertical HXs were found to be 75% efficient in a study conducted in Northern Ireland (Henderson and Hewitt 2001). This difference in efficiency is due to the different hydraulic diameter in both types. In horizontal HXs, heat transfer occurs only along a portion of the pipe wall because the hydraulic diameter is lower than the diameter of the drain pipe. In vertical HXs, the heat transfer occurs along the full boundary of the pipe as the hydraulic diameter is the same as the diameter of the drain pipe (McNabola and Shields 2013).

There are different types of vertical HXs based on their construction – gravity film heat exchangers (GFX), helical HXs and pressure pipe HXs (Culha et al. 2015). GFXs are the most
common type used for domestic heat recovery. In this type of HX, hot shower drain water forms a thin film along the pipe walls as it flows down by the effect of gravity and hence the name GFX (Garmsiri et al. 2017). Several manufacturers have modified GFXs to improve the efficiencies. In one such modification, the cold water is split into four tubes coiled around the central drain pipe. Eight different types of GFXs were tested for their energy recovery and performance in a Canadian study (Zaloum et al. 2007b). The performance of the HXs depend on their design and geometric characteristics such as the length of the HX, the number of passes of cold water, the squareness of the cold-water pipe, the space between the tube coiling and the diameter of tubes.

As renewable sources of energy are of topical interest for researchers, the DWHRS are gaining widespread attention. The drain water HXs have received Energy Star recognition for energy efficiency from National Resources Canada (Natural Resources Canada 2014). HXs from various manufacturers have been tested for heat recovery efficiency and pressure drop and are available for public access. The design aspects of the HXs are also available (Natural Resources Canada 2018). In addition, building codes for the DWHRS are available in certain Canadian regions. The DWHRS is thus evolving as an alternative heat source for energy efficient operation in houses.

2.2.2 Various Configurations of the DWHRS

In a DWHRS, cold water flows through the heat recovery unit where it is preheated. The preheated water can be directed to the electric water heater or the mixing valve for the shower. The hot water from the electric water heater is sent to the mixing valve where it is mixed with either preheated or cold water to obtain the desired temperature for the shower. The mixed water
is used for the shower. The drain water generated is passed through the heat recovery unit and then sent to the sewer. The different flow options for preheated water results in different options for mounting the heat recovery unit of the DWHRS. Figure 2 shows the three possible configurations of the DWHRS with one heat recovery unit in a residential house. In option A, the preheated water is fed only to the electric water heater and cold water is fed to the mixing valve. In option B, preheated water is fed to both the electric water heater and the mixing valve. In option C, preheated water is fed to the mixing valve and cold water is fed to the electric water heater (Ecoinnovation n.d.; Słyś and Kordana 2014; Zaloum et al. 2007a).

![Figure 2](image)

**Figure 2** A schematic representation of three different mounting options for the heat recovery unit in a DWHRS: (A) Configuration where preheated water is entirely supplied to the electric water heater; (B) Configuration where preheated water is supplied to both the electric water heater and the mixing valve; (C) Configuration where preheated water is entirely supplied to the mixing valve.

A financial assessment of the different configurations was performed in a study conducted in Poland. It was found that option B was economically more beneficial than option A.
and C irrespective of the shower length and water flow rate. The payback period for option B was estimated as 2.5 years (Słyś and Kordana 2014). Another study evaluated the amount of energy recovered in the three configurations using pinch analysis and mass balance. Heat recovery was calculated to be 49%, 74% and 48% for options A, B and C, respectively (Bertrand et al. 2017). In this study option B is used for analysis since it was shown to have the highest energy recovery potential and to perform economically better than the other two options.

2.3 Medium-Scale Wastewater-Based Thermal Energy Recovery Systems

In medium-scale wastewater-based thermal energy recovery systems heat is recovered in the sewer network leveraging the large quantities of wastewater (Culha et al. 2015). The temperature of wastewater is slightly lower than that available for small-scale recovery systems because of the heat loss along the pipeline (Meggers and Leibundgut 2011). The heat can be recovered at any point along the sewer network. The ideal location for heat recovery depends on the energy demand and the wastewater treatment requirements. A framework was developed to find the suitability of a location in the sewer network for heat recovery and applied in a case study (Kretschmer et al. 2016b). Wastewater source heat pumps (WWSHP) are used for heat recovery in the medium-scale systems. WWSHPs have been in use for many decades (Elías-Maxil et al. 2014). The recovered heat is used for either district heating or for domestic hot water supply.

2.3.1 Wastewater Source Heat Pumps (WWSHPs)

Mechanical WWSHPs consist of an evaporator, condenser, compressor, expansion valve and a heat exchange medium. A schematic representation of the district heating system using
WWSHPs is shown in Figure 3. The wastewater in the sewer network passes through the evaporator where it transfers its heat to the fluid in the heat pump. The evaporated fluid is compressed to increase its heat content and then condensed. During condensation, heat is transferred to the fluid used for district heating. The condensed fluid in the heat pump is passed through an expansion valve to obtain the desired pressure before entering the evaporator and the cycle continues (Culha et al. 2015).

**Figure 3** A schematic representation of district heating using WWSHPs.

WWSHPs are classified into three types based on their mode of operation – monovalent, bivalent and multivalent. Monovalent heat pumps are standalone heat sources whereas bivalent heat pumps are supported by other heat sources and multivalent heat pumps operate in conjunction with cogeneration systems (Culha et al. 2015). Based on the operation principle, WWSHPs can be classified into three types – compression heat pump, reversible chemical reaction heat pump and sorption heat pump (Wongsuwan et al. 2001). To improve the heat recovery efficiency, modifications to the WWSHPs have been tested. Indirect heat transfer to the heat pump from the wastewater using heat exchangers are prevalent (Culha et al. 2015; Hepbasli
et al. 2014; Postrioti et al. 2016; Spriet and Hendrick 2017). As the presence of solids in the wastewater hinders the performance of a WWSHP, a filth block device was included before the WWSHP to block solid particles from entering the heat exchanger to address this issue (Liu et al. 2014; Zhao et al. 2010). A recent study analyzed heat recovery using a combination of heat exchanger and heat pipes (Gabor et al. 2016).

Several studies evaluating the performance of WWSHPs have been conducted (Cipolla and Maglionico 2014; Postrioti et al. 2016; Spriet and Hendrick 2017). In Korea, a feasibility study conducted for a hotel with a sauna estimated a yearly mean coefficient of performance (COP) of 4.8, i.e., 4.8 units of heat is produced for every unit of electric energy consumed (Baek et al. 2005). Another study determined a COP of 4.3 for heating using an urban sewage source heat pump (Zhao et al. 2010). Multi-location heat recovery in sewers at a city level was modeled for various seasons (Abdel-aal et al. 2018). For a Belgian sewer network of 3000 pipes serving 79500 people, it was found that waste heat recovered from the sewer can supply 7% to 18% of the heat demand during various seasons (Abdel-aal et al. 2018). The economic benefits of WWSHPs was reviewed by researchers in China (Shen et al. 2018). It was shown that after two years of service time, a heat recovery system had lower total costs (initial and operating costs) than other conventional heating systems such as coal, oil, gas and electric boilers (Shen et al. 2018). The thermal economic benefits were analyzed by Qin and Hao ((2017) and the COP was approximated to 4. Issues in the technical, economic and environmental aspects of WWSHPs was discussed in two studies (Fiore and Genon 2014; Schmid 2008). In terms of the technical aspect, fouling in the pipes is the primary factor hindering the efficient operation of the heat pump (Schmid 2008). The trade-off between the cost benefits due to the heat recovery system and the expenses associated with the installation
and operation of the system is the main economic issue (Fiore and Genon 2014). The impact of externalities such as climate on the emissions associated with the heat recovery system is another important issue to be addressed (Fiore and Genon 2014). Existing literature reveals that medium-scale heat recovery systems are well studied when compared to the small-scale systems.

2.4 Large-Scale Wastewater-Based Thermal Energy Recovery Systems

In large-scale wastewater-based thermal energy recovery systems heat is recovered at the WWTP. The treated water and some internal streams in the WWTP have higher temperatures than the influent streams, exhibiting a potential for heat recovery from these streams (Elías-Maxil et al. 2014). The large-scale systems benefit from a large flow rate of treated water and do not affect the wastewater treatment since the heat recovery is done after treatment. But these systems are generally far from district heating consumers (Culha et al. 2015). These large-scale systems are easier to install than the small-scale drain water heat recovery systems (Frijns et al. 2013). Similar to medium-scale heat recovery systems, WWSHPs are used for heat recovery at the large scale. The operation of large systems differs in that the heat source is waste heat from a WWTP rather than the in-sewer heat source. The recovered heat has various end uses such as district heating, snow melting, preventing disinfectant storage buildings from freezing, sludge drying and other heating requirements in WWTPs (Chae and Ren 2016; Elías-Maxil et al. 2014; Funamizu et al. 2001; LeVasseur and McPartland 2010).

Few studies have analyzed the feasibility of large-scale thermal energy recovery systems and evaluated the economic and environmental benefits. The potential for district heating in Hungary using heat recovered from a WWTP has been assessed (Somogyi et al. 2018). The study
estimated that the system was technically feasible only for a population equivalent greater than 14000. In Sweden, a LCI of municipal WWTPs with heat recovery was performed with the consumption of fossil fuel energy as the environmental indicator (Tillman et al. 1998). The heat pump had the highest impact on the use of fossil fuels, while the heat recovered from the system had the highest benefits in this category (Tillman et al. 1998). It was found that a WWTP with heat recovery has a net benefit on the use of fossil fuel, while a WWTP with a urine separation system had a net positive impact on the use of fossil fuel (Tillman et al. 1998). In an Austrian study, it was found that thermal energy recovered from a WWTP can meet the onsite heat requirements of that plant (Kretschmer et al. 2016a). Heat recovery from industrial wastewater has also been investigated and the performance of the system was evaluated (Xie et al. 2016). This system was found to be more energy efficient than systems using air as a heat source. Although a large number of district heating systems with thermal ratings between 10 MW and 20 MW have been implemented worldwide, the factors affecting the sustainability of these systems is not well studied (Schmid 2008).

2.5 Internal Factors Affecting the Sustainability of Heat Recovery Systems

The operation of wastewater-based heat recovery systems depends on numerous design and geometric factors associated with the system. In small-scale systems, the design aspects of the HX used for heat recovery impact the amount of energy recovered from the system. The effect of the geometric characteristics of the HX on the pressure loss along the length of the HX and energy recovery efficiency was studied (Zaloum et al. 2007a; b). The number of transfer unit (NTU)-effectiveness was calculated for eight different HXs that vary slightly in geometry and
configuration, but with the same basic design. The HX with four coiled tubes around the drain pipe was found to have the highest efficiency. The squareness of the tube positively affects the efficiency as the contact area increases with an increase in the squareness. Also, the efficiency increases when the tubes are coiled tightly without any air spaces since air is a bad conductor of heat (Zaloum et al. 2007a; b).

