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Evaluation of the impact of integrating shower water heat exchangers into domestic water heating systems electrification

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Resumo

O impacto negativo das alterações climáticas nas civilizações tem vindo a agravar-se progressivamente. Com vista a um futuro melhor é imperativo que se reduzam as emissões dos gases de efeito de estufa.

Em Portugal, o sector residencial é responsável por 19,5% do consumo de energia, sendo cerca de 19,7% dedicados à produção de água quente sanitária (AQS). Embora os edifícios tenham feito progressos na melhoria da eficiência do aquecimento ambiente, a eficiência da produção de AQS tem recebido relativamente pouca atenção. É, portanto, imperativo implementar medidas que reduzam o consumo de energia na produção de AQS, com o objetivo de mitigar as consequências ambientais e económicas.

Neste trabalho foram analisadas as vantagens da introdução de um recuperador de calor vertical da Zypho na base do duche, de modo a aproveitar essa água para fazer um pré-aquecimento da água da rede, num sistema de AQS que usa um típico esquentador a gás, para um edíficio residencial unifamiliar com 4 pessoas, um edíficio residencial multifamiliar com 50 pessoas e um hotel 4 estrelas sem lavandaria com 200 camas.

Foram consideradas 3 diferentes configurações para o recuperador de calor: na configuração 1 a água pré-aquecida pelo recuperador de calor vai para o esquentador e para a válvula misturadora do chuveiro; na configuração 2 a água pré-aquecida pelo recuperador de calor vai apenas para a válvula misturadora do chuveiro; na configuração 3 a água pré-aquecida vai apenas para o esquentador. Foram calculadas as eficiências do permutador de calor nas 3 configurações consideradas.

Para cada configuração analisada (sem recuperação de calor e as 3 diferentes configurações com recuperação de calor), foi calculada a percentagem de água que passa no esquentador.

Para os edifícios residenciais foi escolhida a configuração 1 e para o hotel foi escolhida a configuração 2. Foram calculadas as necessidades de AQS para cada situação, e calculada a energia necessária para aquecimento da água com e sem recuperação de calor, bem como a energia final, energia primária, emissões de CO_2 e custo. Posteriormente calcularam-se as reduções nas emissões de CO_2 bem como nos custos, para as situações sem recuperador de calor e com recuperador de calor.

Foram também analisadas as vantagens de substituir o típico esquentador a gás por uma bomba de calor, mais uma vez calculando energia final, energia primária, emissões de CO_2 e custo. Foram analisadas as reduções nas emissões de CO_2 bem como os custos para as duas situações. Por fim, da mesma forma, foi analisado o impacto que a combinação da bomba de calor com um recuperador de calor tem nas emissões de CO_2 e nos custos de produção de AQS, quando comparado com um típico esquentador a gás.

Por fim conclui-se que a implementação de um recuperador de calor na base do duche apresenta uma elevada redução nas necessidades energéticas para produção de AQS, o que resulta em menores emissões de CO_2 e menores custos. A substituição do típico esquentador a gás por uma bomba de calor resulta em valores de energia final necessária bastante menores, o que mais uma vez resulta em menores emissões de CO_2 e menores custos. Finalmente, a combinação da bomba de calor com o recuperador apresenta reduções nas emissões de CO_2 que podem chegar até aos 83% e uma diminuição dos custos de produção de AQS que pode chegar até aos 91%.

Abstract

Climate change is having a detrimental effect on civilizations and has been getting worse over time. For a better future, it is imperative that greenhouse gas emissions are reduced.

In Portugal, the residential sector accounts for 19.5% of energy consumption, with approximately 19.7% of that energy dedicated to domestic hot water (DHW) production. While buildings have made progress in improving energy efficiency for space heating, little has been done to enhance the efficiency of DHW production. Thus, it is imperative to implement measures that decrease energy consumption in DHW production, aiming to reduce both the environmental and economic impacts.

In this work, the advantages of introducing a Zypho vertical heat recovery device in the shower tray were analyzed in order to use the shower water to pre-heat the mains water in a DHW system that uses a typical gas water heater, for a single-family residential building with 4 people, a multi-family residential building with 50 people and a 4-star hotel without laundry with 200 beds.

Three different configurations for the heat recovery unit were considered: in configuration 1, the water preheated by the heat exchanger goes to the water heater and to the shower mixer valve; in configuration 2, the water preheated by the heat exchanger goes only to the shower mixer valve; and in configuration 3, the preheated water goes only to the water heater. Heat exchanger efficiencies were calculated for the 3 configurations considered.

For each configuration analyzed (without heat recovery and the 3 different configurations with heat recovery), the percentage of water passing through the water heater was calculated.

For the residential buildings, configuration 1 was chosen and for the hotel, configuration 2 was chosen. The DHW needs for each situation were calculated, and the energy required for water heating with and without heat recovery was calculated, as well as the final energy, primary energy, CO_2 emissions and cost. Subsequently, the reductions in CO_2 emissions and costs were calculated for the situations without heat recovery and with heat recovery.

The advantages of replacing the typical gas water heater with a heat pump were also analyzed, again calculating final energy, primary energy, CO_2 emissions and cost. The reductions in CO_2 emissions were analyzed as well as the costs for the two situations. Finally, in the same way, the impact that the combination of the heat pump with a heat recovery unit has on the CO_2 emissions and on the costs of DHW production, when compared to a typical gas heater, was analyzed.

Finally, it is concluded that the implementation of a heat recovery unit at the base of the shower presents a significant reduction in the energy needs for DHW production, which results in lower CO_2 emissions and lower costs. Replacing the typical gas water heater with a heat pump water heater results in much lower final energy requirements, which again results in lower CO_2 emissions and lower costs. Lastly, the combination of a heat pump water heater and heat recovery results in reductions in CO_2 emissions of up to 83% and a decrease in DHW production costs of up to 91%.

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I would like to take this opportunity to express my deepest gratitude to all those who have played a pivotal role in my academic journey and the completion of this thesis. Without your unwavering support, this accomplishment would not have been possible.

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Thank you all sincerely.

Gabriela

"Progress is impossible without change,
and those who cannot change their minds cannot change anything."

George Bernard Shaw

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Nomenclature

Roman symbols

C	Heat capacity rate	$[W/K]$
c_p	Specific heat at constant pressure	$[J/(kg \cdot K)]$
E_{final}	Final energy	$[J]$
$E_{primary}$	Primary energy	$[J]$
E_{useful}	Useful energy	$[J]$
$\dot{m}$	Mass flow rate	$[kg/s]$
$\dot{m}_{water\ heater}$	Mass flow rate that passes through the water heater	[%]
T	Temperature	[°C]
V	Volume	$[m^3]$
$\dot{V}$	Volumetric flow rate	$[m^3/s]$
Q	Heat	$[J]$
$\dot{Q}$	Heat rate	$[W]$

Greek symbols

ρ	Density	$[kg/m^3]$
ε	Efficiency	[%]

Acronyms

AAHP	Air-to-Air Heat Pump
ASHP	Air Source Heat Pump
AWHP	Air-to-Water Heat Pump
COP	Coefficient Of Performance
CPC	Compound Parabolic Collector
DHW	Domestic Hot Water
EAHP	Exhaust Air Heat Pump
ETC	Evacuated Tube Collector
FPC	Flat Plate Collector
GSHP	Ground Source Heat Pump
HP	Heat Pump
HPWP	Heat Pump Water Heater
ICS	Integral Collector Storage
IEA	International Energy Agency
IGWH	Instantaneous Gas Water Heater
PTC	Parabolic Trough Collector
SAHP	Solar Assisted Heat Pumps
SWH	Solar Water Heating
SWHRU	Shower Water Heat Recovery Unit
WSHP	Water Source Heat Pump

Subscripts

avail	Available
cold	Water from the mains
cold,in	Water from the mains
cold,mix	Water the enter the cold side of the shower mixing valve
cold,out	Water that comes out of the heat exchanger after being pre-heated
hot	Water that passes through the hot side of the heat exchanger
hot,in	Water that enters the hot side of the heat exchanger
shower	Water that comes out of the shower
source	Water that comes out of the water heater

1. Introduction

The combustion of fossil fuels is responsible for the emission of greenhouse gases, primarily carbon dioxide (CO_2), which contributes to climate change. These gases trap the sun's heat, which causes the planet's temperature to rise. For decades, there has been a consistent high proportion of fossil fuels in the global energy mix, hovering around 80% [1]. Given the current context of climate change, it is imperative to seek new solutions that seek to mitigate the impact of the massive use of fossil fuels.

The International Energy Agency (IEA) reported that in 2021, the buildings sector contributed to 30% of the total global final energy consumption and 15% of the total CO_2 emissions from end-use sectors. However, when indirect emissions from electricity and heat production are taken into account, this last percentage doubles [1]. Therefore, increasing building efficiency is recognized as a crucial strategy to address ongoing and future energy and environmental problems.

By observing an example of an energy Sankey diagram in Figure 1, we can see that only a small portion of primary energy actually becomes useful energy. From primary energy to final energy, there are losses associated with transformation, transport, and distribution. From final to useful energy, there is a significant amount of energy that is lost in usage. This results in less than 50% of primary energy actually being useful.

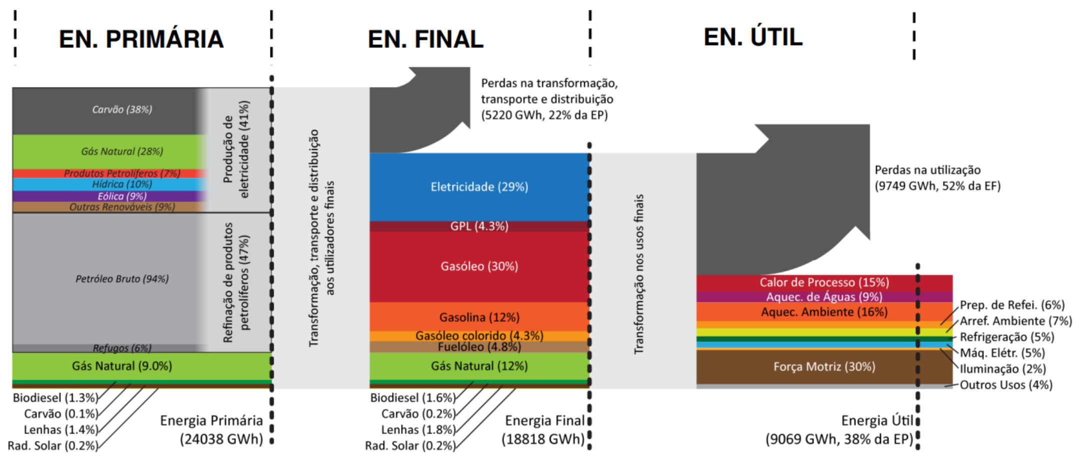


Figure 1: Estimated Sankey diagram of Energy for the AMP-N in 2009 [2].

In regions with cold winter climates, a substantial amount of energy consumed by the building sector is attributed to heating. Among the various sources of thermal energy usage, space heating holds a significant portion, but this can be effectively diminished by improving the thermal efficiency of both building envelopes and heating/ventilation systems. Consequently, national building regulations have been strengthened with the aim of achieving this goal. Presently, newly constructed and renovated buildings are mandated to comply with nearly Zero Energy Building standards, leading to a noteworthy decrease in space heating demands. In recent decades, there has been a consistent decline in energy consumption for space heating in buildings. However, the demand for energy in producing domestic hot water (DHW) has remained relatively steady, as exemplified by Portugal, where DHW energy consumption was 583,040 tep in 2010 and 562,599 tep in 2020. Consequently, the proportion of energy consumed by DHW in the overall energy balance of buildings is progressively gaining significance. With the tightening of building regulations concerning the efficiency of indoor space conditioning, while the energy demand for domestic hot water is being overlooked, it is likely that the share of energy dedicated to DHW will continue to rise globally. Moreover, the population, particularly in developed countries, has undergone shifts in practices and preferences related to DHW. Nowadays, individuals prioritize enhanced hygiene and greater comfort, leading to longer showers and baths, while also expecting minimal waiting times for hot water at the tap. As a result, both developed and developing nations exhibit a tendency to increase their annual consumption of DHW per capita [3].

Bearing in mind these demographic trends, it is thus evident that there is a need to improve the efficiency and operation of DHW systems.

Energy poverty is a term that refers to the lack of access to modern energy services by people or groups. This is a condition that affects people from different nations, whether developed or not. Lack of access to electricity can lead to problems such as excessive cold/heat inside the home, difficulties in basic nutrition, among others. In the data released on January 6, 2020 by Eurostat, Portugal is the fifth country in the European Union where people have the least economic conditions to keep their homes properly heated, with about 19% of the Portuguese being in energy poverty. Below Portugal are countries such as Bulgaria (34%), Lithuania (28%), Greece (23%) and Cyprus (22%) [4].

Considering a significant part of building energy use is associated with domestic hot water, thermal recovery of part of the waste heat from showers can significantly reduce the heat required for heating sanitary water. This also results in less energy waste.

1.1 Portugal's Energy Consumption Data

The Energy Balance 2020 data reveals that in Portugal, after the transport (32.7%) and industry (31.1%) sectors, the residential sector is the third largest consumer of energy (19.5%), followed by services (13.5%) and finally agriculture and fisheries (3.3%). However, it's worth noting that the Energy Balance doesn't factor in fuel consumption for vehicles used by residents for personal transport from their homes. This information is reflected in Figure 2.

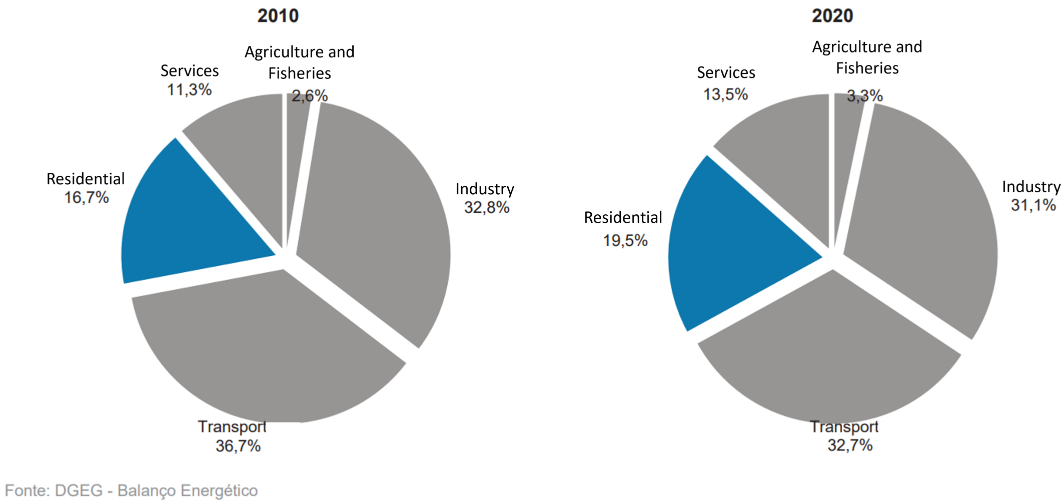


Figure 2: Breakdown of final energy consumption by sector, 2010 and 2020 [5].

Regarding energy consumption in housing, we can see in Figure 3 that in 2020, the largest share of energy was allocated to cooking, which accounted for 34.6% of the total energy consumption. This was followed by space heating, accounting for 23.2% of consumption, electrical equipment at 19.9%, and water heating at 19.7%. Conversely, the lowest energy consumption in households was in space cooling, which accounted for 1.0%, and lighting, which accounted for 1.6%.