The operation parameters of the system such as the shower length, flow rate of the shower head and operation temperature affect the energy recovered from the system. The effect of the flow rate of the shower head and operation temperature on the economic sustainability of the DWHRS has been extensively studied. As the flow rate increases, the amount of water going down the drain also increases, hence more energy is recovered. For a constant incoming cold water temperature, the energy recovery increases with an increase in the temperature of the drain water (Gabor et al. 2017; Henderson and Hewitt 2001; Torras et al. 2016). The impact of shower length and flow rate of the shower head on the net present value (NPV) of three different configurations of the DWHRS was evaluated (Słyś and Kordana 2014). The NPV was found to increase with an increase in both of the parameters considered. The efficiency of the electric water heater also affects the NPV of the system because the amount of electricity consumed by the DWHRS and hence the cost savings are influenced by the efficiency.

In medium- and large-scale systems, the effect of control parameters such as the temperature of the wastewater, mass flow rate and compressor speed on the various operating temperatures such as the temperature difference of fluid entering and leaving the evaporator and the condenser in a WWSHP was elucidated (Motorcu et al. 2018). The wastewater
temperature had the most significant influence on the temperature difference of fluid entering and leaving the evaporator while the compressor speed had the most significant influence on the temperature difference of the fluid entering and leaving the condenser. Also, the variability of the wastewater flow rate and temperature was analyzed by Cipolla and Maglionico (2014). From the literature review, it is apparent that the internal factors that are directly associated with the heat recovery systems are well studied.

2.6 External Factors Affecting the Sustainability of Resource Recovery Systems

The wastewater-based resource recovery systems are not only affected by internal factors directly associated with it, but also influenced by the location specific factors such as the climatic conditions, population density and topography of the area in consideration. For example, the amount of energy recovered from a wastewater-based hydro energy system depends on the difference in elevation, in other words, the terrain slope along the direction of the wastewater flow in the sewer network (Chae and Kang 2013). It was also stated that the feasibility of implementing a heat recovery system in the sewer network depends on factors such as the temperature of the wastewater, temperature of treated effluent at the WWTP, flow rate in the given area, sewer characteristics, climatic conditions in the area and distance of end users from the point of heat recovery (Fiore and Genon 2014). The number of inhabitants in a building impacts the amount of energy recovered from a DWHRS (Bertrand et al. 2017). This shows that wastewater-based resource recovery systems are location specific. Therefore, it is important to perform a comprehensive analysis on the influence of local conditions on the sustainability of heat recovery systems.
2.6.1 Influence of Climate on the Temperature of Water in Underground Pipelines

The climatic conditions of a given location are found to influence the temperature of drinking water in underground pipelines. In this vein, climate indirectly influences the sustainability of a DWHRS as the amount of energy recovered from the DWHRS is affected by the temperature of incoming cold water. Very few studies have modeled this relation between the climatic conditions of a place and the temperature of water transported in pipelines. A model developed in the Netherlands can predict the temperature of water in the pipelines given the climatic conditions of the region. The study divided the atmosphere and soil into four layers. Heat balance equations were written for each of the layers and solved to obtain the temperature of water in the pipelines. Wind speed, solar radiation, ambient temperature, latent heat of evaporation, heat flux due to the vegetation, height of the atmospheric roughness layer (ARL), velocity of water in the pipelines and other characteristics of air, water, soil surface, soil and underground pipelines are the parameters included in the model (Blokker and Pieterse-Quirijns 2013). The temperature of drinking water in domestic water supply systems was modeled in a similar way (Moerman et al. 2014; Zlatanovic et al. 2017). A correlation between the ambient temperature and the temperature of water in the underground pipelines was developed (Hendron and Burch 2007). Consequently, the influence of climate on the sustainability of a DWHRS needs to be studied to obtain a holistic view.

2.6.2 Influence of Population Density on the Water Consumption

The population density of a place affects the mode of potable water supply to the houses. For example, in places like Tampa and New York City with a high population density potable
water is supplied to the residential houses by a central treatment plant via the drinking water distribution network (National Research Council 2000). In low population density places such as the McMullen county in Texas, individual wells are the source of water for domestic use (Harris 1965). The distance between the water treatment plant and the residential end user in places with a high population density is longer than that between the ground water well and the residential end user in places with a low population density. This difference in distance affects the residence time of water in the pipelines which in turn influences the temperature of incoming water (Moerman et al. 2014). Also, the number of inhabitants in the house affects the amount of energy recovered from a DWHRS (Bertrand et al. 2017). To comprehensively evaluate the sustainability of a DWHRS, it is thus essential to include the effects of population density.

2.7 Previous Studies on the Economic Sustainability of Heat Recovery Systems

In small-scale heat recovery systems, the cost of the HXs vary with the length of the HX and the different manufacturers, ranging from $300 to $500 (U S Department of Energy n.d.). The installation of HXs is easy in a new house construction, but it may be expensive to retrofit in a built structure. The payback period of the DWHRS ranges from 2.5 years to 7 years. The payback period depends on factors such as the operation frequency of the heat recovery unit, configuration of the DWHRS and the location of the system (U S Department of Energy n.d.). Several studies have performed the economic analysis of a DWHRS. A payback period of more than 50 years was estimated for one inhabitant households (Bertrand et al. 2017). For 3 person households, payback periods of 7 years was estimated for conditions in Poland (Słyś and Kordana 2014). A 5-year payback period was calculated by McNabola and Shields (2013) for horizontally
installed HXs. A study on the sports facility in a university in the UK estimated that the DWHRS is economically beneficial only in places where the electricity prices are high (Ip and She 2018). In low electricity price regions, the investment cost of the HX cannot be recovered by the contribution from energy savings alone. Henderson and Hewitt (2001) plotted the variations in annual cost savings with changes in hot water temperature and the time of operation of the DWHRS. The cost savings was found to increase with increase in either hot water temperature or time of operation of the DWHRS (Henderson and Hewitt 2001).

The operating cost of WWSHP was compared with that of conventional heating systems (Liu et al. 2014). The study estimated that the WWSHP were more expensive than coal-fired boilers and less expensive than the gas and oil-fired boilers. Another study in China determined an operation cost of ¥16.77/m² ($2.48/m²) for WWSHP and annual cost savings of about ¥444,000 ($65,553) (Qin and Hao 2017). A study analyzing the potential of district heating for Hungary estimated that the payback period was less than 10 years when the distance between the district heating users and the point of recovery of heat is about 1 km (Somogyi et al. 2018). A techno-economic feasibility study for the Brussels region concluded that the levelized cost of recovered heat energy is highly dependent on the electricity prices in the region (Spriet and Hendrick 2017). Though several studies have evaluated the economic aspects of heat recovery systems, these studies failed to include the effects of external factors like climate and population density on the economic analysis.
2.8 Previous Studies on the Environmental Sustainability of Heat Recovery Systems

Only a few studies have evaluated the environmental sustainability of heat recovery systems. An LCA of the waste heat recovery using a DWHRS in a university sports facility in the UK was performed and the results indicate that the use of a DWHRS reduces the greenhouse gas emissions (Ip and She 2018). An annual savings of 33.81 kg CO₂ eq was estimated for medium use (defined as 15 people taking a 5 minute shower 3 times a week) of the DWHRS (Ip and She 2018). A feasibility study for waste heat recovery in the Brussels capital region estimated a 49% reduction in CO₂ eq compared to gas boilers for a lifetime of 20 years (Spriet and Hendrick 2017). Relative CO₂ emissions for conventional heating methods and the sewer heat recovery system were tabulated by Fiore and Genon (2014). The sewer heat recovery system was found to produce 1/2 to 1/4 times as much CO₂ emissions when compared to oil boilers. The electric boilers produced 8 to 20 times more emissions than sewer heat recovery systems (Fiore and Genon 2014). All these studies evaluate just one environmental indicator – CO₂ emissions, while the environmental sustainability can be assessed based on several other indicators such as ecotoxicity, eutrophication, acidification, carcinogens, non-carcinogens, and particulate matter. Also, the studies conducted have not included the effects of external factors on the environmental sustainability of the system.

2.9 Research Gap

An extensive literature review was conducted. The type of analysis and the internal and external factors analyzed in each study are summarized in Table 1. Most studies evaluated the thermal performance and the economic sustainability of the heat recovery systems. Some
environmental aspects of these systems were studied, but only at the medium and large scales. Also, the studies that evaluated the environmental aspects, with the exception of the analysis ofIp and She (Ip and She 2018), were not performed exclusively for the heat recovery systems, but for the entire WWTP. Since the heat recovery systems are a small component of a WWTP, a detailed analysis on their environmental sustainability is not available in these studies. The influence of internal factors associated with the heat recovery systems have been well analyzed. Although some studies have explored the influence of some external factors such as the number of inhabitants per house, in-sewer air temperature, time of the day and seasons, no studies include the analysis of all climatic conditions and the population density of a place. Additionally, there is a research gap in that no study evaluates the influence of the external factors such as climate and population density on the economic and environmental sustainability of a DWHRS. This study aims to bridge this gap in research as it is essential to understand the effects on the local conditions of a place on the heat recovery system for obtaining a holistic view of their sustainability.
Table 1 Summary of the factors analyzed and of the type of analysis performed in previous studies on wastewater-based thermal energy recovery systems.