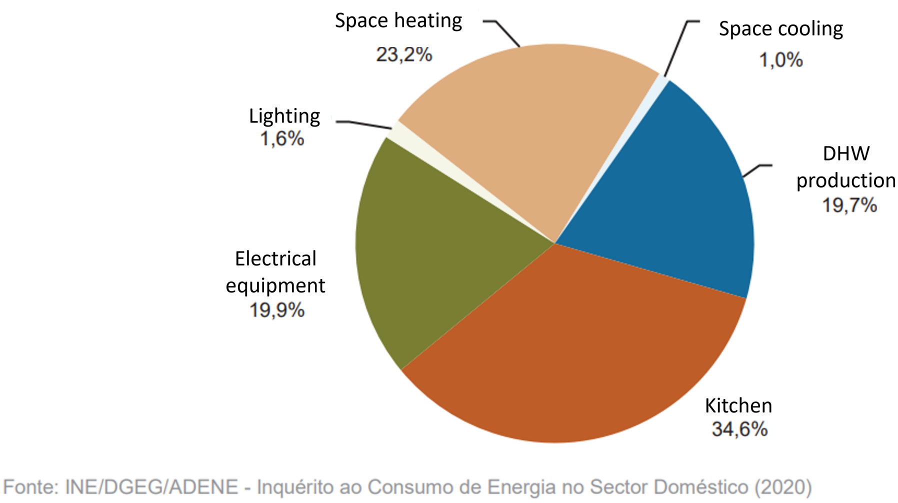
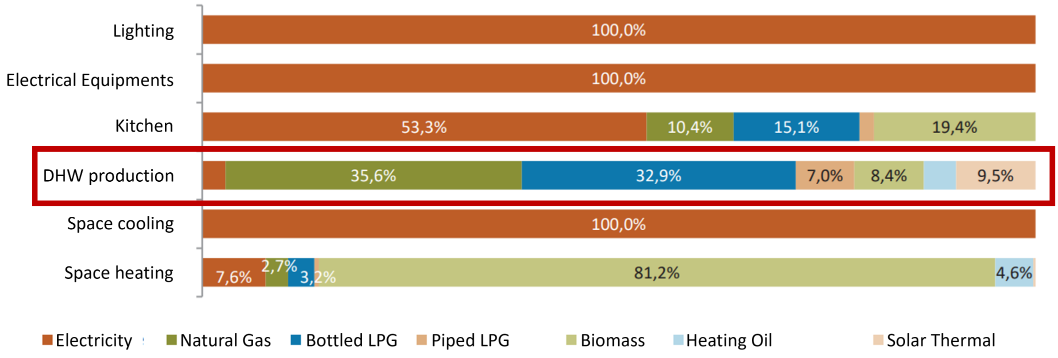


Figure 3: Distribution of energy consumption in housing by type of use - Portugal, 2020 [5].

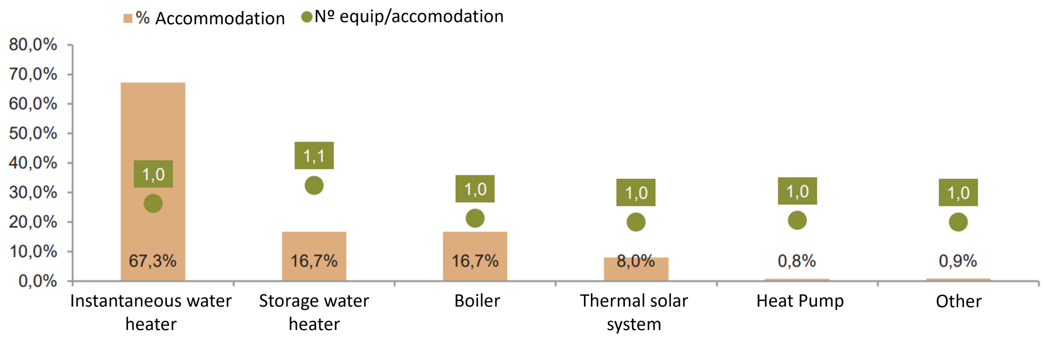
In Figure 4, it is shown that water heating was mainly provided by gas (natural gas and LPG) as an energy source. Natural gas made up 35.6% of the total consumption for this purpose, followed by bottled LPG at 32.9% and piped LPG at 7.0%. Biomass represents 8.4% and solar thermal 9.5%.



Fonte: INE/DGEG/ADENE - Inquérito ao Consumo de Energia no Sector Doméstico (2020)

Figure 4: Distribution of energy consumption in housing by type of use and type of energy source - Portugal, 2020 [5].

In 2020, for DHW production, instantaneous water heaters were mainly used, present in 67.3% of households (78.6% in 2010). On average, each household had only one of these type of equipment. These were followed by storage water heaters and boilers, which were used in 16.7% of the accommodations (same share for both equipment). Regarding the use of boilers, it's worth noting that 60.4% of the households that use them have them connected to the central heating system, while the remaining 39.6% have independent boilers for water heating. Solar thermal systems accounted for 8.0% in all households, indicating a growth in usage over the past decade (only 1.8% in 2010). Although this equipment can be used for space heating as well (which requires a larger installation area), its primary application has been for heating water. Heat pumps for water heating are not widely used across the country, with only 0.8% of dwellings reporting their use. The exception to this is the Autonomous Region of the Azores, where 2.6% of dwellings reported using this technology for water heating. This information is shown in Figure 5.



Fonte: INE/DGEG/ADENE - Inquérito ao Consumo de Energia no Sector Doméstico (2020)

Figure 5: Dwellings by type of equipment used for DHW production and average number of equipment per dwelling - Portugal, 2020 [5].

1.2 Objectives

This work is focused on the implementation of a waste water heat recovery device at the base of the shower.

It is intended to develop a simplified numerical model of the existing shower water heat recovery unit and a methodology for estimating domestic hot water needs for the residential and hotel sectors.

It also pretended to model the impact of introducing heat recovery on the energy needs of two residential buildings and one hotel and do the analysis of heat pump operational gains when pre-heating mains water with Zypho's heat recuperators.

Finally, it is intended to assess the overall energy efficiency increase of the DHW system associated with the different integration modes of the shower water heat recovery system and estimate the reduction in energy needs of two residential buildings and one hotel with the use of the shower water heaters and the impact on heat pump efficiency in DHW supply.

1.3 Structure

This dissertation is divided into 6 chapters, this one included, where the relevant data and the main objectives of this work are presented.

Chapter 2 presents the literature review, which explains DHW systems, distinguishes centralized systems from decentralized systems, and presents the different types of DHW systems.

In Chapter 3, the methodology adopted in this work is presented, where every step taken and tool used is explained.

The results obtained are presented in Chapter 4, where a brief analysis of the results is also made.

Chapter 5 draws conclusions about the work developed and describes future work that could potentially be interesting.

2. Literature Review

2.1 Domestic Hot Water Systems

Domestic hot water (DHW) is used by millions of people each day, mostly for health reasons. Fresh, potable water must first be heated by a heating source. Burning fossil fuels, natural gas, biomass, electricity, district heating, or, even better, connecting to renewable energy sources like solar panels are just a few of the technologies that are currently available to do this [6].

Three categories of DHW-related energy use can be identified:

- End use: energy used to heat the new, cold water so it will be hot when it reaches the draw-off points;
- Distribution: pressure and heat losses associated with the distribution and circulation of the hot water in the pipes;
- Storage/conversion: heat loss related to hot water storage tank or exchanger [3].

The energy used for DHW currently makes up between 15 and 40% of the total energy required in households (in Portugal, as seen in Figure 3, it is 19.7%). This percentage is expected to rise as the amount of energy used for space heating continues to decrease.

2.2 Centralized vs Decentralized DHW Systems

2.2.1 With Storage

There is generally hot water storage regardless of the heating source, allowing the system to give the right water supply in terms of temperature and flow [6].

A storage tank for hot water is associated with high heat losses, thus needing to be well insulated. With a storage tank, there is usually the need for distribution/circulation to guarantee the hot water reaches the draw-off points, which means that there will be heat losses not only in the tank but also in the distribution and circulation of the hot water [3]. For thermal disinfection of legionella and other pathogenic germs, hot-water generation needs to be at least 55°C [7]. This temperature is higher than is necessary at the draw-off points and results in higher heat losses. To avoid this high temperature, instantaneous DHW production without any storage can be a solution to the legionella problem.

Storage tanks contain various important elements. There is a drain valve at the bottom of the tank that can be opened when sediments start to build up, flushing them out. The anode rod holds significant importance within a conventional water heater as it serves a crucial role in safeguarding the tank against corrosion and rust formation. It runs down the middle of the tank and is a steel wire that has been wrapped in aluminium, aluminium/zinc alloy, or magnesium. Its goal is to deplete itself so that the tank can be maintained. As the anode rod gradually deteriorates, it releases electrons into the water heater tank, effectively slowing down or even preventing corrosion within the tank. Thus, its lifespan is frequently much lower than that of the water heater itself. Because of this, it must be periodically inspected and, if needed, replaced [8]. For safety reasons, there is a temperature and pressure relief valve. If, for some reason, the water heater keeps continuously heating the water without stopping, eventually the water will start to boil and it will create steam. The valve has a spring, and with enough pressure, it will open and allow the steam and water to leave the tank.

The supply of cold water is commonly at the top of the water tank, which usually has a dip tube connected that takes the cold water to the bottom of the tank. As the water heats up, it will go up and leave the tank through a tube that connects the hot water tank to the draw-off points. This way, the hottest water is always at the top.

DHW systems with storage are usually centralized, serving the entire building or various apartments. In a central system, domestic hot water is generated either through a central heat exchanger or a central hot water storage tank. From there, the DHW is distributed to the various draw-off points throughout the building. An example of this type of system is shown in Figure 6. Most often, distribution systems also have circulation to reduce the waiting time for hot water [3].

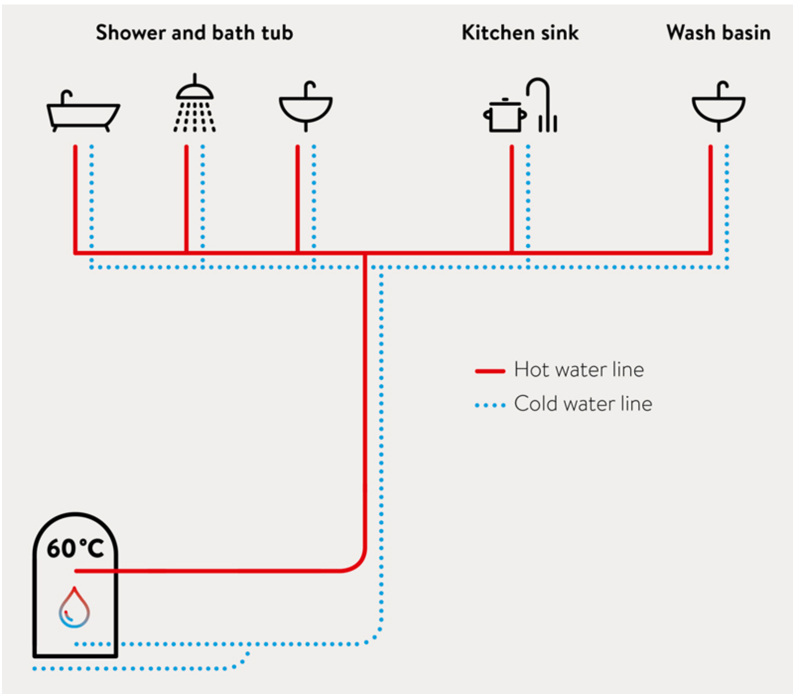


Figure 6: Centralized system [9].

2.2.2 Without Storage

On-demand water heater systems, also known as tankless or instantaneous, have no anode and virtually no hot water storage and eliminate standby losses, which can account for up to 50% of the energy required by storage systems. According to the DOE, depending on average daily water use, using electric, centralized on-demand systems can result in energy savings between 8 and 34% compared to electric tank storage units, and using a point-of-use demand system can reduce energy use by 27 to 50% [10].

These types of water heaters can be used in centralized or decentralized systems. While both systems operate similarly, there are significant differences between them in terms of their benefits, drawbacks, energy consumption, and public health issues.

In centralized systems, a large central demand system would be installed somewhere in the home, and a hot water delivery system would then be responsible for distributing the heated water to various draw-off points throughout the building. By employing heat exchange coils instead of a storage tank, storage-type system losses due to standby heat dissipation would be eliminated. However, with this type of system, the heat losses through the pipe network would still need to be taken into account [10].

Decentralized systems use more compact tankless units that are located right at the draw-off points. These systems either offer small multiple point use (all faucets in a particular bathroom, including the sink and shower/tub) or single-source use (one shower/tub). An example of this type of system is shown in Figure 7. With this type of system, the hot water doesn't need to "travel" to the draw-off points, thus eliminating both standby losses from the storage tank as well as pipe losses through the network [10].

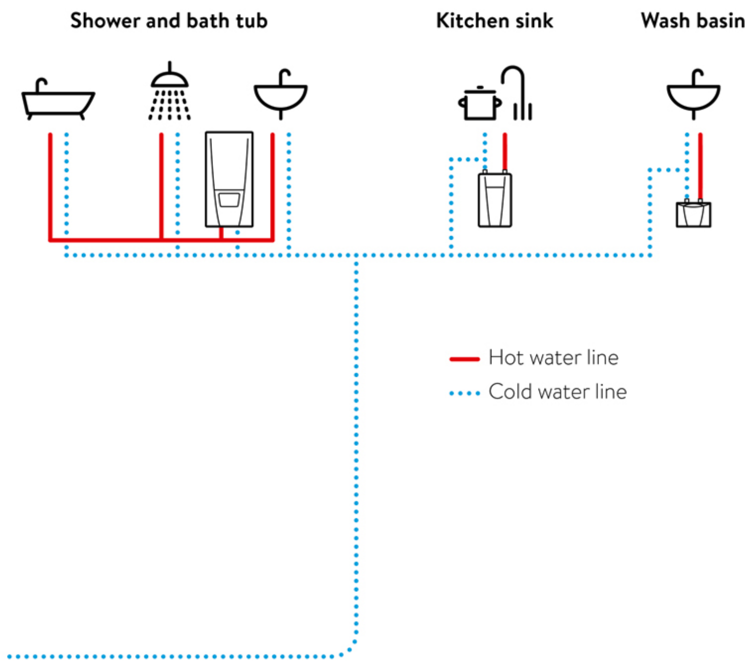


Figure 7: Decentralized system [9].

Decentralized heaters are viewed as hygienically safe since they allow for small pipe volumes (no circulation is needed). Decentralized systems are thought to have a lower risk of Legionella contamination because hot water is directly produced from fresh cold water by employing an indirect heat exchanger [7].

Instantaneous water heaters come with several disadvantages, such as elevated costs, high peak energy consumption, limited flow capacity, temperature fluctuations at different tap distances, and an increased risk of scalding near the heater. However, these water heaters overcome the need for tank heating by employing heat exchange coils, which heat the water to a predefined temperature only when required. When cold water enters the unit from the distribution line, an electric element or gas burner is activated to heat the water to the desired temperature [10].