<table>
<thead>
<tr>
<th>Serial Number</th>
<th>Source</th>
<th>Scale of system evaluated</th>
<th>Flow rate (MGD)</th>
<th>Factors analyzed</th>
<th>Type of analysis</th>
<th>Energy recovery efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(Abdel-aal et al. 2018)</td>
<td>Medium</td>
<td>0.57 to 4.56</td>
<td>Flow rate of wastewater</td>
<td>In-sewer air temperature, Time of the day</td>
<td>x</td>
</tr>
<tr>
<td>2</td>
<td>(Baek et al. 2005)</td>
<td>Medium</td>
<td>0.07 to 0.09</td>
<td>—</td>
<td>Time of day, Seasons</td>
<td>x</td>
</tr>
<tr>
<td>3</td>
<td>(Bertrand et al. 2017)</td>
<td>Small</td>
<td>0.0016</td>
<td>—</td>
<td>Number of inhabitants in the house</td>
<td>x</td>
</tr>
<tr>
<td>4</td>
<td>(Chae and Kang 2013)</td>
<td>Large</td>
<td>7.92</td>
<td>Wastewater temperature</td>
<td>Ambient temperature</td>
<td>x</td>
</tr>
<tr>
<td>5</td>
<td>(Chae and Ren 2016)</td>
<td>Large</td>
<td>6.6 to 7.92</td>
<td>Heat pump speed</td>
<td>—</td>
<td>x</td>
</tr>
<tr>
<td>6</td>
<td>(Cipolla and Maglionico 2014)</td>
<td>Medium</td>
<td>1.14 to 13.7</td>
<td>Wastewater flow rate &amp; temperature</td>
<td>—</td>
<td>x</td>
</tr>
<tr>
<td>7</td>
<td>(Dong et al. 2015)</td>
<td>Small</td>
<td>0.000015 to 0.000024</td>
<td>Drain water flow rate &amp; temperature</td>
<td>—</td>
<td>x</td>
</tr>
<tr>
<td>8</td>
<td>(Gabor et al. 2017)</td>
<td>Small</td>
<td>0.000019</td>
<td>Drain water flow rate</td>
<td>—</td>
<td>x</td>
</tr>
<tr>
<td>9</td>
<td>(Gabor et al. 2016)</td>
<td>Medium</td>
<td>0.007</td>
<td>—</td>
<td>—</td>
<td>x</td>
</tr>
<tr>
<td>10</td>
<td>(Henderson and Hewitt 2001)</td>
<td>Small</td>
<td>—</td>
<td>Drain water flow rate &amp; temperature</td>
<td>—</td>
<td>x</td>
</tr>
<tr>
<td>Serial Number</td>
<td>Source</td>
<td>Scale of system evaluated</td>
<td>Flow rate (MGD)</td>
<td>Factors analyzed</td>
<td>Type of analysis</td>
<td>Energy recovery efficiency</td>
</tr>
<tr>
<td>---------------</td>
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<td>-----------------</td>
<td>--------------------------------------------------------------------------------</td>
<td>--------------------------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>11</td>
<td>(Ip and She 2018)</td>
<td>Small</td>
<td>—</td>
<td>—</td>
<td>Internal</td>
<td>—</td>
</tr>
<tr>
<td>12</td>
<td>(Liu et al. 2014)</td>
<td>Medium</td>
<td>0.42</td>
<td>Fouling thermal resistance in heat exchanger</td>
<td>Internal</td>
<td>—</td>
</tr>
<tr>
<td>13</td>
<td>(Ma et al. 2017)</td>
<td>Medium</td>
<td>—</td>
<td>Heat pump working fluid temperature</td>
<td>Internal</td>
<td>—</td>
</tr>
<tr>
<td>14</td>
<td>(McNabola and Shields 2013)</td>
<td>Small</td>
<td>—</td>
<td>Drain water flow rate, temperature of the shower drain water</td>
<td>Internal</td>
<td>—</td>
</tr>
<tr>
<td>15</td>
<td>(Motorcu et al. 2018)</td>
<td>Medium</td>
<td>0.0003 to 0.0008</td>
<td>Compressor speed, Wastewater flow rate, Heat pump working fluid temperature</td>
<td>Internal</td>
<td>—</td>
</tr>
<tr>
<td>16</td>
<td>(Postrioti et al. 2016)</td>
<td>Medium</td>
<td>0.00075</td>
<td>Heat pump working fluid temperature</td>
<td>Time of day</td>
<td>—</td>
</tr>
<tr>
<td>17</td>
<td>(Qin and Hao 2017)</td>
<td>Medium</td>
<td>—</td>
<td>Time of day</td>
<td>Internal</td>
<td>—</td>
</tr>
</tbody>
</table>

Table 1 (Continued)
<table>
<thead>
<tr>
<th>Serial Number</th>
<th>Source</th>
<th>Scale of system evaluated</th>
<th>Flow rate (MGD)</th>
<th>Factors analyzed</th>
<th>Type of analysis</th>
<th>Energy recovery efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>(Słyś and Kordana 2014)</td>
<td>Small</td>
<td>0.000018 to 0.000152</td>
<td>Shower length &amp; Drain water flow rate</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>(Somogyi et al. 2018)</td>
<td>Medium</td>
<td>0.45</td>
<td>Distance between heat source and end user</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>(Spriet and Hendrick 2017)</td>
<td>Medium</td>
<td>0.16</td>
<td>Time of day</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>21</td>
<td>(Stec et al. 2017)</td>
<td>Small</td>
<td>0.000019 to 0.000059</td>
<td>Drain water flow rate</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>(Tillman et al. 1998)</td>
<td>Large</td>
<td>—</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>(Torras et al. 2016)</td>
<td>Small</td>
<td>0.000005 to 0.000016</td>
<td>Drain water flow rate &amp; temperature</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>24</td>
<td>(Wong et al. 2010)</td>
<td>Small</td>
<td>—</td>
<td>Drain pipe diameter</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>25</td>
<td>(Xie et al. 2016)</td>
<td>Large</td>
<td>0.061</td>
<td>Air temperature</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>26</td>
<td>(Zaloum et al. 2007a)</td>
<td>Small</td>
<td>0.000043 to 0.000086</td>
<td>HX geometry and length</td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>
Table 1 (Continued)

<table>
<thead>
<tr>
<th>Serial Number</th>
<th>Source</th>
<th>Scale of system evaluated</th>
<th>Flow rate (MGD)</th>
<th>Factors analyzed</th>
<th>Type of analysis</th>
<th>Energy recovery efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>(Zaloum et al. 2007b)</td>
<td>Small</td>
<td>—</td>
<td>HX geometry and length, Drain water flow rate &amp; temperature</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>28</td>
<td>(Zhao et al. 2010)</td>
<td>Medium</td>
<td>5.07 to 6.36</td>
<td>Heat pump working fluid temperature</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
CHAPTER 3: METHODS

3.1 Drain Water Heat Recovery System

The configuration of the DWHRS used in this study is displayed in Figure 4. In this configuration, all of the cold water entering the house is directed through the drain water heat recovery (DWHR) unit, i.e., the HX. The cold water is preheated when it leaves the DWHR. The preheated water is fed to both the electric water heater and the mixing valve. The hot water heated using the conventional electric water heater is mixed with the preheated water in the mixing valve to obtain the desired shower temperature. The mixed water is used for shower. The water which goes down the shower drain is sent to the sewer through the DWHR where it transfers its heat to the incoming cold water. This configuration of the DWHRS was chosen because it was reported to be the most economically beneficial configuration irrespective of the drain water flow rate and

**Figure 4** Configuration of the DWHRS analyzed in this study.
shower length (Słyś and Kordana 2014). The design specifications of the HX and the other parameters associated with the DWHRS are summarized in Table 2.

Table 2 Design specifications of the DWHRS.*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of the HX</td>
<td>40 inches</td>
</tr>
<tr>
<td>Diameter of the vertical drain pipe in HX</td>
<td>3 inches</td>
</tr>
<tr>
<td>Diameter of the coiled copper tube in HX</td>
<td>0.5 inches</td>
</tr>
<tr>
<td>Pipeline material</td>
<td>Copper</td>
</tr>
<tr>
<td>Efficiency of electric water heater, $\eta$</td>
<td>0.95</td>
</tr>
<tr>
<td>Temperature of hot water, $T_{wh}$</td>
<td>333.15 K</td>
</tr>
</tbody>
</table>

*all values were obtained from (Słyś and Kordana 2014)

Figure 5 Configuration of the baseline system without heat recovery.

For comparison purposes, a conventional system without heat recovery is taken as the baseline system. The configuration of the baseline system is presented in Figure 5. The baseline system is different from the DWHRS in that there is no DWHR unit. Instead of the preheated water in a DWHRS, here, the cold water is directly fed to the electric water heater and the mixing valve. The shower drain water is sent to the sewer without recovering energy.
3.2 District Heating System

The configuration of the district heating system is displayed in Figure 3. The wastewater generated in the community is transported to the WWTP through the sewer network. The working of the heat pump is described in Section 2.3.1. Steam is used to absorb heat from the working fluid in the heat pump. Hot steam is circulated to the district for space heating and low temperature steam after space heating is sent back to the heat pump. The wastewater from the evaporator is then sent to the WWTP. A 3.3 MW heat capacity WWSHP used to heat about 4.9 million square feet of building surface is considered in this study.

3.3 Model

Figure 6 Simplified flow chart of the model displaying the parameters calculated at each step; ARL: Atmospheric Roughness Layer; DWHRS: Drain Water Heat Recovery System.
Figure 7 Schematic of the DWHRS showing the temperature of the different layers considered in the heat transfer model and the components of the system.

A MATLAB-based model was developed to calculate the amount of energy recovered from the system and to perform the economic analysis. The model consists of two parts – one that calculates the amount of energy recovered and another that estimates the NPV of the system. A simplified flow chart of the model is presented in Figure 6. The influence of climate conditions on the temperature of cold water inside underground distribution mains was modeled using heat transfer equations in a previous study (Blokker and Pieterse-Quirijns 2013). A modification of the model was used in this study to calculate the amount of energy recovered. A schematic of the system is shown in Figure 7.

3.3.1 Calculation of the Amount of Energy Recovered from a DWHRS

For the first part of the model, five layers were considered to calculate the cold-water temperature – atmosphere, ARL, ground surface, soil and the distribution mains pipe wall.
(Blokker and Pieterse-Quirijns 2013). Heat transfer equations were written for the ARL, soil and the pipe wall and were solved to find the temperature of the water inside the distribution mains (refer to Equation 2, Equation 3 and Equation 4). The latent heat of evaporation ($L_v E$) and the energy required to heat the vegetation ($Q$) is not included in this study. Hence the heat balance in the soil is simplified as in Equation 5. The general form of the heat balance equation is shown in Equation 1. The calculated cold-water temperature was then used to estimate the amount of energy recovered from the DWHRS using Equation 6.

The general form of the heat balance equation for a layer is as follows. – Equation 1

Change in the amount of heat stored in the layer for a given time = Heat transferred into the system – Heat transferred out of the system + Heat generated

The heat balance for the ARL is as follows. – Equation 2

$$h_{ARL} \frac{\partial T_{ARL}}{\partial t} = \frac{(T_{GS} - T_{ARL})}{R_g} + C_D u (T_{atm} - T_{ARL}) f_h$$

The heat balance in the soil is as follows. – Equation 3

$$\rho_s C_{ps} \frac{\partial T_s}{\partial t} = \lambda_s \frac{\partial^2 T_s}{\partial z^2} + \frac{1}{\Delta z} \left[ (1 - a) R_s + \epsilon_{eff} \sigma T_{atm}^4 - \sigma T_{GS}^4 - \rho_a C_{p,a} (T_{GS} - T_{ARL}) \frac{R_g}{R_g} - Q - L_v E \right]$$

The heat balance for the distribution mains pipe wall is as follows. – Equation 4

$$\frac{dT_{wc}}{dt} = \frac{\alpha_{wc}}{r^2 \left( \lambda_r + \frac{1}{N_u} \right)} (T_{pw,o} - T_{wc})$$

$$\alpha_{wc} = \frac{\lambda_{wc}}{\rho_{wc} * C_{p,wc}}$$
\[ \lambda_r = \lambda_{wc} \left( \frac{9.9}{100 \cdot \lambda_{pw}} + \frac{0.1}{100 \cdot \lambda_{pw'}} \right) \]

A simplified heat balance for the soil used in this study is as follows. \textit{Equation 5}

\[ \rho_s C_p, s \frac{\partial T_s}{\partial t} = \lambda_s \frac{\partial^2 T_s}{\partial z^2} + \frac{1}{\Delta z} \left[ \left( 1 - a \right) R_s + \epsilon_{eff} \sigma T_{atm}^4 - \sigma T_{GS}^4 + \frac{\rho_a C_p, a (T_{GS} - T_{ARL})}{R_g} \right] \]

The amount of energy recovered from the DWHR unit is as follows. \textit{Equation 6}

\[ R = UA (T_{wm} - T_{wc}) \cdot \eta_{DWHR} \]

3.3.2 Estimating the Electricity Savings Due to the Operation of the DWHRS

First the temperature of the preheated water is calculated using \textit{Equation 7}. The flow rate of hot water from the electric water heater is calculated based on two equations: the first equation is the assumption that the heat energy lost by the drain water equals the heat energy gained by the incoming cold water and the second equation states that the flow rate of mixed water is equal to the sum of the flow rate of hot water and that of preheated water entering the mixing valve (refer to \textit{Equation 8}). In the DWHRS, electricity consumed for heating the water in the electric water heater is calculated based on the amount of water heated, the energy required to heat water to the hot water temperature and the efficiency of the electric water heater (refer to \textit{Equation 9}). To find the energy and cost saved due to the use of the DWHRS, the flow rate of hot water and the electricity consumed by a baseline system that does not employ a heat recovery unit is calculated using \textit{Equation 10} and \textit{Equation 11}. In the next step, electricity savings are calculated by taking the difference in the electricity costs between the baseline system and the DWHRS (refer to \textit{Equation 12}).
The temperature of preheated water leaving the HX is as follows. – Equation 7

\[ T_{wp} = \frac{R}{\rho_r \cdot C_{pr} \cdot q_{he}} + T_{wc} \]

The following two assumptions are made for finding the flow rate of hot water from the electric water heater.