2.3 Types of DHW Systems

2.3.1 Electric Water Heater

As the name indicates, an electric water heater heats fresh cold water by means of electricity. An example of a typical electric water heater is shown in Figure 8.

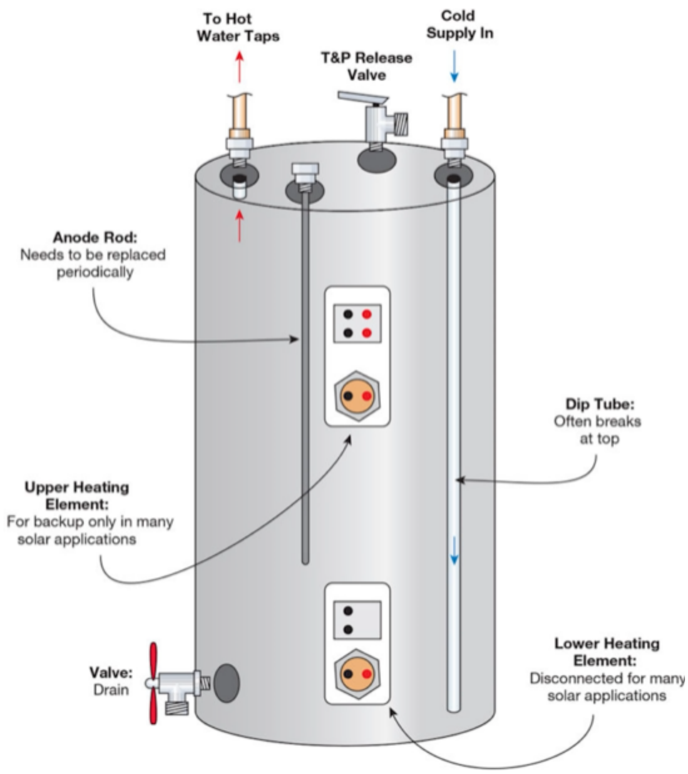


Figure 8: Example of a typical electric water heater [11].

This type of system employs a storage tank, as described in section 2.2.1, with two electric heating elements. The upper and lower heating elements don't work at the same time. The upper element is turned on first, and after it has heated up, the bottom element is turned on. If the water reaches a determined limit temperature (usually meaning there is something wrong), the reset button pops, shutting the heater down. The thermostats represented in Figure 9 determine when each of the heating elements will turn on and off.

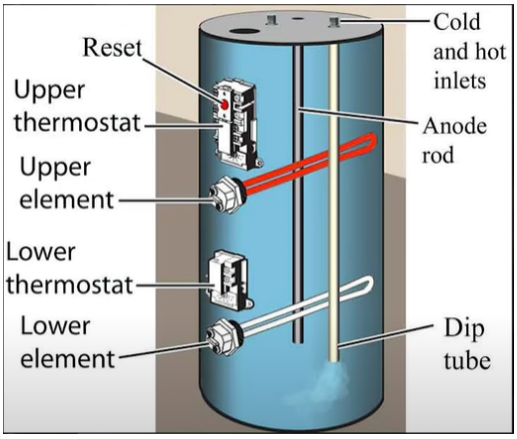
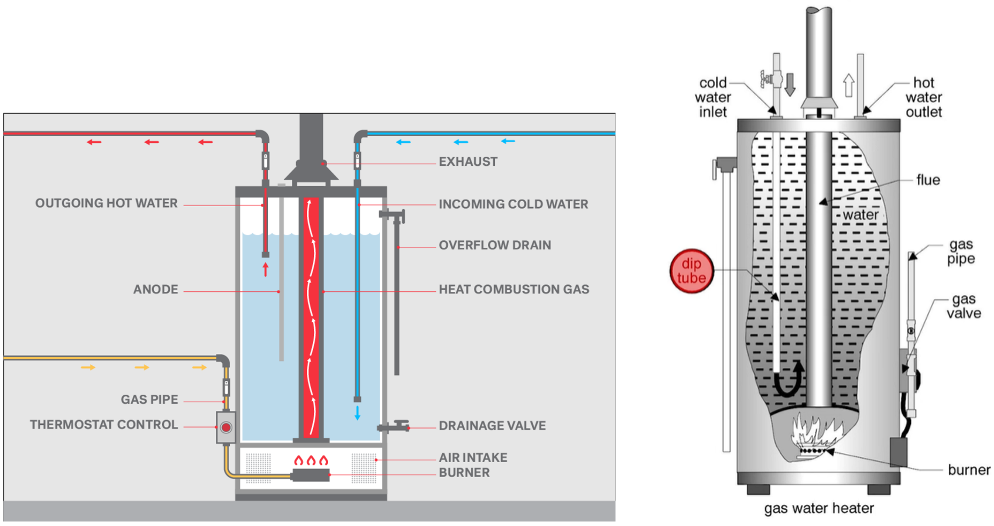


Figure 9: Typical heating elements in an electric water heater [11].

2.3.2 Gas Water Heater

A gas water heater employs a storage tank, similarly to an electric water heater. Instead of the electric heating elements, we now have a flue, a burner, a gas pipe, and a gas valve. These new elements can be seen in Figure 10.



(a) Gas water heater [12]. (b) Gas water heater, cutaway view [13].

Figure 10: Typical gas water heaters.

In a typical gas water heater, gas is burned to heat the water that is stored within an insulated tank. As hot water is utilized, cold water enters the tank through a dip tube and fills the bottom of the tank. The gas valve, equipped with a built-in thermostat, continuously monitors the water temperature. When the thermostat detects that the water has cooled down, it opens the main gas valve. Air is drawn in from below the tank and mixes with the gas. Subsequently, the main burner ignites, and the resulting exhaust gases are expelled through the flue vent. The burner continues to heat the water until the desired temperature is reached.

2.3.2.1 Standing Pilot Heaters

Most older homes will feature a standing pilot water heater with an atmospheric vent. They use a small pilot flame that burns continuously, igniting the main burner when heat is needed. These heaters must be vented vertically.

Standing pilot water heaters will either use a conventional or an electronic gas valve.

2.3.2.2 Power Vent Water Heaters

Unlike standing pilot heaters, power vent water heaters, shown in Figure 11, don't rely on atmospheric pressure. Instead, they use a draft inducer blower to push the exhaust through the vent.

When the thermostat detects cold water, the draft inducer pulls fresh air into the burner. The pressure switch then verifies that there's enough airflow for combustion. Next the hot surface ignitor heats up and ignites the burner and the flame sensor monitors the burner to confirm that there is a flame. The burner runs until the water in the tank reaches the set temperature. After the burner shuts off, the inducer will stay on for several minutes to purge the system of exhaust gases.

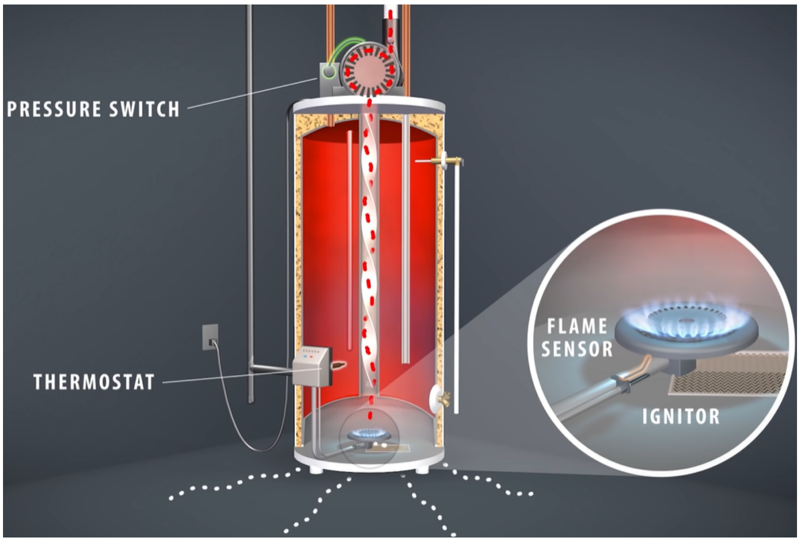


Figure 11: Power vent water heater [14].

2.3.3 Solar Water Heaters

Solar water heating (SWH) is a clean, dependable, and economical way of harnessing solar energy effectively to provide 50-80% of hot water needs. SWH systems may function effectively in any geographic location and climatic zone in the world, but there are still concerns about the system's installation and overall effectiveness. They are one of the best examples of solar thermal collectors in renewable energy technologies and have been getting a lot of attention due to their low cost, low impact on global warming, and longevity [15].

The combination of solar thermal collectors and heat pumps is a more robust technology known as solar-assisted heat pumps (SAHP). SAHP offers improved system performance and reduced electrical energy consumption. However, one of the primary challenges associated with direct SAHP implementation is the long-term maintenance costs [15].

2.3.3.1 Types of SWH Systems

Solar Water Heaters convert solar energy into thermal energy. The main components in SHW systems are solar thermal collectors and hot water storage tanks. These systems can be divided into two types: Active SWH system and Passive SWH system.

Active SWH systems

Active SWH systems have circulating pumps as well as additional parts like valves and electronic controllers. They convert solar energy into thermal energy and have an efficiency of 35-80% [15].

There are two types of active solar water heating systems:

- **Direct circulation system:** Water is used as a heat transfer fluid and flows directly into the collector. The direct circulation system's primary drawback lies in the vulnerability of the heat transfer fluid to freezing. However, since the water is heated directly and intended for domestic use, there is no need to incorporate antifreeze solutions or heat exchangers into the system [15, 16].
- **Indirect circulation system:** Pumps are employed to circulate a heat-transfer fluid through the collectors and a heat exchanger. This process effectively heats the water, which subsequently flows into the home. In order to prevent freeze damage, antifreeze solutions can be utilized as circulation fluid [15, 16]. The indirect circulation system using antifreeze heat transfer fluid is shown in Figure 12.

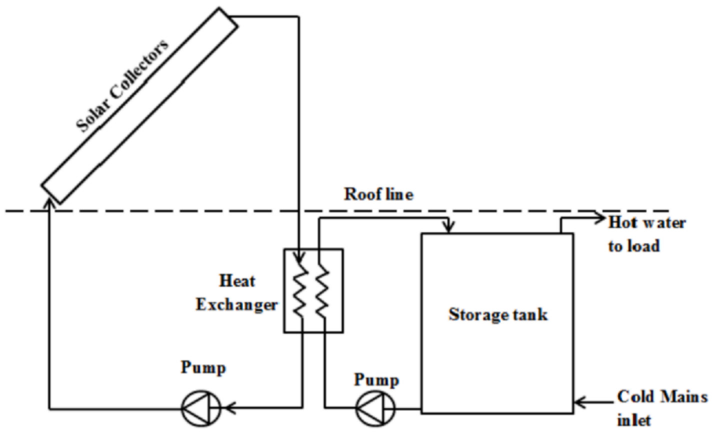


Figure 12: Schematic diagram of indirect circulation system [15].

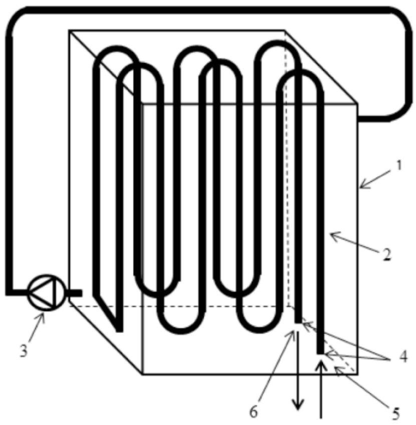
Passive SHW system

A passive SWH system doesn't need any external sources or pumps. These systems are different from other system types in that heat is generated through natural convection. Furthermore, these systems rely on solar radiation and water pressure to work. Passive SWH systems are usually less expensive than active systems, although they are frequently less effective, with an efficiency of 30-50% [15, 16].

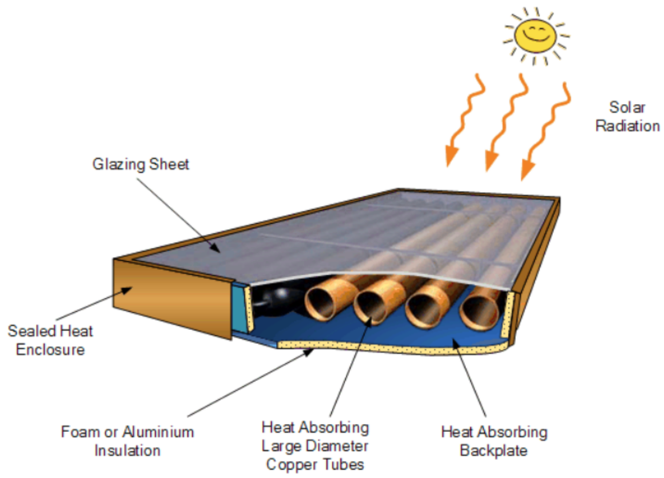
There are two types of passive SWH systems:

- **Integral collector storage (ICS) system:** In these systems, the water is preheated before it enters a traditional water heater. It consists of a tank and tubes that serve as the solar collector and storage in a glass-enclosed, insulated box. They are mainly used in warm climates, given the high heat losses that can occur, especially at night [17].

  A schematic diagram of an ICS system and a typical ICS system are shown in Figure 13.



(a) Schematic diagram of ICS (1) storage tank, (2) heat exchanger, (3) pump, (4) flow sensors, (5) water inlet and (6) water outlet [15].



(b) Typical ICS system [18].

Figure 13: ICS systems.

- **Thermosyphon systems:** When a fluid is heated, its density decreases, which means it will rise. These systems work based on that principle. They are commonly used in an open-loop system for nonfreezing climates, where potable water enters the bottom of the collector and gets heated, rising to the tank [19].

  The primary benefits of this type of system include simple installation, high efficiency, immunity to power outages, and because it is a passive system, the lack of need for external sources to pump heat through the pipes.

  A diagram of a typical thermosyphon system is shown in Figure 14. Typical collector configurations include flat plate or evacuated tube collectors. This topic is further explored in section 2.3.3.2.

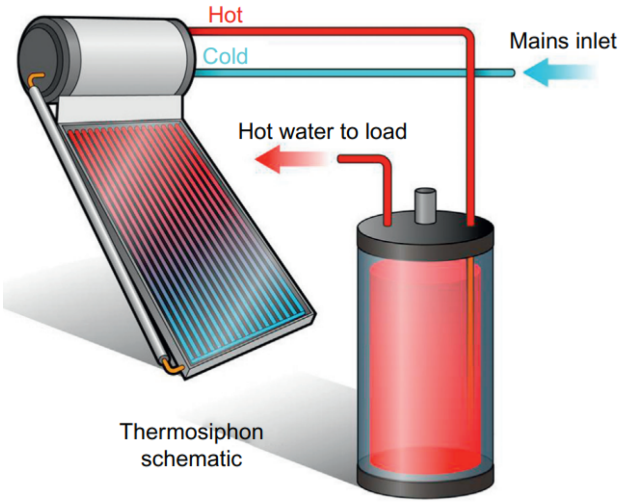


Figure 14: Diagram of a thermosyphon system [17].

2.3.3.2 Types of Solar Collectors

The main element of all solar systems is the solar collector, which is a device that absorbs solar radiation and converts it into heat, transferring this heat to a fluid flowing through the collector (usually water, air, or oil). The solar energy captured is conveyed from the circulating fluid either directly to the hot water or space conditioning equipment, or it is directed to a thermal energy storage tank. This storage tank allows the captured energy to be utilized during nighttime or on cloudy days when solar energy generation is limited [20].