- Assumption 1: \( q_{wh} \cdot \rho_{wh} \cdot C_{p,wh} \cdot (T_{wh} - T_{wm}) = q_{wc} \cdot \rho_{wp} \cdot C_{p,wp} \cdot (T_{wm} - T_{wp}) \)
- Assumption 2: \( q_{wm} = q_{wh} + q_{wc} \)

The flow rate of hot water from electric water heater in the DWHRS is as follows. – Equation 8

\[ q_{wh} = \frac{q_{wm} \cdot \rho_{wp} \cdot C_{p,wp} \cdot (T_{wm} - T_{wp})}{\rho_{wh} \cdot C_{p,wh} \cdot (T_{wh} - T_{wm}) + \rho_{wp} \cdot C_{p,wp} \cdot (T_{wm} - T_{wp})} \]

The electricity consumption in the DWHRS is as follows. – Equation 9

\[ E_c = \frac{D \cdot n \cdot s \cdot q_{wh} \cdot p \cdot \rho_{wp} \cdot C_{p,wp} \cdot (T_{wh} - T_{wp})}{\eta \cdot 3.6 \cdot 10^6} \]

The flow rate of hot water from electric water heater in baseline system is below. – Equation 10

\[ q_{wh,b} = \frac{q_{wm} \cdot \rho_{wc} \cdot C_{p,wc} \cdot (T_{wm} - T_{wc})}{\rho_{wh} \cdot C_{p,wh} \cdot (T_{wh} - T_{wm}) + \rho_{wc} \cdot C_{p,wc} \cdot (T_{wm} - T_{wc})} \]

The electricity consumption in the baseline system is as follows. – Equation 11

\[ E_{c,b} = \frac{D \cdot n \cdot s \cdot q_{wh,b} \cdot p \cdot \rho_{wc} \cdot C_{p,wc} \cdot (T_{wh} - T_{wc})}{\eta \cdot 3.6 \cdot 10^6} \]

The electricity savings per annum due to heat recovery is as follows. – Equation 12

\[ ES_n = E_{c,b} - E_c \]
3.4 Study Scenarios

Four different study scenarios were developed to capture the influence of climate and population density on the sustainability of a DWHRS. The different places for the scenario generation were selected based on the climatic conditions and population density. A map of the different climatic zones in the United States is used to identify places with different climatic conditions (refer to Figure 8). The same shower conditions were used for the four scenarios (refer to Table 3). It was assumed that the HXs used in the DWHRS were manufactured in Toronto, Canada and shipped to the various regions considered for the study. Two scenarios were designed to evaluate the effects of the external factors in medium-scale district heating systems.

Figure 8 A map of the different climatic zones in the US highlighting the five locations used for the scenarios in this study.
Table 3: Shower conditions for the four scenarios.*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ns</td>
<td>Number of showers</td>
<td>1 shower per person per day</td>
</tr>
<tr>
<td>p</td>
<td>Length of one shower</td>
<td>15 minutes per shower</td>
</tr>
<tr>
<td>$T_{wm}$</td>
<td>Temperature of mixed water used for shower</td>
<td>315.15 K</td>
</tr>
<tr>
<td>D</td>
<td>Number of inhabitants in one house</td>
<td>3 people per house</td>
</tr>
</tbody>
</table>

* all values are assumptions

Scenario 1 is based on the local conditions in Tampa, Florida. Tampa is a city with a population density of 2970 people per square mile situated in the Hot-Humid region of the United States (“Tampa population” 2018). The residential houses in the city of Tampa are supplied with water from a central water treatment plant through the drinking water distribution network. A scenario where the potable water is sent from the water treatment plant to a residential house with a DWHRS 10 miles from the treatment plant was studied. Three weeks of annual vacation where no shower is taken was included in the scenario. A baseline system with conditions similar to scenario 1, but with no heat recovery was also evaluated. The local conditions in scenario 1 are listed in Table 4. The following assumptions are made for the evaluation:

- Clear skies are observed at all times,
- The soil type is sandy soil,
- The latent heat flux due to evaporation and the energy to heat the vegetation have no effect on the cold-water temperature,
- The effect of impurities in the drain water is negligible,
- There is no maintenance cost for the DWHR as the copper pipelines prevent fouling, and
- There is no heat loss through the pipelines.
Table 4 Local conditions considered for Scenario 1 – Tampa, Florida.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
<th>SOURCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_{ARL}$</td>
<td>10 m</td>
<td>(Blokker and Pieterse-Quirijns 2013)</td>
</tr>
<tr>
<td>$C_D$</td>
<td>$1.5 \times 10^{-2}$</td>
<td>(Padhra 2010)</td>
</tr>
<tr>
<td>$\epsilon_{eff}$</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>$f_h$</td>
<td>0.4</td>
<td>(Blokker and Pieterse-Quirijns 2013)</td>
</tr>
<tr>
<td>$R_g$</td>
<td>30 s/m</td>
<td></td>
</tr>
<tr>
<td>$Q_s$</td>
<td>1.2 kg/m$^3$</td>
<td></td>
</tr>
<tr>
<td>$C_{p,a}$</td>
<td>1010 J/kg K</td>
<td></td>
</tr>
<tr>
<td>$T_{atm}$</td>
<td>280.5 – 305 K</td>
<td>(Natural Resources Conservation Services 2018)</td>
</tr>
<tr>
<td>$R_{global}$</td>
<td>0 – 723 W/m$^2$</td>
<td>(National Renewable Energy Laboratory n.d.)</td>
</tr>
<tr>
<td>$u$</td>
<td>3.26 – 4.42 m/s</td>
<td>(The Southeast Regional Climate Center 2007)</td>
</tr>
<tr>
<td>$a$</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>$Q_s$</td>
<td>1600 kg/m$^3$</td>
<td>(Blokker and Pieterse-Quirijns 2013)</td>
</tr>
<tr>
<td>$C_{p,s}$</td>
<td>900 J/kg K</td>
<td></td>
</tr>
<tr>
<td>$\lambda_s$</td>
<td>1.4 W/m K</td>
<td></td>
</tr>
<tr>
<td>$\Delta z$</td>
<td>0.127 m</td>
<td></td>
</tr>
<tr>
<td>Distance</td>
<td>16093.4 m from treatment plant to house</td>
<td>Assumed value</td>
</tr>
<tr>
<td>$z$</td>
<td>0.92 m</td>
<td></td>
</tr>
<tr>
<td>Diameter of the distribution mains</td>
<td>Ranges from 0.2032 to 1.3716 m</td>
<td>(Hillsborough County 2017)</td>
</tr>
<tr>
<td>Distribution mains pipeline material</td>
<td>Ductile iron pipe with concrete lining</td>
<td></td>
</tr>
<tr>
<td>$C_e$</td>
<td>0.1154 $/kWh</td>
<td>(U S Energy Information Administration 2018b)</td>
</tr>
</tbody>
</table>

Scenario 2 is based on the conditions in New York City (NYC). NYC is a metropolitan area with a population density of over 27,000 people per square mile. It is the most populous city in the United States (NYC Department of City Planning 2018). This city falls in the Mixed-Humid climatic zone. Water is treated in a central treatment plant and the finished water is stored in the Hillview reservoir. Potable water is then supplied to the city through the water distribution
network. Some of the pipelines in the distribution network run in the bedrock deep below the ground surface. The conditions for scenario 2 are listed in Table 5.

Table 5 Local conditions used for Scenario 2 – NYC.*

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
<th>SOURCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{atm}$</td>
<td>270 – 300.5 K</td>
<td>(National Renewable Energy Laboratory n.d.)</td>
</tr>
<tr>
<td>$R_{global}$</td>
<td>0 – 758 W/m²</td>
<td></td>
</tr>
<tr>
<td>Distance</td>
<td>32186.9 m from treatment plant to house</td>
<td>Assumed value</td>
</tr>
<tr>
<td>$z$</td>
<td>182.88 m</td>
<td>(National Research Council 2000; New York City Department of Environmental Protection n.d.)</td>
</tr>
<tr>
<td>Diameter of the distribution mains</td>
<td>Ranges from 0.6096 to 7.3152 m</td>
<td></td>
</tr>
<tr>
<td>Distribution mains pipeline material</td>
<td>Concrete, stainless steel</td>
<td>(The City of New York 2014; “Water supply and distribution” 2008)</td>
</tr>
<tr>
<td>$C_e$</td>
<td>0.1928 $/kWh</td>
<td>(U S Energy Information Administration 2018c)</td>
</tr>
</tbody>
</table>

* the remaining parameters are the same as for Scenario 1

Table 6 Local conditions for Scenario 3 – Grand Forks, North Dakota.*

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
<th>SOURCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{atm}$</td>
<td>258 – 300.5 K</td>
<td>(National Renewable Energy Laboratory n.d.)</td>
</tr>
<tr>
<td>$R_{global}$</td>
<td>0 – 752 W/m²</td>
<td></td>
</tr>
<tr>
<td>Distance</td>
<td>48280.3 m from treatment plant to house</td>
<td>Assumed value</td>
</tr>
<tr>
<td>$z$</td>
<td>2.82 m</td>
<td></td>
</tr>
<tr>
<td>Diameter of the distribution mains</td>
<td>Ranges from 0.2032 to 0.9144 m</td>
<td>(The City of Grand Forks Subdivision 2014)</td>
</tr>
<tr>
<td>Distribution mains pipeline material</td>
<td>Ductile iron pipe with polyethylene encasement</td>
<td></td>
</tr>
<tr>
<td>$C_e$</td>
<td>0.1223 $/kWh</td>
<td>(U S Energy Information Administration 2018c)</td>
</tr>
</tbody>
</table>

* the remaining parameters are the same as for Scenario 1
Scenario 3 is based on Grand Forks, North Dakota. This city, being one of the coldest cities in the United States, falls under the Very Cold climatic zone. The city has a population density of 2600 people per square mile (“Grand Forks population” 2018). Drinking water is supplied to the city from a central water treatment plant through underground distribution mains. The local conditions for scenario 3 are listed in Table 6.

Scenario 4 is based on McMullen County, Texas. This county is a rural area with a very low population density of 0.6 people per square mile (U.S. Census Bureau n.d.). Individual and public groundwater wells are the source of domestic water in this county (Harris 1965). These wells are located very close to the house and hence the distance travelled by the water in pipelines is much less (less than 0.2 miles) when compared to that in the cities evaluated in scenarios 1, 2 and 3. The local conditions used for the evaluation of scenario 4 is listed in Table 7.

**Table 7** Local conditions considered for Scenario 4 – McMullen County, Texas.*

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
<th>SOURCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{atm}}$</td>
<td>293 – 303 K</td>
<td>(National Renewable Energy Laboratory n.d.)</td>
</tr>
<tr>
<td>$R_{\text{global}}$</td>
<td>0 – 860 W/m$^2$</td>
<td></td>
</tr>
<tr>
<td>Distance</td>
<td>160.9 m from the ground well to house</td>
<td></td>
</tr>
<tr>
<td>$z$</td>
<td>0.92 m</td>
<td>Assumed value</td>
</tr>
<tr>
<td>Diameter of the pipeline</td>
<td>0.0508 m</td>
<td></td>
</tr>
<tr>
<td>Distribution mains pipeline material</td>
<td>Ductile iron pipe</td>
<td></td>
</tr>
<tr>
<td>$C_e$</td>
<td>0.1159 $/kWh</td>
<td>(U.S. Energy Information Administration 2018c)</td>
</tr>
</tbody>
</table>

* the remaining parameters are the same as for Scenario 1

Scenario 5 is based on Vancouver, Canada. This scenario is designed to evaluate district heating using heat recovered from wastewater in downtown Vancouver. Vancouver is one of the
most populous cities in North America with a population density of about 5500 people per square kilometer (Statistics Canada 2017). A 3.3 MW central district heating system provides space heating for the South East False Creek neighborhood near downtown Vancouver (Lee 2015). The local conditions used in the scenario are summarized in Table 8.

**Table 8** Local conditions considered for Scenario 5 – Vancouver, Canada.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
<th>SOURCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{atm}$</td>
<td>268 – 295 K</td>
<td>(National Renewable Energy Laboratory n.d.)</td>
</tr>
<tr>
<td>$R_{global}$</td>
<td>0 – 720 W/m$^2$</td>
<td></td>
</tr>
<tr>
<td>Distance</td>
<td>4000 m from the user to the point of heat recovery</td>
<td></td>
</tr>
<tr>
<td>$z$</td>
<td>1.92 m</td>
<td>Assumed value</td>
</tr>
<tr>
<td>Diameter of the pipeline</td>
<td>0.2032 m</td>
<td></td>
</tr>
<tr>
<td>Distribution mains pipeline material</td>
<td>Ductile iron pipe with polyethylene encasement</td>
<td></td>
</tr>
<tr>
<td>District heating pipeline material</td>
<td>Steel pipe with polyurethane insulation and polyethylene casing</td>
<td>(Fröling et al. 2004)</td>
</tr>
<tr>
<td>Energy losses in district heating pipelines</td>
<td>8.6%</td>
<td>(Marinova et al. 2008)</td>
</tr>
<tr>
<td>$C_e$</td>
<td>0.1142 $/kWh</td>
<td>(Hydro-Quebec 2018)</td>
</tr>
</tbody>
</table>

### 3.5 Life Cycle Cost Analysis (LCCA)

The life cycle cost is expressed as net present value (NPV) and estimated using Equation 13 to Equation 15. The electricity savings in Equation 13 is calculated using the model presented in Section 3.3.2. The initial investment for the procurement and installation of the HX was taken to be $450. The NPV was calculated over a lifetime of 20 years with an annual discount rate of 8% (Słyś and Kordana 2014). It was assumed that there are no additional operation and maintenance costs associated with the use of the HX as it would just replace a section of the existing vertical shower drain pipe.
The annual cost savings due to heat recovery is as follows. – Equation 13

\[ S_y = \sum_{i=1}^{12} ES_n \ast C_e \ast nd_i \]

The discount factor for one year is as follows. – Equation 14

\[ d_y = \frac{1}{(1 + r)^y} \]

The NPV of the DWHRS is as follows. – Equation 15

\[ NPV = \sum_{y=0}^{n} (S_y - Inv_y) \ast d_y \]

3.6 Life Cycle Assessment

![Diagram of Life Cycle Assessment](image)

**Figure 9** Stages in the life cycle of the DWHRS included for the LCA.

The LCA was performed using SimaPro. As shown below, there are four parts to every LCA as per the ISO 14044 requirements (International Organization for Standardization 2006).

- Goal and Scope of the analysis
- Life cycle inventory (LCI)
• Life cycle impact assessment (LCIA)

• Interpretation of the results

The goal of this LCA is to evaluate the environmental sustainability of the DWHRS and to examine the influence of climate and population density on the environmental sustainability. The scope of the LCA is shown in Figure 9. All stages starting from the manufacture of the HX to its recycle are included in the LCA. Only the components of the DWHRS that are different from the baseline system are included in the study as this would give the environmental impact caused

Figure 10 Differences between the DWHRS and baseline system.
exclusively by heat recovery. The differences between the DWHRS and baseline system are highlighted in Figure 10. A functional unit of one liter of water heated to a temperature of 333.15 K is used for the LCA of the DWHRS. The LCA for the district heating system is performed using a functional unit of one m² of heated surface is used. In order to compare the DWHRS with the district heating system the LCA for both the systems was performed using a functional unit of one kWh of heat energy recovered from the system.

**Table 9** LCI part 1 – data common to all study scenarios.

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight of the copper heat exchanger</td>
<td>12 kg</td>
</tr>
<tr>
<td>Pipe and pipe fittings required during installation</td>
<td>$40</td>
</tr>
<tr>
<td>Disposal</td>
<td>100% recycle of copper</td>
</tr>
<tr>
<td>Water consumption over lifetime</td>
<td>2167200 litres</td>
</tr>
<tr>
<td>Lifetime of the DWHRS</td>
<td>20 years</td>
</tr>
</tbody>
</table>

**Table 10** LCI part 2 – data specific to the study scenarios.

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>SCENARIO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport from manufacturer to consumer (by air freight) (*10^5 m)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Transport from manufacturer to consumer (by delivery van on road) (*10^4 m)</td>
<td>16.1</td>
</tr>
<tr>
<td></td>
<td>7.24</td>
</tr>
<tr>
<td></td>
<td>14.40</td>
</tr>
<tr>
<td></td>
<td>24.14</td>
</tr>
<tr>
<td>Energy used by electric water heater in the DWHRS in kWh/ lifetime</td>
<td>26965</td>
</tr>
<tr>
<td></td>
<td>69798</td>
</tr>
<tr>
<td></td>
<td>86265</td>
</tr>
<tr>
<td></td>
<td>35156</td>
</tr>
<tr>
<td>Energy recovered from drain water in kWh/ lifetime</td>
<td>15956</td>
</tr>
<tr>
<td></td>
<td>34015</td>
</tr>
<tr>
<td></td>
<td>41176</td>
</tr>
<tr>
<td></td>
<td>19595</td>
</tr>
<tr>
<td>Transport from consumer to recycling center (by passenger car) in (*10^4 m)</td>
<td>1.610</td>
</tr>
<tr>
<td></td>
<td>1.99</td>
</tr>
<tr>
<td></td>
<td>9.66</td>
</tr>
<tr>
<td></td>
<td>6.00</td>
</tr>
<tr>
<td>Energy used by electric water heater in baseline system in kWh/lifetime</td>
<td>43960</td>
</tr>
<tr>
<td></td>
<td>106939</td>
</tr>
<tr>
<td></td>
<td>131665</td>
</tr>
<tr>
<td></td>
<td>56074</td>
</tr>
</tbody>
</table>

The LCI is compiled from various sources. The data common to all scenarios is presented in Table 9. The amount of energy recovered and consumed are specific to each scenario. These
values are estimated using the model described in Section 3.3 and is presented in Table 10. The LCIA was then performed using the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) 2 method on SimaPro. The impact on the following categories was estimated: global warming, acidification, carcinogens, non carcinogens, respiratory effects, eutrophication, ozone depletion, ecotoxicity and smog. A more detailed analysis on quantifying the environmental impacts of the DWHRS focuses on three indicators, namely, carbon footprint, eutrophication potential and ecotoxicity.
CHAPTER 4: RESULTS AND DISCUSSION

4.1 Diurnal Temperature Profile of the Incoming Cold Water in Tampa, Florida

The hourly diurnal temperature profile of the cold-water entering a residential house obtained using the first part (Equation 1 to Equation 5) of the MATLAB-based model is shown in Figure 11. The figure shows two plots: the water temperature during a representative day in the summer (August) and winter (January). The ambient temperature and the temperature of the soil is also shown for reference. The cold water leaves the treatment plant at a temperature of 70 degrees F in the winter and 90 degrees F in the summer. From Figure 11, the temperature of cold water increases with the increase in ambient temperature and vice versa, but the degree of increase is small when compared to that of the ambient temperature. Also, it is evident that the temperature of the water is almost the same as the temperature of the soil near the pipe wall because the ductile iron pipeline used here is not a good insulator. There is a transition time of about one hour for the temperature of water to reach equilibrium with the soil temperature after the water leaves the water treatment plant. Moreover, from Figure 11, it is clear that in the summer, the soil temperature and water temperature are warmer than the ambient temperature during all times of the day, whereas, in the winter, this is not the case. In the winter, the soil temperature and water temperature are colder than the ambient temperature during the afternoons. Additionally, the figure shows the distance travelled by the cold water from the water treatment plant, which relates to the time taken for the water to reach the house.
Figure 11 Hourly diurnal temperature profiles of the cold-water temperature for a representative day in the Winter (Graph A) and Summer (Graph B) in Tampa.
4.2 Scenario 1 – Tampa, Florida

In Tampa, for a house situated at 10 miles from the water treatment plant, it is estimated to take about seven and half hours for the water to reach the house, i.e., the residence time of the cold water in the distribution mains is seven and half hours. The influence of the local conditions in Tampa, Florida on the DWHRS installed in the residential house was modeled and the results are reported in this section.