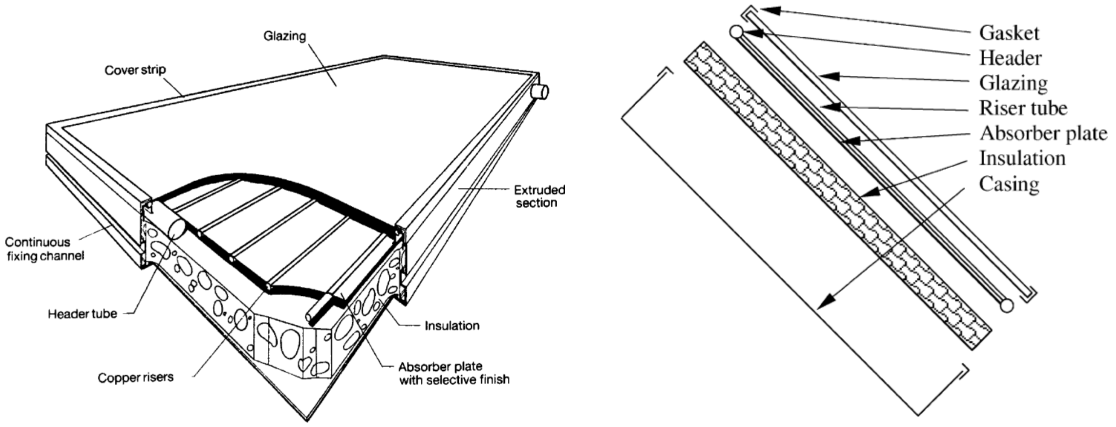
Solar collectors are categorized into two main types: non-concentrating collectors and concentrating collectors. They are also differentiated based on their motion: stationary, single-axis tracking, two-axis tracking, or operating temperature. Non-concentrating collectors are permanently fixed in one specific position and do not track the sun [15].

Non-concentrating

A non-concentrating collector has the same area for capturing and absorbing solar radiation. On the other hand, concentrating solar collectors, which are designed to track the sun's movement, often feature concave reflecting surfaces. These surfaces are utilized to capture and concentrate the sun's beam radiation onto a smaller receiving area, resulting in an amplified radiation flux [20].

- **Flat plate collector (FPC):** A typical flat plate collector is shown in Figure 15. FPCs are typically permanently fixed. As solar radiation passes through a transparent cover and reaches the blackened surface with high absorption properties, a significant amount of this energy is absorbed by the plate and then transferred to the transport medium in the fluid tubes to be transported for storage or use [20].

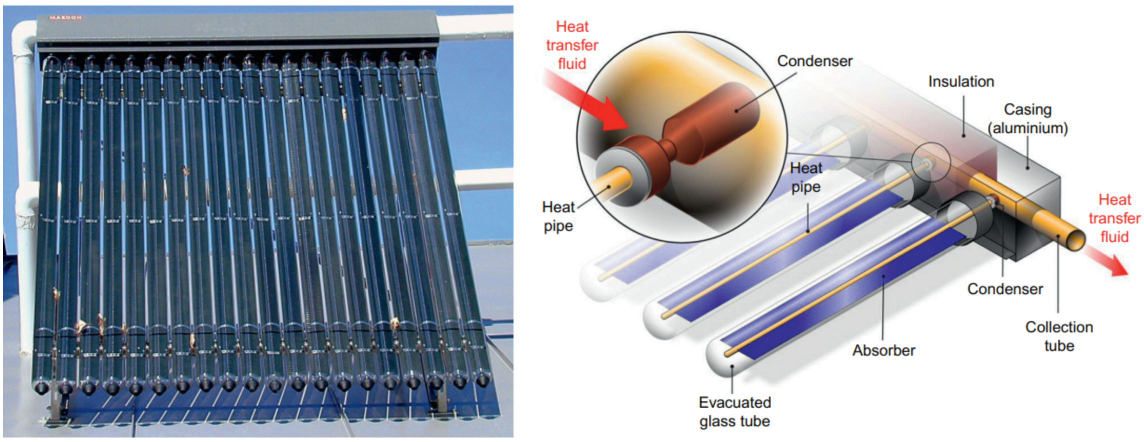
  Traditional flat-plate solar collectors were created to be used in warm, sunny climates. However, their advantages are significantly diminished when weather conditions are unfavorable, such as on cold, cloudy, and windy days. Furthermore, weathering elements such as condensation and moisture can accelerate the degradation of internal materials. This deterioration can have adverse effects on the system's performance, ultimately leading to system failure.



(a) (b)

Figure 15: Flat plate collector. (a) Pictorial view [20]. (b) Exploded view [20].

- **Evacuated tube collector (ETC):** A typical ETC and its components is shown in Figure 16. Traditionally, they are made of parallel rows of identical glass tubes, each featuring a metal heat pipe connected to an absorber fin. In order to form a vacuum, the air between the two glasses is evacuated, which results in lower convective and conductive losses. They can reach temperatures higher than 200°C [17]. They also absorb both direct and diffuse radiation, like FPCs, but have a higher efficiency for low incidence angles, which means ETCs usually outperform FPCs throughout the day [20].



(a) (b)

Figure 16: Evacuated tube collector. (a) Typical ETC [17]. (b) Components of an ETC [17].

Concentrating

Energy delivery temperatures can be raised by reducing the area where heat is lost. If a significant amount of solar radiation is focused on a relatively small collection area, temperatures that are significantly higher than those that are possible with FPC can be reached. This is accomplished by placing an optical device in front of the energy-absorbing surface.

Comparing concentrating collectors to the traditional flat-plate type reveals some advantages: higher temperatures; higher thermal efficiency; simpler than FPC; lower cost per unit area.

The disadvantages of these collectors are that they: collect little diffuse radiation; usually need a sun tracking system; may loose reflectance over time and require periodic cleaning and refurbishing [20].

There are various types of concentrating collectors, the most known being:

- **Compound parabolic collectors (CPC):** CPCs are non-imaging concentrators. With these collectors, all of the incident radiation can be reflected, within certain bounds, to the absorber. The use of a trough with two parabola sections facing each other, as seen in Figure 17, reduces the need to move the concentrator to account for the shifting solar orientation. They have the ability to capture radiation from a wide range of angles. Any radiation that enters through the aperture and falls within the collector's acceptance angle is guided towards the absorber surface located at the bottom of the collector. This is achieved through multiple internal reflections. The absorber can take different configurations: it can be cylindrical, as in Figure 17, or flat [20].

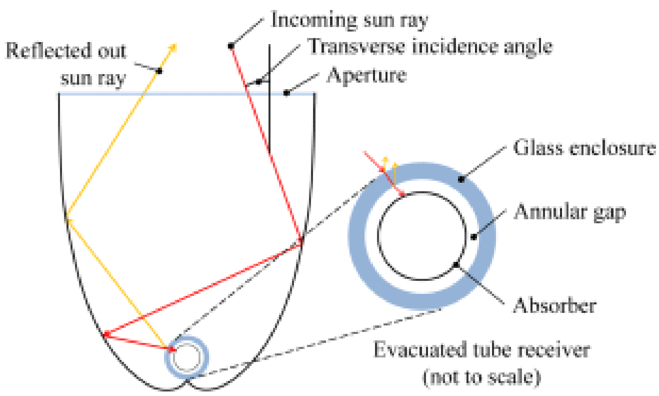


Figure 17: Schematic diagram of a compound parabolic collector [21].

- **Parabolic trough collectors (PTC):** PTCs consist of a sheet of reflective material bent into a parabolic shape and a black metal tube along the receiver's focal line, protected from heat loss by a glass tube. When the parabola is facing the sun, parallel rays incident on the reflector are reflected onto the receiver tube. A single-axis tracking of the sun is sufficient, and therefore long collector modules are produced. They can effectively generate heat between 50 and 400°C [20]. A schematic of a parabolic trough collector is shown in Figure 18.

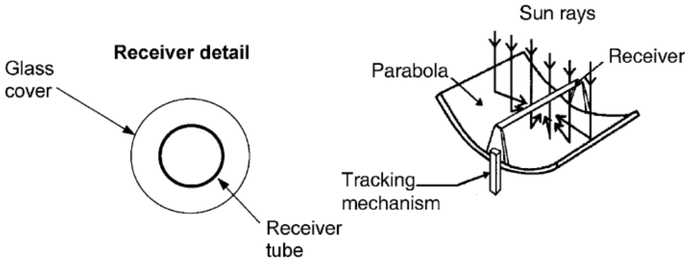


Figure 18: Schematic of a parabolic trough collector [20].

2.3.4 Heat Pump Water Heater

Heat pumps are often used by homeowners to heat and cool their houses. However, a heat pump may also be employed to heat water, either as a stand-alone water heating system or as a combination water heating and space conditioning system [22].

Heat pump water heaters (HPWH) are a promising technology that operate on an electrically powered vapor-compression cycle and on the same mechanical tenets as refrigerators and air conditioners. Refrigerators work by extracting heat from their interior and releasing it into the surrounding environment, typically the kitchen. In contrast, HPWHs operate by extracting heat from the surrounding environment and concentrating it to efficiently heat water for various household purposes [23]. A typical heat pump water heater, shown in Figure 19, uses an air source heat pump that is connected to a water tank. There's a water tank, as seen in section 2.2.1, and inside it are a condenser coil and back-up electric heating elements.

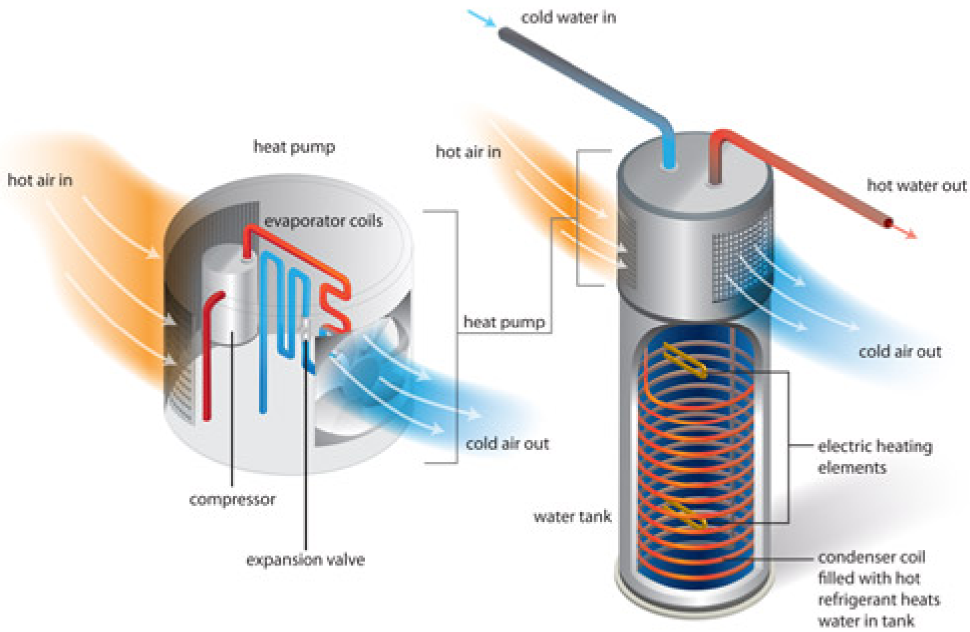


Figure 19: Typical heat pump water heater [24].

A heat pump has four main components: compressor, condenser, expansion valve and evaporator. A schematic of the vapor-compression cycle that heat pumps operate on, and its T-s diagram, is shown in Figure 20.

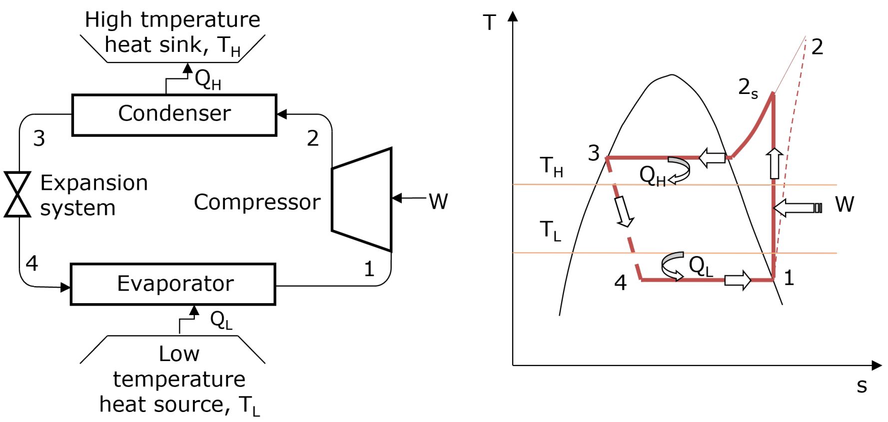


Figure 20: Vapor-compression cycle schematic and its representation in a T-s diagram [25, 26].

Heat pumps for heating purposes operate as per the following steps:

1. In the evaporator, the liquid refrigerant absorbs heat from a heat source, Q_L, and evaporates. After the refrigerant in the evaporator is in low-pressure vapor condition, the temperature increases.

2. The refrigerant enters the electrical compressor in a vaporized state; here the pressure is increased, which increases temperature.

3. At high temperatures, vapor flows to the condenser. As a result of the heat transfer to the building's heating system, Q_H, the refrigerant cools down and condenses into a high-pressure, high-temperature liquid.

4. The liquid, at a high temperature, passes through an expansion valve, where its pressure decreases, lowering the temperature. Then, the refrigerant returns to the evaporator, and the cycle is repeated [27].

In heat pumps, the intended effect is the heat released in the condenser, Q_H, for heating the environment or material [25]. The COP is calculated by the following equation:

$$COP = \frac{Q_H}{W} \tag{1}$$

The normal range of COP for conventional vapor-compression heating systems used in buildings is between 3 and 5. The energy efficiency of heat pumps heavily relies on the temperature difference between the heat source and the heat sink. Vapor-compression heat pumps generally achieve a COP of around 40% to 60% of the maximum ideal Carnot efficiency [3], as shown in Figure 21.

Hence, reducing the system's temperature output will significantly raise the system's COP for both DHW generation and space heating applications (as long as the output temperature is still adequate to fulfill the purpose). On the heat source side, a warmer environment results in a lower temperature span and a greater energy efficiency [3]. When the temperature decreases below a certain limit (usually 0°C depending on the refrigerant and unit design), the HP is no longer able to extract any significant heat, and an electric resistance back-up element is used (shown in Figure 19) [23].

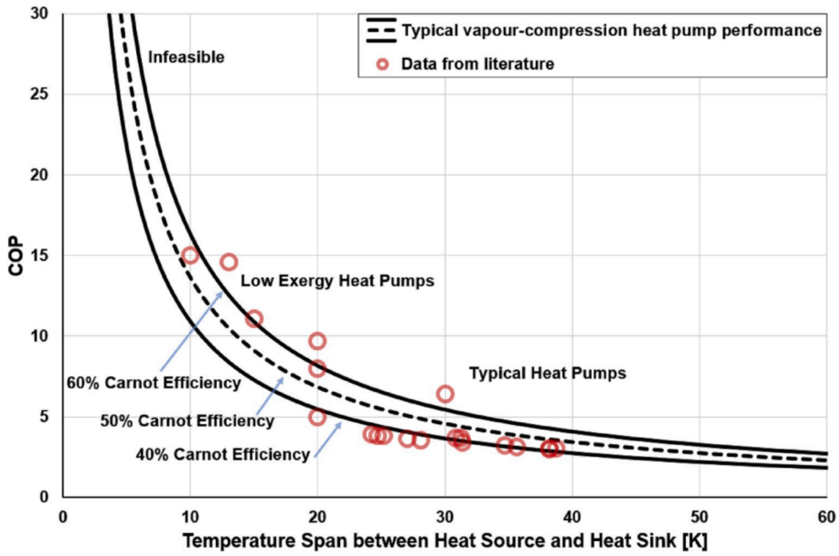


Figure 21: Energy efficiency of vapor-compression heat pump systems as function of the temperature span between heat source and heat sink [3].