4.2.1 Amount of Energy Recovered for Conditions in Tampa

The amount of energy recovered in the DWHRS is influenced by the temperature of the incoming cold water to the house. Three different shower times, namely, morning, afternoon and evening were modeled. Table 11 lists the amount of energy recovered per annum for each shower time. More energy is recovered when a shower is taken in the evening than when taken in the afternoon. This might be due to the lower ambient temperature in the evening, which lowers the incoming cold-water temperature to the house. As the temperature of the drain water is kept constant irrespective of the climatic conditions, the temperature gradient between the cold water and drain water in the HX increases with the decrease in the incoming cold-water temperature. A higher temperature gradient results in a greater rate of heat transfer and hence more energy is recovered for the same shower length in the evening. Additionally, from Table 11 it is apparent that the total amount of energy saved due to the operation of the DWHRS is more than just the energy recovered from the HX. This is due to the efficiency of the electric water heater; the energy that is used to operate the electric water heater, but not transferred to the water being heated is saved when the DWHRS is used.
Table 11 Amount of energy recovered from the DWHR unit at different shower times.

<table>
<thead>
<tr>
<th>Shower Time</th>
<th>Energy Recovered from HX (kWh/annum)</th>
<th>Energy Saved Due to Heat Recovery (kWh/annum)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morning</td>
<td>798</td>
<td>850</td>
</tr>
<tr>
<td>Afternoon</td>
<td>753</td>
<td>802</td>
</tr>
<tr>
<td>Evening</td>
<td>821</td>
<td>873</td>
</tr>
</tbody>
</table>

4.2.2 LCCA

Table 12 NPV of the DWHRS for different shower times.

<table>
<thead>
<tr>
<th>Shower Time</th>
<th>NPV of DWHRS ($)</th>
<th>Payback Period (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morning</td>
<td>513</td>
<td>5.94</td>
</tr>
<tr>
<td>Afternoon</td>
<td>458</td>
<td>6.40</td>
</tr>
<tr>
<td>Evening</td>
<td>540</td>
<td>5.74</td>
</tr>
</tbody>
</table>

The NPV of the DWHRS with a lifetime of 20 years was estimated for the three shower times discussed in Section 3.3.2 using part two (Equation 6 to Equation 12) of the MATLAB-based model followed by the method described in Section 3.5 (Equation 13 to Equation 15) and the results are tabulated in Table 12. The NPV was found to be higher when showers are taken in the evening as more energy is being recovered in the evening. As the amount of energy recovered increases, the temperature of preheated water leaving the HX also increases. Consequently, less energy is used by the electric water heater to heat water to the desired hot water temperature, thus reducing the amount of money spent on electricity. Therefore, the DWHRS is economically more beneficial for evening showers when the ambient temperature is low. Also, the payback period of the system was found to be between 5 to 6 years for the morning and evening shower times and more than 6 years for the afternoon shower time. Though taking a shower in the evening was found to be economically more beneficial, people mostly take a shower in the
morning and hence, only the morning shower time was used for the analysis of the remaining scenarios in this study (Mayer et al. 1999).

### 4.2.3 LCA

![Figure 12](image)

**Figure 12** Impact assessment of the DWHRS for Scenario 1 using TRACI showing the contribution of the DWHRS life cycle stages for each indicator.

The life cycle analysis was performed using the TRACI impact characterization method and the results of the impact assessment are shown in Figure 12. The percent contribution of the five life cycle stages included in the assessment to each of the 9 indicators is presented. The manufacture of the HX has a significant impact only on ozone depletion and carcinogenics. The transport does not have a significant impact on any of the indicators. The electric water heater usage has a significant contribution for most of the indicators. The energy recovered from the HX is found to show benefits on most indicators as the recovered energy replaces a portion of the
electricity that would otherwise be required. The disposal of the HX is also found to show benefits as the recycling of the copper HX avoids the primary copper production, which includes copper ore mining and production of copper tubes. The impact assessment was also performed using the ReCiPe midpoint heuristic tool and the results are presented in the Appendix C. The results obtained using the ReCiPe method were similar to that obtained by using TRACI.

![Figure 13 Comparison of the impact assessment of the DWHRS and baseline system using TRACI.](image)

Also, the impact assessment was performed for the baseline system, which has no heat recovery and the results were compared to that of the DWHRS (refer to Figure 13). The baseline system includes only the electric water heater usage as the other life cycle stages are specific to the DWHRS. The DWHRS was found to perform better than the baseline system in all indicators except ozone depletion. The manufacture of the HX in the DWHRS is the sole major contributor
to ozone depletion; this being absent in the baseline system explains the higher impact of the DWHRS on the ozone depletion indicator. For carcinogenics, non-carcinogenics, eutrophication and ecotoxicity, the DWHRS was estimated to have negative values (i.e., benefits) while the baseline system had positive values (i.e., impacts) on these indicators due to the domination of the disposal of the heat exchanger in the DWHRS on these indicators. As the heat exchanger is being 100% recycled, the disposal scenario showed high benefits in these indicators.

The environmental impact of the DWHRS operated during the three different shower times was evaluated using the global warming, eutrophication and ecotoxicity indicators. These results are displayed in Figure 14. The contributors to global warming are the electricity usage and the energy recovered from the DWHR (refer to Figure 12 and Figure 14A). Since these two values change with the shower time, it can be observed that the impact on global warming changes with shower time, but the change is very small. Although taking a shower in the evening was found to be the most economically beneficial option, taking a shower in the afternoon was the best option for global warming. This might be because of the higher ambient temperature in the afternoon resulting in a higher temperature of the incoming cold water than that in the evening or morning. Consequently, less energy would be required to heat the water to the hot water temperature in the afternoon. The temperature rise required to reach the hot water temperature is smaller in the afternoon than at other times.
Figure 14 Comparison of the impact for three different shower times using TRACI: (A) Global warming; (B) Eutrophication; (C) Ecotoxicity.
The main contributor to eutrophication and ecotoxicity is the disposal of the HX (refer to Figure 12, Figure 14B and Figure 14C). The high value of these indicators associated with the disposal makes the effect of the other life cycle stages negligible. Since the method of disposal was considered to be the same irrespective of the shower time, there is no significant difference in the eutrophication impact and ecotoxicity impact between the three shower times.

4.3 Influence of Climatic Conditions on the Sustainability of the DWHRS

The influence of climatic conditions, namely, ambient temperature and solar radiation, were extensively analyzed. The other climatic conditions such as wind speed and height of the atmospheric layer did not have a significant impact on the amount of energy recovered from the DWHRS; the sensitivity of the DWHRS to these parameters is presented in Section 4.7. Scenario 1 represented a hot place while Scenario 3 was based on one of the coldest places in the USA. It was observed in the literature review that in cold regions pipelines were laid deeper than those in hot places, i.e., the soil depth increases in colder places. This is because pipelines were installed below the frost line to prevent the freezing and bursting of pipelines. Additionally, the pipeline material was also found to be influenced by the ambient temperature. In cold places, more insulation was provided to pipes to prevent freezing of the pipelines. NYC was an extreme case of soil depth where the pipelines were installed at a depth of about 600 feet to 800 feet below the ground level in bedrock. So, this case was analyzed using Scenario 2.

4.3.1 Impact on the Economic Sustainability of the DWHRS

The amount of energy recovered from a DWHRS installed in a cold place is much higher than that in a hot place (refer to Figure 15). The low ambient temperature and solar radiation
lower the incoming cold-water temperature to the house; therefore, causing an increase in the temperature gradient between the hot and cold sides of the HX and consequently, an increase in the amount of heat recovered. In all scenarios 34 to 39% of the total energy requirement is supplied by the heat recovered in the DWHRS. The NPV of the system is also expected to increase with a decrease in the ambient temperature, but the cost of electricity overrides the influence of ambient temperature (refer to Table 13). This explains why the DWHRS installed in a house in NYC has a higher NPV than that in Grand Forks though NYC is not as cold as Grand Forks. Although, Tampa and McMullen County have similar ambient temperature and electricity prices, the NPV of scenario 4 is higher than that of scenario 1. This is because of the differences in population density between the two places. The impacts of population density are discussed in Section 4.4.

![Figure 15](image)

*the baseline system is the system with no heat recovery*

**Figure 15** Amount of energy recovered from the DWHRS in the different scenarios when a shower is taken in the morning.
Since the cost of electricity has a high impact on the economic sustainability of the DWHRS, a threshold cost above which the system is economically beneficial in the 20-year lifetime was determined and the results are shown in Table 13. Also, to explicitly state the economic benefits for the residential customers using the DWHRS in their houses, the annual savings on their electricity bill is presented in Table 13.

Table 13 Influence of climatic conditions on the economic sustainability of the DWHRS for 4 scenarios.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Place</th>
<th>Average ambient temperature (K)</th>
<th>Actual Cost of electricity ($/kWh)</th>
<th>NPV ($)</th>
<th>Cost savings ($/annum)</th>
<th>Threshold cost of electricity ($/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tampa, FL</td>
<td>293.95</td>
<td>0.1154</td>
<td>513</td>
<td>98.06</td>
<td>0.0540</td>
</tr>
<tr>
<td>2</td>
<td>New York City, NY</td>
<td>284.13</td>
<td>0.1928</td>
<td>3065</td>
<td>358.04</td>
<td>0.0247</td>
</tr>
<tr>
<td>3</td>
<td>Grand Forks, ND</td>
<td>278.40</td>
<td>0.1223</td>
<td>2275</td>
<td>277.62</td>
<td>0.0202</td>
</tr>
<tr>
<td>4</td>
<td>McMullen County, TX</td>
<td>294.76</td>
<td>0.1159</td>
<td>740</td>
<td>121.22</td>
<td>0.0439</td>
</tr>
</tbody>
</table>

4.3.2 Impact on the Environmental Sustainability of the DWHRS

The influence of the climatic conditions on the environmental sustainability of a DWHRS was assessed and the impact on three indicators – global warming, eutrophication and ecotoxicity is presented in this section. Impact on global warming was found to increase with decrease in ambient temperature and solar radiation (refer to Figure 16). The main contributor to global warming is the electricity usage to heat water and the major benefits are from the recovery of heat. As the ambient temperature decreases, the electricity consumption and the amount of heat recovered increases. The electricity consumption has a higher impact on global warming than the benefits produced by heat recovery and hence, the value of the indicator is high in cold places.
such as the ones indicated in scenarios 2 and 3. But, the impact of the DWHRS on global warming is lower than the conventional system without heat recovery in all the scenarios, thus concluding that the operation of the DWHRS is better for the environment in this vein. The impact assessment was also performed for a landfill disposal scenario. The difference in the type of disposal did not have any significant impact on the global warming as shown in Figure 16.