Heat pump technology is often categorized according to its source, function, type of energy, and application. The most common way to classify heat pumps is according to their heat source. The three main types of HPs based on heat source, which are going to be described in the following sections, are air source heat pumps (ASHP), ground source heat pumps (GSHP), and water source heat pumps (WSHP). The other heat sources are worth mentioning too: waste water, industrial waste heat, geothermal water flue gas, district cooling, or solar heat. These technologies are very promising but still have limited use [27].

2.3.4.1 Air Source Heat Pump (ASHP)

The three most common types of ASHPs are air-to-air heat pumps (AAHP), air-to-water heat pumps (AWHP), and exhaust air heat pumps (EAHP) [28].

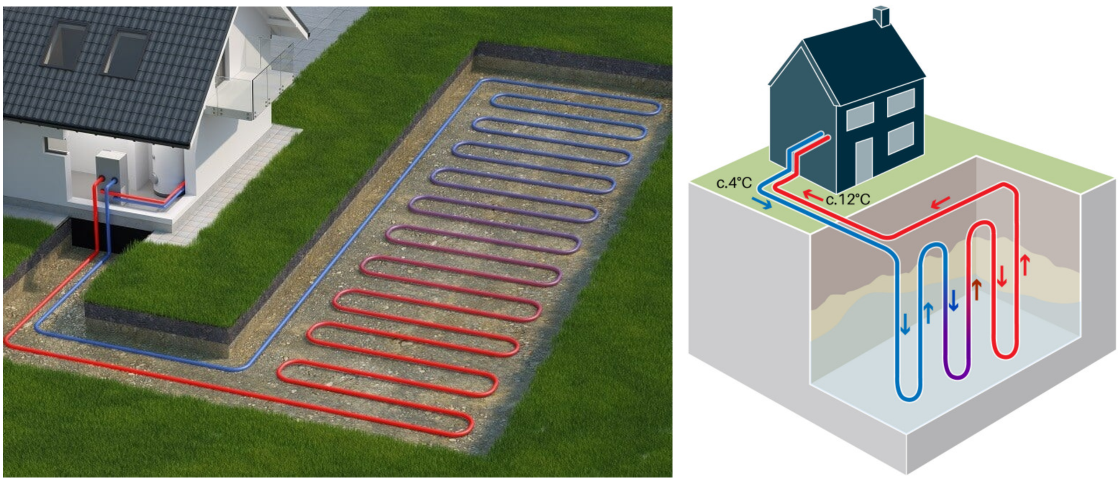
For air source heat pumps (air-to-air and air-to-water), the evaporator is typically situated outdoors. These systems offer a low installation cost. However, compared to heat sources like ground sources, they tend to have a lower seasonal COP due to the colder ambient air temperatures during the heating season as opposed to the warmer ground temperatures [3]. For domestic purposes, the air-to-air heat pump is the most common. In these systems, heat is transported from air in one location (heat source) to air in another location (heat sink). In the winter, a heat pump pulls heat from the outside air and transfers it to the interior of the house using a working fluid. The ASHP employs electric resistance heat when the ambient air temperature falls below a certain limit (modern ASHPs can operate at outside air temperatures as low as -15°C to -30°C). In the summer, the heat pump reverses the process, removing heat from the home and transporting it to outside air and cooling it as a result [23, 27].

Exhaust air heat pump (EAHP), often referred to as ventilation air heat pump, exchanges heat with the house's exhaust air and uses it for space heating/cooling purposes as well as to heat water. Compared to air-to-air heat pumps (AAHP), this type of heat pump is less common. This is because EAHPs can only be utilized in homes with reliable ventilation systems, and they are mostly employed to recycle the heat already present within buildings rather than to get heat from outside. EAHPs can act as a complementary system with other types of heat pumps to increase the efficiency of building heating systems [28].

A significant drawback of air source heat pumps is the formation of ice on the evaporator, which requires defrosting cycles and thus lowers the system's energy efficiency [3].

2.3.4.2 Ground Source Heat Pump (GSHP)

Ground source heat pumps use the ground as a heat source. As mentioned in 2.3.4.1, in GSHP installations, on a daily basis, there is a much lower variation of the source temperature compared to ASHP installations. Ground temperature variations are more evident on a seasonal basis than on a daily basis. As is the case with the ASHP, when the difference between the inside and outside temperatures is wide, more energy is needed to produce the same amount of heat, which lowers the COP [27]. GSHP comprises heat exchange loops installed horizontally or vertically, which are shown in Figure 22.



(a) (b)

Figure 22: Closed-loop ground source heat pump system. a) Horizontal circulation loops [29]. b) Vertical circulation loops [30].

2.3.4.3 Water Source Heat Pump (WSHP)

In a typical WSHP, water is brought directly to the HP unit and used as a heat source. The term "open-loop" is used to describe this kind of HP when there is no barrier between the water heat source (ground water or a surface water body) and the evaporator.

When installing open-loop systems, a number of factors must be taken into account, with water quality ranking among the most crucial. It can cause fouling, corrosion, and blockage of the groundwater-refrigerant heat exchanger, which affects how well it functions. Adequate water volume and flow rates are the second crucial factor. The third crucial element is how the released water is handled. There are two possibilities: the groundwater can either be released into surface water basins, such as rivers, lakes, etc., or it can be injected back into the earth through separate wells. The local codes and regulations determine the viability of open-loop systems.

These systems present some advantages when compared with GSHP, such as lower installation costs and better thermodynamic performance than closed-loop systems. Additionally, the system can be combined with a potable water supply well, resulting in reduced operating costs when water is already being pumped for other purposes such as irrigation [27].

2.4 Waste Water Heat Recovery

From an economic standpoint, the appeal of extracting heat from wastewater in buildings is steadily growing. Showers, sinks, dishwashers, and washing machines are the main sources of drain water that are used in waste water heat recovery systems (WWHRS). The basic concept of this approach is to increase the temperature of the mains water by utilizing the heat from the drain water, effectively preheating the mains water before it reaches the water heater [31].

In Figure 23 it is shown how the main part of a WWHR system, the heat exchanger, works.

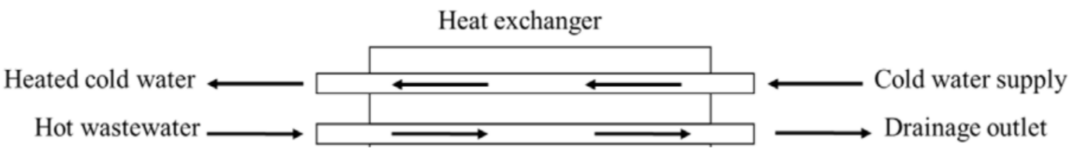


Figure 23: Working principle of waste water heat recovery systems [32].

Different types of heat exchangers can be incorporated into the systems to optimize the heat transfer process. The surface area of heat transfer and the thickness of the water affect the heat transfer rate that results from the temperature difference between the mains water and the drain water. The suitability of various types of WWHR units for residential buildings relies on several factors, such as the building's construction and available space.

Copper pipes are commonly employed in waste water heat recovery systems due to their excellent thermal conductivity, allowing for optimal heat transfer [31].

2.4.1 WWHR Classification

Heat exchanger types and structures can be categorized into four groups based on their structure: vertical systems, horizontal systems, orientated systems, and storage tank-based systems [31]. Figure 24 illustrates the flow chart outlining the reviewed systems and the respective categories to which each system belongs.

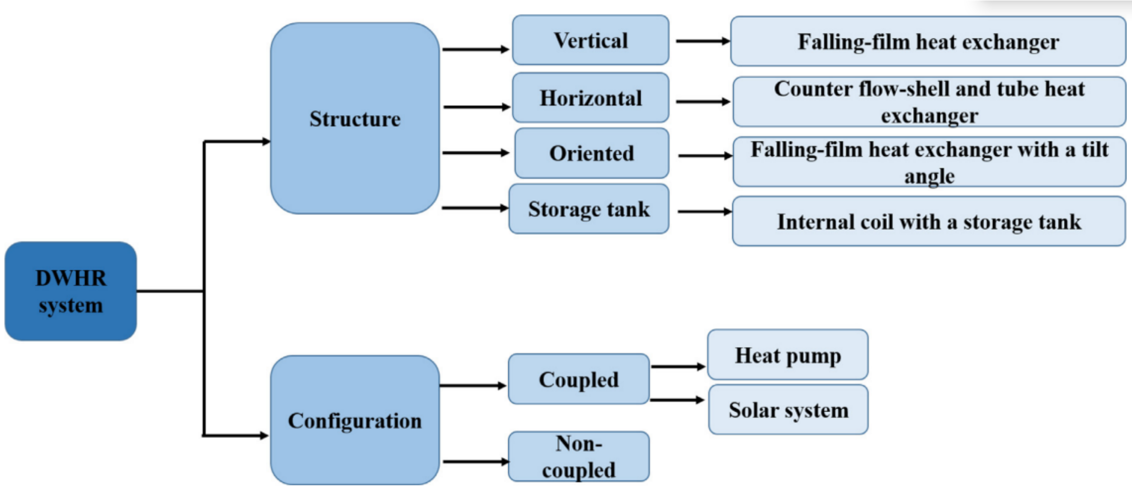


Figure 24: WWHRS classification [31].

2.4.1.1 Vertical Systems

A vertical waste water heat recovery system installed on a shower is shown in Figure 25. It differs from others by having a gravity film heat exchanger. As shown in Figure 25, the system offers a larger heat transmission area than a straight pipe by wrapping a spiral coil around the main inner pipe. The amount of heat transferred in this type of heat exchanger depends on the design [31].

The top of the main pipe is where the hot water is delivered, adhering to the inlet walls. Before the process of removing heat from hot water starts, cold water is fed into the spiral coil. The system is then completed with warmed water at the top of the unit [31].

There is another installation scenario that makes use of vertical systems and a storage tank. In this instance, the water is heated or preheated by the WWHR system prior to storage, and is then heated to the proper temperature to meet the needs of the building [31].

The issue with WWHR systems is that the low temperature can occasionally cause the drain water heat to be wasted inside or outside the system's enclosure. The water heater must be installed close to the recovery system in order to get better performance [31].

Additional factors that have a significant impact on the system's overall effectiveness include the length of the shower, the temperature of the cold water, the flow rates, the fouling effect, the pipe's flow regime, and the temperature difference between the shower head and the drain point [31].

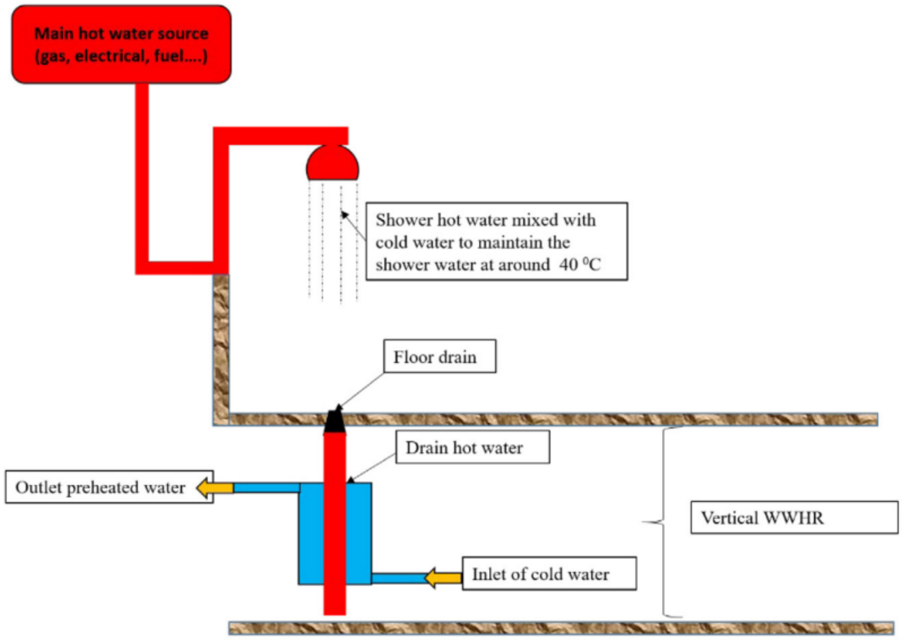


Figure 25: Schematic for vertical drain water heat recovery system applied on a shower drain [31].

2.4.1.2 Horizontal Systems

There may not always be enough room in residential buildings for a vertical unit to fit underneath the shower trays. Horizontal WWHR systems might be adequate in these cases.

As seen in Figure 26, horizontal systems directly connect a water heater to a straightforward single pass counter flow heat exchanger.

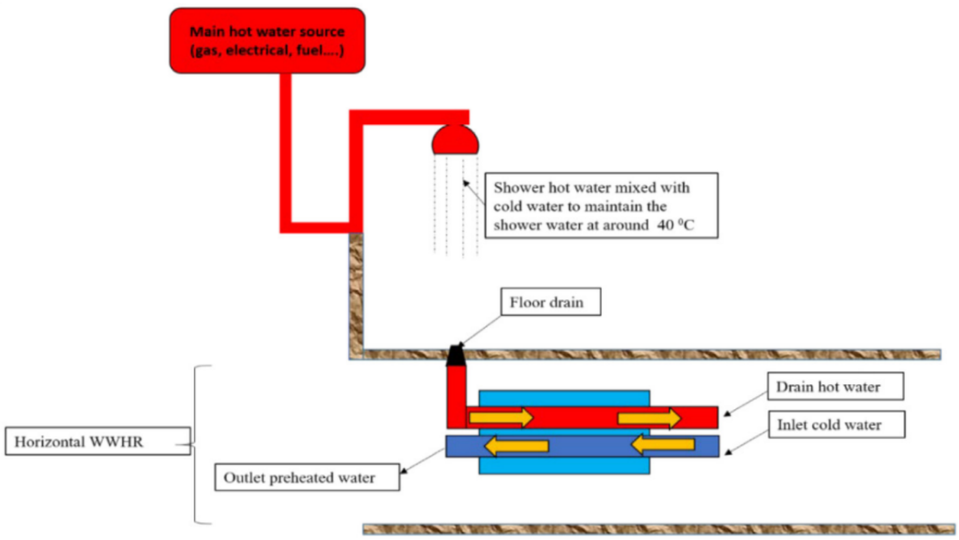


Figure 26: Schematic for horizontal drain water heat recovery system applied on a shower drain system [31].

In the vertical system, water will flow all around the pipe's surface, ensuring good conductive efficiency. In the horizontal system the water flows through the bottom of the pipe, resulting in a reduction of heat transfer rates, which means the efficiency is also lower than for vertical systems, which is why this method is rarely used [31].

2.4.1.3 Inclined Systems

Some WWHR systems may not be installed vertically due to building structure, so inclined system may be a solution.