![Impact Assessment Diagram]

*represents the baseline system without heat recovery in each of the scenarios

**Figure 16** Impact of the climatic conditions and population density on the global warming estimated using TRACI.

Similar to global warming, the impact of the DWHRS on eutrophication was also found to increase with a decrease in the ambient temperature (refer to Figure 17). Scenario 1 had lower impact on the eutrophication than scenarios 2 and 3 representing cold places. This increase is also attributed to the higher electricity consumption in colder regions. As the DWHRS showed overall
benefits on the eutrophication, the benefits decrease slightly with a decrease in the ambient temperature. The benefits associated with the amount of heat recovered becomes more significant in colder places represented in scenarios 2 and 3 as more energy is recovered. When the landfill disposal scenario is used, the overall impact of the DWHRS on the eutrophication showed a positive value whereas the recycling disposal scenario showed overall benefits. This is because the disposal scenario is the major contributor to the credits on eutrophication. During recycling, primary copper production is avoided and hence the difference observed in the impact on eutrophication. The impact of the DWHRS on ecotoxicity is the same as the impact on eutrophication (refer to Figure 18). In all cases, the DWHRS performed better than the baseline system with no heat recovery.

*represents the baseline system without heat recovery in each of the scenarios

**Figure 17** Impact of the climatic conditions and population density on the eutrophication estimated using TRACI.
*represents the baseline system without heat recovery in each of the scenarios

**Figure 18** Impact of the climatic conditions and population density on the ecotoxicity estimated using the TRACI.

### 4.4 Influence of Population Density on the Sustainability of the DWHRS

From the literature review, it was inferred that the source of potable water varies between regions with high and low population densities. In regions with a high population density (as in scenario 1, 2 and 3), the potable water is supplied to the residential houses from a central treatment plant through the water distribution network. For regions with a low population density (as in scenario 4), the source of domestic water is ground water from individual or public wells. The amount of energy recovered in a region with a low population density is higher than that in a region with a high population density. The water from the well takes less than 5 minutes to reach the house; in this short residence time, the water temperature does not reach equilibrium.
with the soil temperature near the surface and ambient temperature. The NPV of the DWHRS in Scenario 4 was estimated to be $740, which is higher than in Scenario 1 ($513) as the energy recovered is higher. An LCA was performed for Scenario 4 to assess the environmental sustainability of the DWHRS installed in a region with a low population density. The global warming is slightly higher when compared to Scenario 1, which is based on similar climatic conditions in Tampa (refer to Figure 16). The overall benefits on eutrophication and ecotoxicity are similar to Scenario 1 because these two indicators are largely impacted by the stage of disposal (refer to Figure 17 and Figure 18). As the disposal is the same irrespective of the population density, the impact on eutrophication and ecotoxicity is similar to high population density regions.

4.5 LCCA and LCA for the District Heating System

The economic analysis of the district heating system was performed. The amount of energy recovered using a WWSHP was estimated to be about 28000 MWh/annum using the model described in Section 3.3. The NPV is then calculated by using the equations presented in Section 3.5. The NPV of the district heating system for a lifetime of 20 years was estimated to be $66,980. A payback period of 17 to 18 years was estimated for this system.

The life cycle analysis was performed using the TRACI impact characterization method and the results of the impact assessment are shown in Figure 19. The normalized impacts of the four life cycle stages included in the assessment on each of the 9 indicators is presented. The contributions from the electricity consumption by the compressor in the WWSHP and the amount of energy recovered from the system are dominant contributors to all the indicators. The impact
caused by the manufacture and installation of all components in the district heating system and the disposal of the components at the end of life is negligible across all indicators. The highest normalized impact was on carcinogenics. The impacts on ozone depletion and respiratory effects was found to be negligible.

Figure 19 Impact assessment of district heating system for Scenario 5 using TRACI showing the contribution of the life cycle stages for each indicator.

4.6 Comparing the DWHRS with a WWSHP Used for District Heating

The economic analysis of the DWHRS and the district heating system were performed for a lifetime of 20 years for each of the systems. For comparison of the small- and medium-scale
systems, the NPV was normalized over the amount of energy recovered from the system. The normalized NPV of the DWHRS installed in a house with three inhabitants in Grand Forks, ND is $0.055$ while the normalized NPV of the district heating system estimated for conditions in Vancouver, Canada is $1.97 \times 10^{-6}$. Grand Forks and Vancouver have similar ambient temperature, but Vancouver has almost 4 times larger population density than Grand Forks. Studies in the literature have reported that a district heating system may not be economically viable in regions with low population density (Marinova et al. 2008). The DWHRS installed in Grand Forks has a payback period of 1 to 2 years, while the district heating system has a payback period of 17 to 18 years. This payback period of a district heating system is even higher than that of a DWHRS in a hot place like Tampa (5 to 6 years).

![Figure 20](image-url)  
**Figure 20** Comparison of the impact assessment of the DWHRS and the district heating system using TRACI.
The environmental impacts of the DWHRS and the district heating system are compared using the results obtained from an LCA of the systems. For ease of comparison, a functional unit of kWh of energy recovered from the heat recovery system was used, although it does not represent the actual function of the overall system. A comparison of the impact on the various indicators caused by the DWHRS and the district heating system are shown in Figure 20. It can be seen that the district heating system shows benefits in all of the indicators presented. In three categories, namely, non-carcinogenics, eutrophication and ecotoxicity, the DWHRS shows more benefits than the district heating system. In the district heating system, only the electricity usage for the compressor and the energy recovered contribute significantly to all the indicators (refer to Figure 19), whereas this is not the case with the DWHRS (refer to Figure 12). In the DWHRS, disposal of the DWHRS is the main contributor to non-carcinogenics, eutrophication and ecotoxicity. This large benefit due to the disposal of the DWHRS might be the reason for the better environmental performance of the DWHRS than the district heating system in these impact categories. Electricity consumption and energy recovered in the DWHRS are the major contributors to global warming, acidification, respiratory effects and smog. Also, in a DWHRS, the percentage benefits due to the energy recovered is smaller than the impact due to electricity consumption in all the impact categories, whereas, in the district heating system, the credits are larger than the impacts due to a higher amount of energy recovered. This results in the district heating system performing better than the DWHRS in the four categories – global warming, acidification, respiratory effects and smog. In ozone depletion, the manufacture of the DWHRS contributes to more than 98% of the impact making it less environmentally friendly than the district heating system. For carcinogenics, manufacture of the DWHRS and electricity
consumption contribute to the impact and the disposal contributes significantly to the benefits; hence, there are overall benefits in this category, but not enough to outweigh the benefits caused by the energy recovery in the district heating system.

From an economic standpoint, it can be concluded that the DWHRS is more beneficial than the district heating system even in hot places where the DWHRS shows the least economic benefits; but this does not align with the results obtained from the environmental analysis. The district heating system performs better in 6 of the impact categories and the DWHRS performs better in 3 of the impact categories analyzed. Also, the district heating system requires a high capital investment and a long time for installation, while the DWHRS has a relatively small capital investment and installation time. The district heating system becomes more economically beneficial as the population density increases. Therefore, it can be concluded that the small-scale heat recovery system is beneficial in regions of low population density and the medium-scale heat recovery system is beneficial in regions of high population density. Also, the DWHRS can be beneficial in all climatic zones, while the district heating system is beneficial only in cold regions.

4.7 Sensitivity Analysis

Apart from the local conditions analyzed in Sections 4.3 and 4.4, there are several other local conditions that were used in the MATLAB-based model to calculate the amount of energy recovered from the HX. The sensitivity of the DWHRS to these local conditions was estimated and the results are tabulated in Table 14. No significant difference in the amount of heat recovered and the NPV of the system was estimated for the ranges of soil thermal conductivity, height of
ARL, wind speed and velocity of water in the pipeline considered. The thickness of the top soil layer and the thermal conductivity of the pipe wall were found to have a significant impact among all parameters included in the sensitivity analysis. The cost of electricity affects only the NPV of the system and not the amount of energy recovered from the HX as it does not affect any of the parameters associated with the heat recovered.

Table 14 Sensitivity of the amount of energy recovered from the DWHRS and the NPV of the system to the local conditions in a place.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>NPV (20 year lifetime)</th>
<th>% change from base case</th>
<th>Energy recovered</th>
<th>% change from base case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil thermal conductivity (W/m K)</td>
<td>0.06</td>
<td>512.74</td>
<td>0</td>
<td>797.78</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>1.4</td>
<td>512.74</td>
<td>0</td>
<td>797.81</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>512.78</td>
<td>0</td>
<td>797.81</td>
<td>0</td>
</tr>
<tr>
<td>Height of the atmospheric roughness layer (m)</td>
<td>10</td>
<td>512.74</td>
<td>0</td>
<td>797.81</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>513.07</td>
<td>0</td>
<td>798.05</td>
<td>0</td>
</tr>
<tr>
<td>Thickness of top soil layer (inches)</td>
<td>2</td>
<td>428</td>
<td>-17</td>
<td>727</td>
<td>-9</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>513</td>
<td>0</td>
<td>798</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>534</td>
<td>4</td>
<td>815</td>
<td>2</td>
</tr>
<tr>
<td>Wind speed (m/s)</td>
<td>3.5</td>
<td>512.63</td>
<td>0</td>
<td>797.69</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>512.74</td>
<td>0</td>
<td>797.81</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>6.5</td>
<td>513.52</td>
<td>0</td>
<td>798.42</td>
<td>0</td>
</tr>
<tr>
<td>Thermal conductivity of pipe wall (W/m K)</td>
<td>0.166</td>
<td>460</td>
<td>-10</td>
<td>754</td>
<td>-5</td>
</tr>
<tr>
<td></td>
<td>36</td>
<td>511</td>
<td>0</td>
<td>796</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>650</td>
<td>27</td>
<td>865</td>
<td>8</td>
</tr>
<tr>
<td>Velocity of water in underground pipeline (m/s)</td>
<td>0.1</td>
<td>519</td>
<td>1</td>
<td>803</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>513</td>
<td>0</td>
<td>798</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>512</td>
<td>0</td>
<td>797</td>
<td>0</td>
</tr>
<tr>
<td>Cost of electricity ($/kWh)</td>
<td>0.09</td>
<td>301</td>
<td>-41</td>
<td>798</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0.1154</td>
<td>513</td>
<td>0</td>
<td>798</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0.28</td>
<td>1886</td>
<td>268</td>
<td>798</td>
<td>0</td>
</tr>
</tbody>
</table>

*The sensitive parameters are highlighted. The length of the color bar represents the relative percentage of the three values in each column of every sensitive parameter.
Table 15 Sensitivity of the amount of energy recovered from the DWHRS and the NPV of the system with system specific parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>NPV (20 year lifetime)</th>
<th>Energy recovered</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$</td>
<td>% change from base case</td>
</tr>
<tr>
<td>Flow rate of shower head (lpm)</td>
<td>5</td>
<td>225</td>
<td>-56</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>513</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9.46</td>
<td>794</td>
<td>55</td>
</tr>
<tr>
<td>Shower length (minutes)</td>
<td>10</td>
<td>192</td>
<td>-63</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>513</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>834</td>
<td>63</td>
</tr>
<tr>
<td>Efficiency of electric water heater</td>
<td>0.9</td>
<td>566</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>0.95</td>
<td>513</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.98</td>
<td>483</td>
<td>-6</td>
</tr>
<tr>
<td>Length of DWHR unit (inches)</td>
<td>36</td>
<td>417</td>
<td>-19</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>513</td>
<td></td>
</tr>
<tr>
<td></td>
<td>72</td>
<td>1277</td>
<td>149</td>
</tr>
</tbody>
</table>

*The sensitive parameters are highlighted. The length of the color bar represents the relative percentage of the three values in each column of every sensitive parameter.