Figure 27 shows an inclined system, where there's a tilt angle between the vertical line and the heat exchanger of the drain system. This type of inclined heat exchanger carries out similar functions to a vertical system.

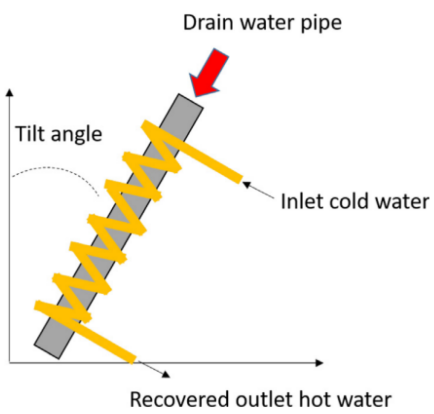


Figure 27: Schematic of an inclined type heat exchanger [31].

2.4.1.4 Storage Tank Based System

Another method that may be applied to WWHR systems is the storage tank. Currently, it is used to hold DHW. In Figure 28 it can be seen that these systems have a spiral pipe carrying cold, fresh water inside a hot water tank.

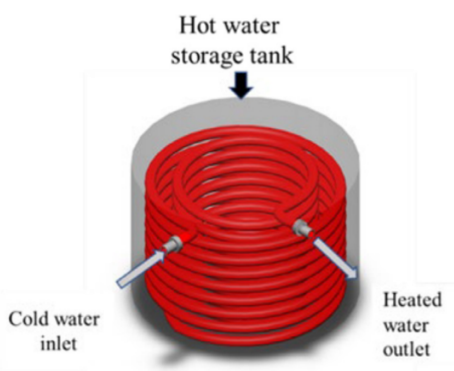


Figure 28: Storage tank heat exchanger [32].

With this kind of system, the top of the tank may remain hot and ready for use by employing a heat exchanger to collect heat from the bottom of the tank [31].

3. Methodology

3.1 Without Heat Recovery

The DHW production system configuration considered was as shown in Figure 29.

A drainage capacity of 9.2 l/min is being considered so, in order to know the volumetric flow rate that passes through the water heater, there is a need to do a mass flow balance and an energy balance at the shower mixing valve, shown in equations 2 and 3, respectively:

$$\dot{m}_{shower} = \dot{m}_{source} + \dot{m}_{cold,mix} \tag{2}$$

$$T_{shower}C_{shower} = T_{source}C_{source} + T_{cold,mix}C_{cold,mix} \tag{3}$$

where $\dot{m}$ is the mass flow rate in $[kg/s]$, T is the temperature in Kelvin [K] and C is given by the following equation, in $[W/K]$:

$$C = \dot{m} \cdot c_p = \dot{V} \cdot \rho \cdot c_p \tag{4}$$

where $\dot{V}$ is the volumetric flow rate in $[m^3/s]$, ρ is the density in $[kg/m^3]$ and c_p is the specific heat at constant pressure in $[J/kg \cdot K]$.

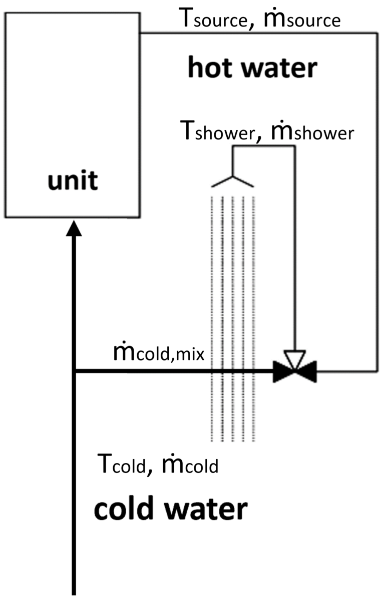


Figure 29: DHW system without heat recovery.

Looking at Figure 29 it becomes clear that $\dot{m}_{source} = \dot{m}_{cold} - \dot{m}_{cold,mix}$. Bearing in mind equations 2 and 3, the energy balance can be rewritten as:

$$T_{shower}(C_{source} + C_{cold,mix}) = T_{source}C_{source} + T_{cold,mix}C_{cold,mix} \tag{5}$$

$$C_{source}(T_{shower} - T_{source}) = C_{cold,mix}(T_{cold,mix} - T_{shower}) \tag{6}$$

$$C_{cold} - C_{cold,mix} = C_{cold,mix}\frac{(T_{cold,mix} - T_{shower})}{(T_{shower} - T_{source})} \tag{7}$$

Finally, C_{cold} is given by:

$$C_{cold} = C_{cold,mix}\frac{(T_{cold,mix} - T_{shower})}{(T_{shower} - T_{source})} + C_{cold,mix} \tag{8}$$

With equations 4 and 8 we can obtain $C_{cold,mix}$, and subsequently, we know the flow rate that goes through the cold side of the shower mixing valve. Consequently, with equation 2 we can obtain the flow rate that passes through the water heater.

3.2 Heat Recovery Configurations

In homes and residential buildings, a shower water heat recovery unit (SWHRU) can be used, where heat from the shower water is used to heat the mains water for use at the cold side of the shower mixing valve and/or the inlet of the unit for domestic hot water production.

In this work, the shower water heat recovery system considered was a vertical solution from Zypho, shown in Figure 30.

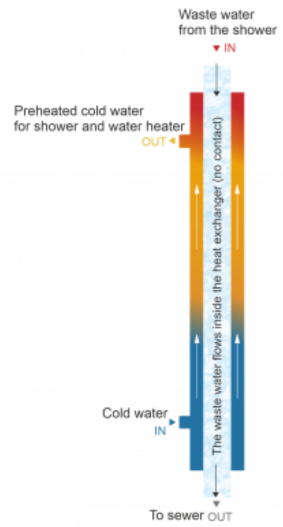


Figure 30: Vertical solution for shower water heat recovery from Zypho [33].

3.2.1 Configuration 1

In this configuration, the cold pre-heated water that comes out of the heat exchanger goes both into the water heating unit and into the shower mixing valve, where it mixes with the hot water that comes out of the water heater to reach the temperature of use.

$T_{cold,in}$ is the temperature of the mains water before being pre-heated; $T_{cold,out}$ is the temperature of the pre-heated cold water that comes out of the heat exchanger; T_{source} is the hot water that comes out of the water heater; and $T_{hot,in}$ is the temperature of the shower water that then enters the heat exchanger to supply heat to the cold water.

The efficiency of the heat exchanger is given by:

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{avail}} \tag{9}$$

where $\dot{Q}_{avail}$ is the total amount of energy available in the system and $\dot{Q}$ is the heat that is actually transferred to the cold water.

For all 3 configurations, $\dot{Q}$ and $\dot{Q}_{avail}$ are respectively given by:

$$\dot{Q} = C_{cold} \cdot (T_{cold,out} - T_{cold,in}) \tag{10}$$

$$\dot{Q}_{avail} = C_{hot} \cdot (T_{hot,in} - T_{cold,in}) \tag{11}$$

Since there is full return, this situation is where we have maximum efficiency because the water flow rates through the hot and cold sides of the heat exchanger are equal. Both $c_{p,cold}$ and $c_{p,hot}$ are calculated for an average of temperatures. This results in C_{cold} and C_{hot} being very close in value, so the difference is dismissed and we consider $C_{cold}/C_{hot} = 1$.

This results in the efficiency for this configuration being:

$$\varepsilon = \frac{T_{cold,out} - T_{cold,in}}{T_{hot,in} - T_{cold,in}} \tag{12}$$

However, the application of this configuration depends on the distance between the heat exchanger and the water heater; if the distance is too long, the heat losses will be too high, and it is no longer feasible. In hotels, there is commonly a centralized DHW system that then distributes hot water to all rooms. Given this fact, it makes it difficult to implement this configuration in a hotel.

To calculate the flow rate that goes through the water heater a mass flow balance can be made at the shower mixing valve:

$$\dot{m}_{shower} = \dot{m}_{source} + \dot{m}_{cold,mix} \tag{13}$$

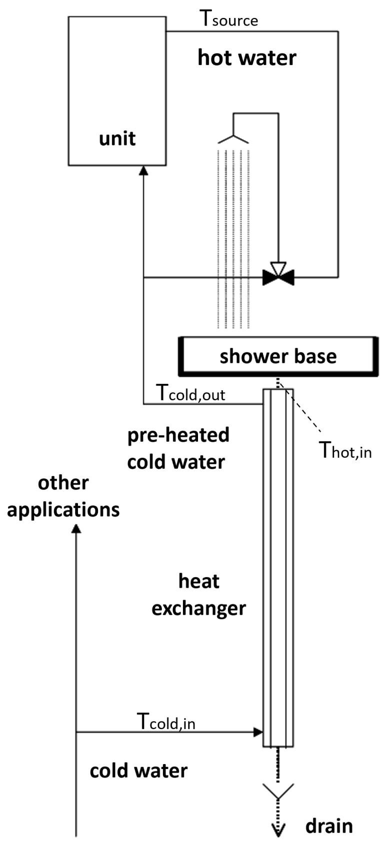


Figure 31: Configuration 1.

and since $\dot{m}_{shower} = \dot{m}_{hot}$ we have:

$$\dot{m}_{hot} = \dot{m}_{source} + \dot{m}_{cold,mix} \tag{14}$$

Then, an energy balance can be made also the shower mixing valve:

$$T_{shower}C_{shower} = T_{source}C_{source} + T_{cold,mix}C_{cold,mix} \tag{15}$$

where T_{shower} and C_{shower} are the same as $T_{hot,in}$ and C_{hot}, respectively, and $C_{hot} = C_{source} + C_{cold,mix}$ (because $\dot{m}_{hot} = \dot{m}_{source} + \dot{m}_{cold,mix}$ and C = $\dot{m} \cdot c_p$). Since $\dot{m}_{source} = \dot{m}_{cold} - \dot{m}_{cold,mix}$, we also know that $C_{source} = C_{cold} - C_{cold,mix}$. Then we have:

$$T_{hot,in}C_{hot} = T_{source}C_{source} + T_{cold,mix}C_{cold,mix} \tag{16}$$

$$T_{hot,in}(C_{source} + C_{cold,mix}) = T_{source}C_{source} + T_{cold,mix}C_{cold,mix} \tag{17}$$

$$C_{source}(T_{hot,in} - T_{source}) = C_{cold,mix}(T_{cold,mix} - T_{hot,in}) \tag{18}$$

$$C_{cold} - C_{cold,mix} = C_{cold,mix}\frac{(T_{cold,mix} - T_{hot,in})}{(T_{hot,in} - T_{source})} \tag{19}$$

Finally, we can calculate C_{cold} with the following equation:

$$C_{cold} = C_{cold,mix}\frac{(T_{cold,mix} - T_{hot,in})}{(T_{hot,in} - T_{source})} + C_{cold,mix} \tag{20}$$

With equations 4 and 20 we can then obtain the flow rate that passes through the cold part of the shower mixing valve and consequently the flow rate that passes through the water heater.

3.2.2 Configuration 2

In this configuration the pre-heated water that comes out of the heat exchanger goes only into the shower mixing valve. The cold water that enters the water heater all comes from the mains, at a lower temperature.

The mass flow balance at the shower mixing valve is shown in equation 21, and since $\dot{m}_{shower}$ is equal to $\dot{m}_{hot}$, equation 22 emerges.

$$\dot{m}_{shower} = \dot{m}_{source} + \dot{m}_{cold} \tag{21}$$

$$\dot{m}_{hot} = \dot{m}_{source} + \dot{m}_{cold} \tag{22}$$

So, in the heat exchanger, the cold flow will be smaller than the hot flow. This is because the latter consists of the cold flow and water from the heater. The unequal flow rate results in a reduction in heat transfer.

The energy balance at the shower mixing valve is the following:

$$T_{shower}C_{shower} = T_{source}C_{source} + T_{cold}C_{cold} \tag{23}$$

The flow rate through the water heater is the difference in the flow rate through the hot and cold sides of the heat exchanger, as shown in equation 24.

$$\dot{m}_{source} = \dot{m}_{hot} - \dot{m}_{cold} \tag{24}$$

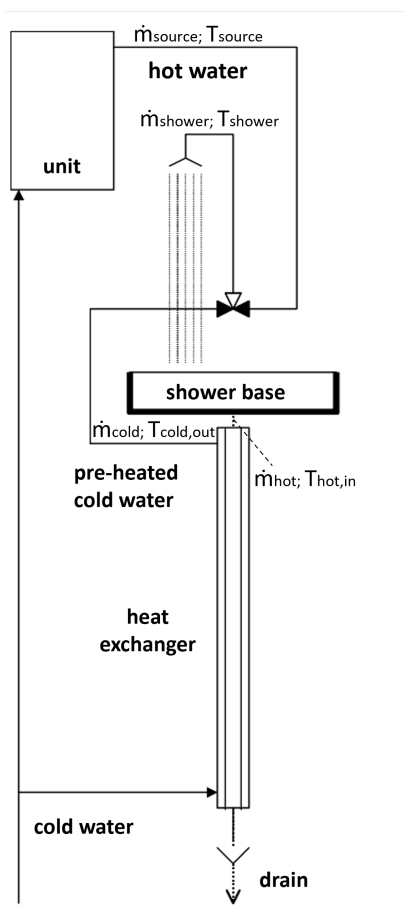


Figure 32: Configuration 2.

The energy balance can then be rewritten as:

$$T_{hot,in}C_{hot} = T_{source}(C_{hot} - C_{cold}) + T_{cold,out}C_{cold} \tag{25}$$

$$T_{cold,out}C_{cold} = T_{hot,in}C_{hot} - T_{source}(C_{hot} - C_{cold}) \tag{26}$$

$$T_{cold,out}C_{cold} = T_{hot,in}C_{hot} - T_{source}C_{hot} + T_{source}C_{cold} \tag{27}$$

$$T_{cold,out}C_{cold} = C_{hot}(T_{hot,in} - T_{source}) + T_{source}C_{cold} \tag{28}$$

$$C_{cold}(T_{cold,out} - T_{source}) = C_{hot}(T_{hot,in} - T_{source}) \tag{29}$$

Finally, C_{cold} can be calculated as seen in equation 4, resulting:

$$C_{cold} = \dot{V}_{cold} \cdot \rho_{cold} \cdot c_{p,cold} \tag{30}$$

and by using the equation that results from the mass flow balance:

$$C_{cold} = C_{hot} \frac{(T_{source} - T_{hot,in})}{(T_{source} - T_{cold,out})} \tag{31}$$

In this case, since $C_{cold} < C_{hot}$, the efficiency of the heat exchanger is given by:

$$\varepsilon = \frac{C_{cold}}{C_{hot}} \cdot \frac{(T_{cold,out} - T_{cold,in})}{(T_{hot,in} - T_{cold,in})} \tag{32}$$

3.2.3 Configuration 3

In this configuration, the pre-heated water that comes out of the heat exchanger goes only into the water heater. The water that enters the cold side of the shower mixing valve all comes from the mains at a lower temperature.

The mass flow balance at the shower mixing valve is given by the following equation:

$$\dot{m}_{shower} = \dot{m}_{source} + \dot{m}_{cold,mix} \tag{33}$$

and $\dot{m}_{shower}$ is equal to $\dot{m}_{hot}$, which results in:

$$\dot{m}_{hot} = \dot{m}_{source} + \dot{m}_{cold,mix} \tag{34}$$

So, as in configuration 2, in the heat exchanger, the cold flow will be smaller than the hot flow, since the hot flow consists of the water from the water heater and the cold flow (that enters in the mixing valve).

Similarly to the previous case, we'll do the energy balance at the shower mixing valve:

$$T_{shower}C_{shower} = T_{source}C_{source} + T_{cold,mix}C_{cold,mix} \tag{35}$$

The flow rate through the water heater is now equal to the flow rate through the cold side of the heat exchanger since there is a direct connection between them ($\dot{m}_{source} = \dot{m}_{cold}$). The temperature at the cold side of the shower mixing valve is now simply the temperature of the mains water, and the flow rate is the difference between the hot and cold flows through the heat exchanger. This mass flow balance is shown in equation 36.

$$\dot{m}_{cold,mix} = \dot{m}_{hot} - \dot{m}_{cold} \tag{36}$$

The energy balance can then be rewritten as:

$$T_{hot,in}C_{hot} = T_{source}C_{cold} + T_{cold,in}(C_{hot} - C_{cold}) \tag{37}$$

C_{cold} is again given by equation 31, and for this configuration can be calculated as the resulting equation:

$$C_{cold} = C_{hot}\frac{(T_{hot,in} - T_{cold,in})}{(T_{source} - T_{cold,in})} \tag{38}$$

As in the previous case, $C_{cold} < C_{hot}$, and so the efficiency is given by the same equation as in configuration 2:

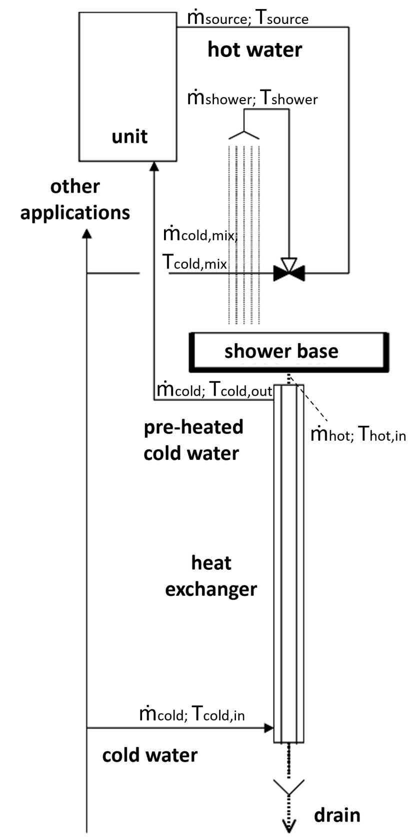


Figure 33: Configuration 3.

$$\varepsilon = \frac{C_{cold}}{C_{hot}} \cdot \frac{(T_{cold,out} - T_{cold,in})}{(T_{hot,in} - T_{cold,in})} \tag{39}$$

3.3 Heat Exchanger Numerical Model

The numerical model of the heat exchanger was made using Excel, based on the information in Section 3.2.

The heat recovery unit considered is a vertical solution from Zypho. For all configurations some considerations were made regarding the temperatures of the water, shown in Table 1.

Table 1: Temperature considerations

Temperature considerations	
	T [°C]
T_{source}	60
$T_{hot,in}$	40
$T_{cold,in}$	10
$T_{cold,out}$	30

As previously mentioned, the values for ρ and c_p were obtained as the mean of the values for various temperatures. ρ_{cold} and $c_{p,cold}$ were calculated as the mean of these values for temperatures between 10 and 25°C, and ρ_{hot} and $c_{p,hot}$ were calculated as the mean of these values for temperatures between 25 and 40°C. These values are shown in Tables 2 and 3.

Table 2: Values of ρ and c_p for different temperatures

Temperature [°C]	ρ $[kg/m^3]$	c_p $[J/(kgK)]$
10	1000	4193
15	999	4186
20	998	4182
25	997	4179
30	995	4178
35	994	4178
40	992	4179

Table 3: Average values of ρ and c_p

	ρ $[kg/m^3]$	c_p $[J/(kgK)]$
Cold	998	4185
Hot	995	4179

Based on the equations presented in Section 3.2, it is possible to calculate the heat exchanger's efficiency for each configuration.

The hot volumetric flow rate (the shower's flow rate that then enters the heat exchanger) is assumed to be 9.2 l/min. In configuration 1, the cold volumetric flow rate is considered equal to the hot volumetric flow rate, and we only need to fill in the values shown in Table 1 to obtain the efficiency. In configurations 2 and 3, we fill in the values shown in Table 1 and then the cold volumetric flow rate is obtained using Excel's solver tool, equating the two cells that calculate the C_{cold} value using the two different equations (equations 4 and 31 for configuration 2 and equations 4 and 38 for configuration 3).

3.4 Estimating DHW Needs For The Residential and Hotel Sector In Portugal

In order to estimate the domestic hot water needs for the residential sector in Portugal, the EN 12831-3 standard was used. The daily DHW consumption values for residential buildings, as provided in the aforementioned standard, are shown in Table 4.

Table 4: Daily DHW consumption for residential buildings, as per EN 12831-3

Building subcategory	DHW Consumption $[l/person]$
Single-family	40
Multi-family	30

The daily DHW consumption is calculated by:

$$\text{daily DHW consumption } [l] = \text{daily DHW consumption/person } [l/person] \cdot \text{n° of people} \tag{40}$$

and the yearly DHW consumption is given by:

$$\text{yearly DHW consumption } [l] = \text{daily DHW consumption } [l] \cdot 365 \tag{41}$$

Both daily and yearly consumption needs are then multiplied by the share of water that actually passes through the water heater.

With these values and recurring to the average ρ values shown in Table 3, we obtain the mass of DHW needed:

$$m = V \cdot \rho \tag{42}$$

where V is the volume in $[m^3]$.

Then we can finally estimate the DHW energy needs (useful energy) for residential buildings using the following equation:

$$Q = E_{useful} = m \cdot c_p \cdot \Delta T \tag{43}$$

where $\Delta T = T_{source} - T_{cold,in}$.

For the hotel sector the same standard is used and the values for daily DHW consumption are shown in Table 5.

Table 5: Daily DHW consumption for hotels, as per EN 12831-3

Type of hotel	DHW Consumption $[l/bed]$
1-star hotels, no laundry	56
1-star hotels, with laundry	70
2-star hotels, no laundry	76
2-star hotels, with laundry	90
3-star hotels, no laundry	97
3-star hotels, with laundry	111
4-star hotels or higher, no laundry	118
4-star hotels or higher, with laundry	132

The daily DHW consumption is given by:

$$\text{daily DHW consumption } [l] = \text{daily DHW consumption/bed } [l/bed] \cdot \text{n}^{\text{o}} \text{ of beds} \quad (44)$$

and the yearly DHW consumption results of:

$$\text{yearly DHW consumption } [l] = \text{daily DHW consumption } [l] \cdot 365 \quad (45)$$

The daily and yearly consumption needs are again multiplied by the share of water that actually goes through the water heater and we can again obtain the mass and energy needs using equations 42 and 43, respectively.

To convert the energy from J to kWh, equation 46 is used.

$$kWh = \frac{J}{3.6 \cdot 10^6} \quad (46)$$

The following equation allows us to calculate the final energy required to heat the desired volume of water with an instantaneous gas water heater, where ε is the water heater's efficiency:

$$E_{final} = \frac{E_{useful}}{\varepsilon} \quad (47)$$

Similarly, if we use a heat pump water heater, the final energy needed is given by:

$$E_{final} = \frac{E_{useful}}{COP} \quad (48)$$

To obtain the cost for either options we multiply the final energy by the cost per kWh. The prices are shown in Table 6.

Table 6: Price per kWh [34]

	Price $[€/kWh]$
Natural gas	0.1403
Electricity	0.1364

The primary energy is calculated by multiplying the final energy by the conversion factor for primary energy, whose values are shown in Table 7.

Table 7: Typical primary energy conversion factors [35]

E_{final}	$E_{primary}$
1 kWh electric	2.5 kWhPE
1 kWh natural gas	1 kWhPE

Finally, to calculate the CO_2 emissions, we need to multiply the primary energy by the respective conversion factors for CO_2 emissions, which are shown in Table 8.

Table 8: Primary energy conversion factors for CO_2 emissions [35]

Energy source	Conversion factor $[kgCO_2/kWh]$
Electricity	0.144
Natural gas	0.202

3.4.1 Calculation Of Energy Savings When Using Heat Recovery

As seen in Section 3.2.1, when there's a centralized DHW production system, configuration 1 may present high losses, therefore not being suitable. In this case, configuration 2 is preferable since the pre-heated water that comes out of the heat exchanger all goes to the shower mixing valve. On the contrary, when there's a decentralized DHW production system (for example, when there's only one shower for that water heater), configuration 1 is preferable since there won't be any significant losses and it is the configuration with the highest efficiency.

To calculate the energy savings when using configuration 1, the volume of hot water estimated is multiplied by the share of water that actually goes into the water heater with this configuration. The mass is then calculated using equation 42. Using this newly determined mass, equation 43 is employed to calculate the revised energy requirements. In this equation, ΔT is now defined as $T_{source} - T_{cold,out}$. The resulting energy requirement is then converted to kWh. The final energy consumption, cost, primary energy, and CO_2 emissions can be calculated using the same methodology as previously described.

For configuration 2, the process is similar to configuration 1, the only difference being when calculating the new energy needs. With this configuration, ΔT is defined as $T_{source} - T_{cold,in}$ in equation 43.

3.5 Heat Pump Operational Gains

The combination of a heat pump water heater with shower water heat recovery can bring big economic and environmental advantages.

The coefficient of performance (COP) measures how much useful heat a heat pump will produce in response to a given energy input. As seen in Section 2.3.4, the COP is given by:

$$COP = \frac{Q_H}{W} \tag{49}$$

For typical heat pumps, the values for COP are between 3 and 3.3. To calculate the operational gains of a heat pump when there's preheating of the mains water with a shower water heat recovery unit we're going to calculate the energy needed to heat the water from 10°C to 60°C (with equation 43) and then, with the introduction of heat recovery that preheats the mains water from 10°C to 30°C, we're going to calculate the energy needed to heat the water from 30°C to 60°C (again with equation 43).

Then, considering a COP of 3.1, the energy required to be supplied to the heat pump to heat the water (W in equation 49, also referred to as final energy) can be calculated using equation 49. The difference in final energy between the case with heat recovery and the case without heat recovery gives us the operational gains of the heat pump when pre-heating the water from the mains with a shower water heat recovery unit.

4. Results And Discussion

4.1 Heat Exchanger's Efficiencies

The results of the efficiencies of the 3 different heat exchanger configurations, calculated using the temperatures presented in Table 1, are presented in Table 9.

Table 9: Results of heat exchanger's numerical model

Configuration	C_{hot} $[W/K]$	C_{cold} $[W/K]$	$\dot{V}_{cold}$ $[l/min]$	ε $[\%]$
1	637.2	640.6	9.200	66.7
2	637.2	424.8	6.102	44.4
3	637.2	382.3	5.491	40.0

As expected, configuration 1 is the most efficient (66.7%), followed by configuration 2 (44.4%) and then configuration 3 (40.0%). $\dot{V}_{cold}$ is the volumetric flow rate that passes through the cold side of the heat exchanger.

With the mass flow and energy balances at the shower mixing valve, the share of water that goes into the water heater was calculated for all configurations and the situation without heat recovery:

Table 10: Share of water that passes through the water heater

Configuration	$\dot{m}_{water\ heater}$ $[\%]$
Without heat recovery	60.0
1	33.3
2	33.4
3	59.9

The water input to the water heater is comparable between the case without heat recovery and configuration 3, as well as between configuration 1 and configuration 2. This is because, in configurations 1 and 2, the water exiting the heat exchanger at 30°C flows into the shower mixing valve in both cases. In contrast, in the absence of heat recovery and in configuration 3, the water entering the cold side of the shower mixing valve is the mains water at 10°C.

4.2 DHW Needs For 2 Residential Buildings And 1 Hotel

4.2.1 Single-family Residential Building (4 people)

Considering a single-family house with only one shower, the DHW needs calculated were the following:

Table 11: DHW needs for a house with four people

	Volume $[l]$	Volume water heater $[l]$	Energy needs E_{useful} $[MJ]$	Energy needs E_{useful} $[kWh]$
Daily	160	96	20.0	5.5
Annual	58400	35040	7285.0	2023.6

Since there is only one shower, configuration 1 was considered for the shower water heat recovery unit. As a result of the energy balance at the shower mixing valve for configuration 1, only 33.3% of the water passes through the water heater. The water enters the water heater at 30°C and is heated to 60°C. The energy needs to heat the water when there is heat recovery, with configuration 1, are shown in Table 12.

Table 12: DHW production needs with heat recovery for a house with four people

	Volume water heater $[l]$	Energy needs E_{useful} $[MJ]$	Energy needs E_{useful} $[kWh]$
Daily	53.3	6.7	1.8
Annual	19466.7	2428.3	674.5

Introducing configuration 1 of a shower water heat recovery unit results in an impressive 67% reduction in energy required for water heating.

The values of final energy, primary energy, CO_2 emissions, and price are shown in Table 13 for an instantaneous gas water heater without heat recovery and with heat recovery.

Table 13: Comparison between instantaneous gas water heater without heat recovery and with heat recovery, configuration 1

	Without Heat Recovery	**With Heat Recovery**
	Final Energy $[kWh]$	
Daily	6.3	2.1
Annual	2299.6	766.5
	Primary Energy $[kWh]$	
Daily	6.3	2.1
Annual	2299.6	766.5
	CO_2 emissions $[kgCO_2]$	
Daily	1.27	0.42
Annual	464.51	154.84
	Price (natural gas) [€]	
Daily	0.88	0.29
Annual	322.63	107.54

When incorporating heat recovery into an instantaneous gas water heater, the result is a reduction of 1533 kWh in final energy consumption. This translates to an annual cost decrease of 215€ for DHW production and a reduction of 310 kg in annual CO_2 emissions.

The values of final energy, primary energy, CO_2 emissions, and price are shown in Table 14 for a heat pump water heater without heat recovery and with heat recovery.

Table 14: Comparison between heat pump water heater without heat recovery and with heat recovery, configuration 1

	Without Heat Recovery	**With Heat Recovery**
	Final Energy $[kWh]$	
Daily	1.8	0.6
Annual	652.8	217.6
	Primary Energy $[kWh]$	
Daily	4.5	1.5
Annual	1631.9	544.0
	CO_2 emissions $[kgCO_2]$	
Daily	0.64	0.21
Annual	235.00	78.33
	Price electricity [€]	
Daily	0.24	0.08
Annual	89.04	29.68

When heat recovery is integrated into the heat pump water heater, it results in a decrease of around 435 kWh in final energy consumption. Consequently, this leads to an annual cost reduction of 59€ for DHW production and a decrease of 157 kg in annual CO_2 emissions.

The final energy consumption of an instantaneous gas water heater is greater compared to a heat pump water heater due to differences in efficiency and coefficient of performance (COP). It was considered an instantaneous gas water heater that operates with an efficiency of 88%, while the heat pump water heater was considered to have a COP of 3.1.

The heat pump water heater offers both economic and environmental advantages, even without heat recovery. In this specific case, the heat pump water heater can save up to 233€ annually compared to a typical instantaneous gas water heater without heat recovery. Furthermore, the use of a heat pump water heater results in a substantial reduction of approximately 49% in CO_2 emissions compared to an instantaneous gas water heater.