The sensitivity of the DWHRS to the system specific parameters was also estimated (refer to Table 15). The flow rate of water from the shower head, shower length and length of the HX were found to have a significant influence on the amount of energy recovered and the NPV. The efficiency of the electric water heater affects only the NPV and not the energy recovered. As the temperature of the hot water and the drain water is kept constant, variations in the efficiency of the electric water heater do not affect the energy recovered, whereas, the efficiency drives the amount of electricity consumed thus affecting the NPV of the system. A sensitivity analysis on the environmental impacts was not conducted. This is because the impact on eutrophication and ecotoxicity wouldn’t change significantly with changes in the parameters. The disposal of the heat exchanger in the DWHRS in the major contributor to these indicators and this remains the same irrespective of the changes in the parameters. As the energy recovery is the major
contributor to the impacts on global warming, the sensitivity of the global warming would be similar to the sensitivity of the energy recovered.
CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The influence of climate and population density on the economic and environmental sustainability of the DWHRS was assessed and the results were compared with that of a medium-scale district heating system. The following conclusions can be drawn from the study.

- The DWHRS is economically more beneficial in cold places like Grand Forks, North Dakota where the payback period is about 4 to 5 times shorter than that in hot places like Tampa, Florida. More energy is recovered for a shower taken when the ambient temperature is low.

- In the environmental analysis, energy consumption by the electric water heater and the energy recovered in the DWHRS are the major contributors to global warming. Recycling of the DWHRS is the main contributor to the credits in eutrophication and ecotoxicity.

- In all climatic regions and population densities, the DWHRS is more environmentally sustainable than the baseline system without heat recovery in that region, across all impact categories.

- The DWHRS in any climatic region performs economically better than a district heating system. The DWHRS (in hot places like Tampa, Florida) has about 3 times shorter payback period than the district heating system in cold places like Vancouver, Canada.
• The DWHRS is environmentally more sustainable than the district heating system in 3 of the 9 impact categories analyzed – non-carcinogenics, eutrophication and ecotoxicity.

• Compared to medium-scale district heating systems, small-scale heat recovery systems are more sustainable in places with a low population density irrespective of the climatic conditions. However, in cold places with a high population density, a trade-off between the economic and environmental sustainability is required to decide whether a small- or medium-scale system can be installed.

The results of this study help bridge the research gap in the assessment of the influence of external factors on the heat recovery systems. Since this study shows that local conditions such as population density and climate play an important role in the sustainability of heat recovery systems, it is essential to perform a detailed location-specific analysis before deciding the optimal type of heat recovery systems for the region under consideration.

5.2 Recommendations for Future Studies

As the heat recovery systems are location-specific, it is difficult to develop a more generalized analysis for these systems. Future studies on the sustainability of heat recovery systems should consider the effects of other external factors such as the presence of vegetation above the underground pipelines, the climatic conditions like cloud cover and rainfall. The presence of vegetation will affect the heat transfer between the soil surface and the atmosphere. Heat is lost to the atmosphere by the latent heat of vaporization as water evaporates from the plant surface. Plants will also affect the amount of solar radiation reaching the soil surface.
In this study, the scenario 4 representing a region with low population density was designed to include just one DWHRS installed per house, while the houses in rural areas with low population density might be bigger with two or more bathrooms. There might be a need for the installation if additional heat exchangers to enable heat recovery in all bathrooms. Another alternative is to connect the drain water from all bathrooms to a single heat exchanger. In both cases the initial investment to install the DWHRS increases, thus affecting the economic and environmental analysis. This aspect requires further investigation.

This study assumed that there was no heat loss in the pipelines in the DWHRS. In reality, there is some heat loss, which can be included in future studies. The effect of impurities present in water might affect the heat transfer rate and needs to be investigated in detail. The impurities present in the drain water might cause fouling of the pipelines in the heat exchanger, thus affecting the efficiency of heat recovery. The incorporation of the DWHRS in a new house is fairly easy compared to retrofitting the piping in a built house. Retrofitting requires re-piping of the drain water pipelines and the incoming cold-water pipelines, which might pose a challenge. Further investigation into the feasibility of installing a DWHRS while retrofitting is needed to evaluate the additional expenses and the environmental impacts.

Also, similar studies on large-scale heat recovery systems can be performed and compared with the small- and medium-scale systems. Additionally, the sustainability of heat recovery system can be compared with that of other resource recovery systems from wastewater. Using a similar method as in this study together with the use of spatial data, a map indicating locations with beneficial implementation of resource recovery systems can be created. The map
can include the system scale and system type that is beneficial at each location. Such maps would help consumers and investors to decide on the type of recovery system that would be most beneficial for them.
REFERENCES


Harris, H. B. (1965). Ground-water resources of La Salle and McMullen counties, Texas. Austin, TX.


New York City Department of Environmental Protection. (n.d.). City water tunnel no. 3.


APPENDIX A: NOMENCLATURE

\( \alpha_{wc} \) thermal diffusion coefficient of cold water (m\(^2\)/s)

\( a \) albedo of the ground surface (-)

\( A \) area of heat transfer in heat exchanger in DWHR system (m\(^2\))

\( C_D \) friction drag coefficient (-)

\( C_e \) electricity cost ($/kWh)

\( C_{p,a} \) specific heat capacity of air (J/kg K)

\( C_{p,s} \) specific heat capacity of soil (J/kg K)

\( C_{p,wc} \) specific heat of cold water (J/kg K)

\( C_{p,wh} \) specific heat of hot water (J/kg K)

\( C_{p,wp} \) specific heat of preheated water (J/kg K)

\( \Delta z \) thickness of the top soil layer (m)

\( D \) number of inhabitants per house

\( \varepsilon_{\text{eff}} \) effective or apparent emissivity (-)

\( E_c \) electricity consumption in the DWHRS (kWh/day)

\( E_{cb} \) electricity consumption in the baseline system (kWh/day)

\( f_h \) factor associated with the surface roughness and atmospheric stability (-)

\( h_{\text{ARL}} \) height of the atmospheric roughness layer (m)

\( \text{Inv}_y \) investment for year \( y \) ($)
\( \lambda_r \) \( \lambda_{wc} / 10 \lambda_{pw} \) (W/m K)

\( \lambda_{pw} \) thermal conductivity of the pipe wall (W/m K)

\( \lambda_s \) thermal conductivity of the soil (W/m K)

\( \lambda_{wc} \) thermal conductivity of cold water (W/m K)

\( L_{E} \) latent heat flux due to evaporation (W/m²)

\( \eta \) efficiency of the electric water heater

\( \eta_{DWHR} \) efficiency of the DWHR unit

\( n \) lifetime of the DWHRS (years)

\( n_d \) number of days in the month (days/month)

\( \text{NPV} \) Net Present Value ($)

\( n_s \) number of showers per person per day (showers/person day)

\( \text{Nu} \) Nusselt number (-)

\( p \) time taken for one shower (s/shower)

\( Q \) energy to heat the vegetation (W/m²)

\( q_{wh} \) flow rate of hot water in the DWHRS (m³/s)

\( q_{wh,b} \) flow rate of hot water in baseline system (m³/s)

\( q_{he} \) flow rate of water in DWHR unit (m³/s)

\( q_{wm} \) flow rate of mixed water (m³/s)

\( \rho_a \) density of air (kg/m³)

\( \rho_s \) density of the soil (kg/m³)

\( \rho_{wc} \) density of cold water (kg/m³)

\( \rho_{wh} \) density of hot water (kg/m³)
\( Q_{wp} \) density of preheated water (kg/m³)

\( r \) inner radius of pipe in distribution mains (m)

\( R \) energy recovered from drain water (W)

\( r_d \) discount rate

\( R_g \) flux resistance associated with heat transfer from roughness layer to soil surface (s/m)

\( R_{lin} \) incoming long wave radiation (J/m²/s)

\( R_{GS\rightarrow atm} \) outgoing long wave radiation (J/m²/s)

\( R_s \) global radiation from the sun (J/m²/s)

\( R_{s, atm\rightarrow GS} \) incoming short wave radiation (J/m²/s)

\( \sigma \) Stefan-Boltzman constant (5.67 \times 10^{-8} \text{ W/m}^2 \text{ K}^4)

\( S_y \) savings in year \( y \) due to the use of the DWHRS ($/\text{year})

\( t \) residence time of water in the pipeline (s)

\( T_{ARL} \) temperature of air in the atmospheric roughness layer (K)

\( T_{atm} \) atmospheric temperature (K)

\( T_{GS} \) temperature of the soil surface (K)

\( T_{pw,o} \) temperature of the outer wall of pipe in the distribution mains (K)

\( T_s \) temperature of soil (K)

\( T_{wc} \) temperature of cold water (K)

\( T_{wh} \) temperature of hot water (K)

\( T_{wm} \) temperature of mixed water (K)

\( T_{wp} \) temperature of preheated water (K)

\( u \) wind velocity (m/s)
\( U \) overall heat transfer coefficient in heat exchanger (W/ m\(^2\) k)

\( v_{wd} \) velocity of water in the distribution mains (m/s)

\( y \) year

\( z_s \) depth of the soil (m)
## APPENDIX B: LIST OF ACRONYMS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>ARL</td>
<td>Atmospheric Roughness Layer</td>
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<tr>
<td>COP</td>
<td>Coefficient of Performance</td>
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<tr>
<td>DWHRS</td>
<td>Drain Water Heat Recovery System</td>
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<tr>
<td>GFX</td>
<td>Gravity Film Heat Exchanger</td>
</tr>
<tr>
<td>HX</td>
<td>Heat Exchanger</td>
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<tr>
<td>LCA</td>
<td>Life Cycle Assessment</td>
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<td>LCCA</td>
<td>Life Cycle Cost Analysis</td>
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<tr>
<td>LCI</td>
<td>Life Cycle Inventory</td>
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<tr>
<td>LCIA</td>
<td>Life Cycle Impact Assessment</td>
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<tr>
<td>NPV</td>
<td>Net Present Value</td>
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<tr>
<td>NTU</td>
<td>Number of Transfer Units</td>
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<tr>
<td>TRACI</td>
<td>Tool for the Reduction and Assessment of Chemical and other Environmental Impacts</td>
</tr>
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<td>WWSHP</td>
<td>Waste Water Source Heat Pump</td>
</tr>
<tr>
<td>WWTP</td>
<td>Waste Water Treatment Plant</td>
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</table>
APPENDIX C: ADDITIONAL RESULTS FOR THE LCA ON THE DWHRS

The results of the LCA on DWHRS using ReCiPe tool will be presented in this appendix section. The results obtained are similar to that evaluated by the TRACI 2 impact assessment method.
Figure A Impact assessment of the DWHRS evaluated using the ReCiPe method showing the contribution of the DWHRS life cycle stages to each indicator.