Finally, a side-by-side comparison between the instantaneous gas water heater (IGWH) without heat recovery and the heat pump water heater (HPWH) with heat recovery is made in Table 15.

Table 15: Comparison between instantaneous gas water heater without heat recovery and heat pump water heater with heat recovery, with configuration 1

	IGWH Without Heat Recovery	**HPWH With Heat Recovery**
	Final Energy [kWh]	
Daily	6.3	0.6
Annual	2299.6	271.6
	Primary Energy [kWh]	
Daily	6.3	1.5
Annual	2299.6	544.0
	CO_2 emissions [$kgCO_2$]	
Daily	1.27	0.21
Annual	464.51	78.33
	Price (Natural Gas) [€]	Price (Electricity) [€]
Daily	0.88	0.08
Annual	322.63	29.68

Here, the benefits of implementing a heat pump water heater with heat recovery instead of the typical instantaneous gas water heater become very clear. There is a huge decrease in CO_2 emissions (83%, around 386 $kgCO_2$ annually) as well as in the annual cost of DHW production. It is estimated that there will be a decrease of about 290€ (around 90%) per year in DHW production costs, which in a few years will compensate for the investment in the heat pump water heater and heat recovery unit.

4.2.2 Multi-family Residential Building (15 families - 50 people)

A multi-family residential building that houses 15 families, 50 people in total, was considered. Each apartment has its own water heater and only one shower. The DHW needs for this building are shown in Table 16.

Table 16: DHW production needs for a residential building with 15 families, 50 people

	Volume [l]	Volume water heater [l]	Energy needs E_{useful} [MJ]	Energy needs E_{useful} [kWh]
Daily	1500	900	187.1	52.0
Annual	547500	328500	68296.9	18971.4

Since there is only one shower per apartment, configuration 1 was again considered for heat recovery. From the energy balance at the shower mixing valve, only 33.3% of the water passes through the water heater. The water enters the water heater at 30°C and is heated to 60°C. The energy needs to heat water when there is heat recovery, with configuration 1, are shown in Table 17.

Table 17: DHW production needs with heat recovery for a residential building with 15 families, 50 people

	Volume water heater $[l]$	Energy needs E_{useful} $[MJ]$	Energy needs E_{useful} $[kWh]$
Daily	500	62.4	17.3
Annual	182500	22765.6	6323.8

Since the same configuration was used, the reduction in energy required for water heating is again at 67%.

The values of final energy, primary energy, CO_2 emissions, and price are shown in Table 18 for an instantaneous gas water heater, without heat recovery and with heat recovery.

Table 18: Comparison between instantaneous gas water heater without heat recovery and with heat recovery, configuration 1

	Without Heat Recovery	**With Heat Recovery**
	Final Energy $[kWh]$	
Daily	59.1	19.7
Annual	21558.4	7186.1
	Primary Energy $[kWh]$	
Daily	59.1	19.7
Annual	21558.4	7186.1
	CO_2 emissions $[kgCO_2]$	
Daily	11.93	3.98
Annual	4354.79	1451.60
	Price natural gas [€]	
Daily	8.29	2.76
Annual	3024.64	1008.21

By implementing heat recovery, there is a significant decrease of 14372 kWh in the final energy required for DHW production. This reduction corresponds to a decrease of 2093 kg in CO_2 emissions and a cost reduction of 2016€ in annual expenses.

Table 19 presents the values of final energy, primary energy, CO_2 emissions, and price for a heat pump water heater, comparing the cases without heat recovery and with heat recovery.

Table 19: Comparison between heat pump water heater without heat recovery and with heat recovery, configuration 1

	Without Heat Recovery	**With Heat Recovery**
	Final Energy $[kWh]$	
Daily	16.8	5.6
Annual	6119.8	2039.9
	Primary Energy $[kWh]$	
Daily	41.9	14.0
Annual	15299.5	5099.8
	CO_2 emissions $[kgCO_2]$	
Daily	6.04	2.01
Annual	2203.12	734.37
	Price electricity [€]	
Daily	2.29	0.76
Annual	834.74	278.25

In this particular case, the integration of heat recovery in a heat pump water heater results in a reduction of 4080 kWh in final energy requirements. This leads to a decrease of 1469 kg in annual CO_2 emissions and a cost reduction of 556€ in annual DHW production expenses.

The final energy is again higher for an instantaneous gas water heater than for a heat pump water heater because of the difference in efficiency and COP, and it is again evident that even without heat recovery, a heat pump water heater presents economic and environmental advantages, saving up to 2190€ annually in this specific case when compared to a typical instantaneous gas water heater and decreasing CO_2 emissions by about 49%..

Finally, a side-by-side comparison between the instantaneous gas water heater without heat recovery and the heat pump water heater with heat recovery is made in Table 20.

Table 20: Comparison between instantaneous gas water heater without heat recovery and heat pump water heater with heat recovery, configuration 1

	IGWH Without Heat Recovery	**HPWH With Heat Recovery**
	Final Energy $[kWh]$	
Daily	59.1	5.6
Annual	21558.4	2039.9
	Primary Energy $[kWh]$	
Daily	59.1	14.0
Annual	21558.4	5099.8
	CO_2 emissions $[kgCO_2]$	
Daily	11.93	2.01
Annual	4354.79	734.37
	Price (Natural Gas) [€]	Price (Electricity) [€]
Daily	8.29	0.76
Annual	3024.64	278.25

Comparing the instantaneous gas water heater without heat recovery with the heat pump water heater with heat recovery shows an enormous improvement both in environmental and economical ways. For the specific case of a residential building that houses 50 people in total, a decrease of 83% in CO_2 emissions (about 3620 kg annually) and a decrease of 91% in total costs (around 2746€ annually) is predicted.

4.2.3 4-star Hotel Without Laundry

To analyze the impact of the introduction of heat recovery in a hotel, a 4-star hotel with 200 beds and without laundry was considered. It was considered that the DHW system for this hotel was centralized. The DHW needs are shown in Table 21.

Table 21: DHW needs for a 4-star hotel without laundry

	Volume $[l]$	Volume water heater $[l]$	Energy needs E_{useful} $[MJ]$	Energy needs E_{useful} $[kWh]$
Daily	23600	14160	2943.9	817.8
Annual	8614000	5168400	1074537.5	298482.6

In this case, since there is a centralized DHW system, configuration 2 was chosen for heat recovery. As a result of the energy balance at the shower mixing valve, only 33.4% of the water passes through the water heater, while the rest passes through the heat exchanger, is heated to 30°C and goes to the shower mixing valve. The water that enters the water heater comes from the mains at 10°C and is heated to 60°C. The energy needs to heat the water when there is heat recovery, with configuration 2, are shown in Table 22.

Table 22: DHW needs, with heat recovery, for a 4-star hotel without laundry

	Volume water heater $[l]$	Energy needs E_{useful} $[MJ]$	Energy needs E_{useful} $[kWh]$
Daily	7890.3	1640.4	455.7
Annual	2879946.7	598756.0	166321.1

In this case, with configuration 2 of heat recovery, a decrease of 44% in energy needs for DHW production is estimated.

The values of final energy, primary energy, CO_2 emissions, and price are shown in Table 23 for a gas water heater without heat recovery and with heat recovery.

Table 23: Comparison between gas water heater without heat recovery and with heat recovery, configuration 2

	Without Heat Recovery	**With Heat Recovery**
	Final Energy $[kWh]$	
Daily	929.3	517.8
Annual	339184.8	189001.3
	Primary Energy $[kWh]$	
Daily	929.3	517.8
Annual	339184.8	189001.3
	CO_2 emissions $[kgCO_2]$	
Daily	187.71	104.60
Annual	68515.33	38178.26
	Price natural gas [€]	
Daily	130.38	72.65
Annual	47587.63	26516.88

In this case, introducing heat recovery with the gas water heater, results in a decrease of around 150184 kWh in final energy, which leads to a reduction of 30337 kg in CO_2 emissions and 21071€ in annual DHW production costs.

The values of final energy, primary energy, CO_2 emissions, and price are shown in Table 24. A comparison was made between a heat pump water without heat recovery and with heat recovery.

Table 24: Comparison between heat pump water heater without heat recovery and with heat recovery, configuration 2

	Without Heat Recovery	**With Heat Recovery**
	Final Energy $[kWh]$	
Daily	263.8	147.0
Annual	96284.7	53652.0
	Primary Energy $[kWh]$	
Daily	659.5	367.5
Annual	240711.8	134129.9
	CO_2 emissions $[kgCO_2]$	
Daily	94.97	52.92
Annual	34662.50	19314.71
	Price electricity [€]	
Daily	35.98	20.05
Annual	13133.24	7318.13

In this case, when heat recovery is implemented for a heat pump water heater, there is a reduction of around 42633 kWh in final energy consumption, which leads to a decrease of 15348 kg in annual CO_2 emissions and 5815€ in terms of annual expenses.

The final energy is higher for a gas water heater than for a heat pump water heater because of the reasons aforementioned.

The substitution of a gas water heater with a heat pump water heater also offers significant economic benefits, even without heat recovery. It was estimated that for this specific case, up to 34454€ could be saved annually. The CO_2 emissions are higher for the gas water heater, decreasing by about 49% with the substitution of a heat pump water heater.

Finally, a side-by-side comparison between the gas water heater without heat recovery and the heat pump water heater with heat recovery is made in Table 25.

Table 25: Comparison between instantaneous gas water heater without heat recovery and heat pump water heater with heat recovery, configuration 2

	Gas Water Heater Without Heat Recovery	**Heat Pump Water Heater With Heat Recovery**
	Final Energy [kWh]	
Daily	929.3	147.0
Annual	339184.8	53652.0
	Primary Energy [kWh]	
Daily	929.3	367.5
Annual	339184.8	134129.9
	CO_2 emissions [$kgCO_2$]	
Daily	187.71	52.92
Annual	68515.33	19314.71
	Price (Natural Gas) [€]	Price (Electricity) [€]
Daily	130.38	20.05
Annual	47587.63	7318.13

In this case, it again becomes very clear that the combination of a heat pump water heater with heat recovery brings remarkable advantages when compared to a traditional gas water heater. It is estimated that CO_2 emissions can be reduced by 72% (around 49200 kg annually). The annual costs of DHW production are estimated to decrease by about 85% (around 40270€).

4.3 Discussion

The introduction of shower water heat recovery, with any configuration, brings enormous economic and environmental advantages.

From the calculations it can be seen that configuration 1, being the only one where the preheated water outlet is connected to both the water heater and the mixing valve, is the most efficient, and therefore the one with the greatest reductions in costs and CO_2 emissions.

Configuration 2, although not as efficient as configuration 1, still presents huge reductions in costs and CO_2 emissions, and can be very useful in cases where it is not possible for the water heater to be close to the heat recovery system, as is the case of the hotel considered.

Analyzing the results obtained it is clear that the replacement of the typical instantaneous gas water heater by a heat pump water heater brings both environmental and economic advantages, due to the great difference in efficiency of the equipment. The combination of heat pump water heater and heat recovery presents the most efficient and environmentally friendly scenario.

5. Conclusions and Future Works

5.1 Conclusions

Considering the present circumstances of climate change, the significance of reducing greenhouse gas emissions has become increasingly imperative. While hot water production may not be the primary contributor to these emissions, any opportunity to mitigate the impact of this practice should be seized.

With the accomplishment of this work, it is possible to conclude that the implementation of a SWHRU in the shower base yields substantial advantages, not only in terms of environmental benefits but also economically. It was observed that with configuration 1, energy requirements can be reduced by as much as 67%, leading to a significant impact on both CO_2 emissions and costs. With configuration 2, the energy requirements were estimated to be reduced by up to 44%. Therefore, even though configuration 2 has a lesser impact on CO_2 emissions and DHW production costs, it remains crucial for certain DHW systems, such as a centralized DHW system, where configuration 1 may not be as practical or feasible.

Furthermore, it has become apparent that replacing a conventional gas water heater with a heat pump water heater, even without incorporating heat recovery, can significantly reduce annual costs for DHW production. Additionally, this switch proves to be much more environmentally friendly. With the results obtained in this work, CO_2 emissions decreased by 49% while the annual costs were reduced by 72% when using a heat pump water heater instead of a typical gas water heater.

The most advantageous scenario examined in this study is the integration of a heat pump with a heat recovery unit. This combination demonstrates a remarkable reduction in both CO_2 emissions and annual costs when compared to a typical gas water heater. Configuration 1 yielded a noteworthy 83% reduction in CO_2 emissions and an impressive 91% reduction in costs. On the other hand, Configuration 2 resulted in a commendable 72% reduction in CO_2 emissions and a significant 85% reduction in costs.

In conclusion, implementing shower water heat recovery systems and heat pump water heaters greatly impact energy transition and building energy efficiency. These technologies promote sustainable and efficient energy use, leading to a greener future.

Shower water heat recovery systems reduce the energy needed for water heating, resulting in significant energy savings. This reduces reliance on traditional energy sources and lowers greenhouse gas emissions related to water heating, contributing to the energy transition.

Heat pump water heaters extract heat from the surrounding air and transfer it to the water, achieving higher energy efficiencies compared to conventional heaters. By reducing electricity demand for water heating, heat pump water heaters conserve energy and mitigate the environmental impact of traditional water heating methods.

The combined implementation of shower water heat recovery systems and heat pump water heaters offers a powerful synergy in maximizing energy savings and improving overall building energy efficiency. By integrating SWHR systems with HPWHs, the preheated water from the SWHR system can be supplied directly to the HPWH, further enhancing the efficiency of the heat pump. This integration reduces the workload on the heat pump, allowing it to operate more efficiently and consume less energy. Moreover, the recovered heat from the SWHR system reduces the load on the HPWH, extending its lifespan and reducing maintenance requirements.

Energy transition is crucial in combating climate change and achieving a sustainable future. By implementing these technologies, buildings significantly contribute to reducing energy consumption, lowering greenhouse gas emissions, and promoting efficient resource use. Additionally, these technologies improve building energy efficiency, leading to long-term cost savings for occupants.

In conclusion, the implementation of SWHR systems and HPWHs presents a significant opportunity to enhance energy efficiency, reduce environmental impact, and drive the energy transition forward. By adopting these technologies, buildings can play a pivotal role in creating a more sustainable and greener future for generations to come.

5.2 Future Works

For each of the situations analyzed in this work (single-family residential building, multi-family residential building, and hotel), a configuration for the SWHRU was considered based on theoretical information. For future work, it would be interesting to do advanced calculations, bearing in mind the storage and distribution losses, to check if the configurations considered for each situation were indeed the most beneficial.

It would also be interesting to repeat the calculations where configuration 1 was used but now using configuration 3, in order to comprehend the extent of influence exerted by the heat exchanger's connection to the shower mixing valve when it is also connected to the water heater.

Future studies could investigate the implementation of the different configurations of heat recovery and heat pump water heaters in other types of buildings, such as a pool or a gym. These applications have high water heating demands, making it worthwhile to investigate the potential energy and cost savings associated with these technologies in these settings.

Future research could focus on exploring potential improvements to the heat exchanger design to enhance its efficiency. Investigating innovative materials, geometries, or configurations for the heat exchanger could lead to optimized heat transfer and improved overall system performance. Understanding and enhancing the efficiency of the heat exchanger would contribute to greater energy savings and increased effectiveness of shower water heat recovery systems and heat pump water heaters.

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