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A Short Review of Recent Studies on Wastewater Heat Recovery Systems: Types and Applications

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Abstract

Reducing energy consumption has its direct impact on the worldwide environmental status. Smart energy processes must be adopted in order to enhance the reduction capacity of energy usage. In this view, both renewable energy as well as heat recovery strategy has been used in a wide range of engineering applications. With this in mind, hot wastewater is considered as a valuable source of energy that could be recovered. The present paper illustrates an overall review on the waste water heat recovery systems (WWHR). All systems can be classified based on their structural configuration and application. It has been shown that under some conditions a 50% energy could be stored or recovered using a heat recovery system. In addition, all systems are considered as an economic as well as environmental effective methods.

Keywords: Heat Recovery; Wastewater; Heat Exchanger.

1. Introduction

Currently, worldwide attention is centralized on climate and environmental changes. Urban residential areas and buildings occupy large proportions of energy which are considered as the main sources of greenhouse and CO₂ emissions [1][2]. Based on some studies, building sector contributes up to 30% of energy used worldwide; this energy is mainly used for either heating/cooling applications or for the production of hot water, which is quite prominent inside buildings [3][4]. Particularly as shown in Fig. 1, China accounts for 9.78% of the total world energy consumption, where 30% of this energy is consumed by buildings [5]. Another study shows that 40% of the total energy consumption is shared by building sectors in the European Union, which is also responsible for 36% of the total EU CO₂ emissions [6].

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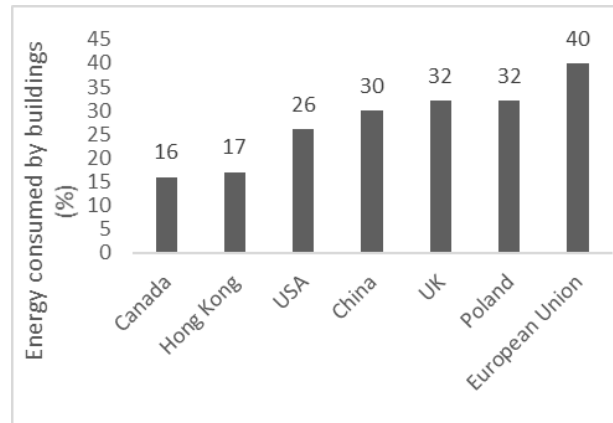


Fig. 1. Percentage of energy consumed by buildings in several countries [5-8].

In order to overcome this high energy demands and costs, several alternatives have been promoted, such as renewable energy sources (solar energy [9][10], wind energy [11][12] and geothermal energy [13][14]), energy management and control systems [15] and energy recovery systems [16,17]. Energy recovery systems are considered one of the most important solutions, where they permits reducing energy consumption by transferring lost energy from one system to another, considering heat loss as a key-element in this process [18][19]. In buildings, water heating represents the largest contribution of energy consumption, and from an energy recovery point of view, hot waste water that is disposed into the sewage system from sinks, dishwashers, showers ...etc., is considered as a valuable source of heat loss. It is noticed that the interest in wastewater heat recovery units has been increased recently using different processes. In this view and to the authors' best knowledge, there are few studies that aim to provide intensive reviews about heat recovery from various sources such as engines [20][21], industrial systems [22][23] and from building sectors mainly from chimneys [24][25] and HVAC systems [26-28]. However, none of the previous studies provide a comprehensive review that would present the classifications of the waste water heat recovery systems used and their applications in buildings.

The present paper is dedicated to focus on the existing recent studies. This review will consider the recent available technologies that deal with wastewater heat recovery systems mainly coming from hot drain water. After reviewing the literature, the work can be done by classifying the available technologies based on their configurations and installations taking into consideration the effect of several parameters on their effectiveness and performance. The paper is organized as follows: Section 2 will present the potential and principle behind waste water heat recovery systems. The existing structural types of waste water heat recovery systems will be clarified in section 3. Section 4 will be devoted to showing different studies using various configurations for wastewater heat recovery systems. Finally, Sections 5 and 6 will be dedicated to the discussion and conclusions respectively.

Nomenclature

WWHR	Wastewater heat recovery system
DWHR	Drain water heat recovery system
EU	European Union
CO ₂	Carbon dioxide emission
°C	Degree Celsius
UK	United Kingdom
USA	United states of America
MJ/Home/day	Joules per home every day
PCM	Phase change material
SWH	Solar water heater
COP	Coefficient of performance

SDW shower drain water

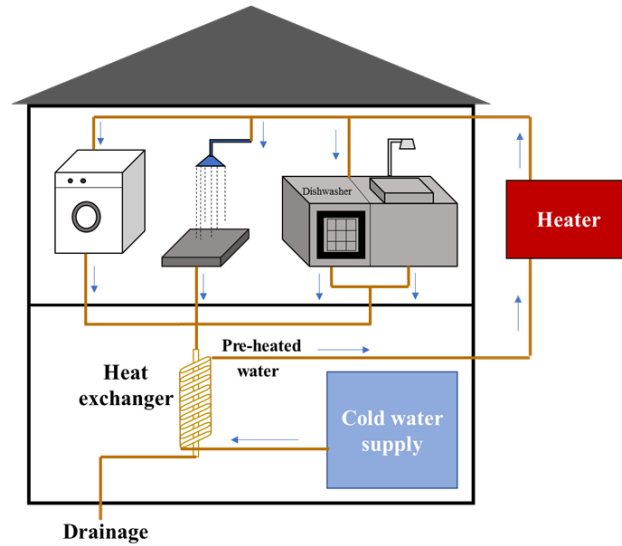


Fig. 2. Schematic of wastewater sources inside a house.

2. Wastewater heat recovery

2.1. Potential of energy in wastewater

Heat recovery from wastewater is a highly activated technology in countries like the UK, Norway, USA and Netherlands where a large amount of hot wastewater is produced every year and especially from residential buildings. For example, in a Dutch house, the average temperature of drain water is about 27 °C, giving a heat potential of 21.3 MJ/home/day [29-31]. Generally, the hot water generated from buildings has a high thermal capacity and its average temperature can range between 40-50 °C. In Netherlands and Switzerland, the heat loss from buildings that can be found in the sewer systems and originated from waste hot water, contributes about 40% and 30% of the total energy loss from buildings respectively, keeping the rest for other applications and building envelopes. With this in mind, studies have shown that implementing an energy recovery system in the sewer network or inside buildings through a heat exchanger can help exploit the heat loss from domestic hot water better than studying treatment optimization [32].

2.2. Concept of wastewater heat recovery system

As this paper takes into consideration the heat recovery from drain water mainly at the building level, Fig. 2 presents a schematic of different drain water sources. Heating a supply water before entering the water heater by the heat carried from the drain water is the main idea behind this concept, in other terms raising the water supply temperature after passing through the drainage system as a preheating step [33][34]. Fig. 3 shows the working principle of a heat

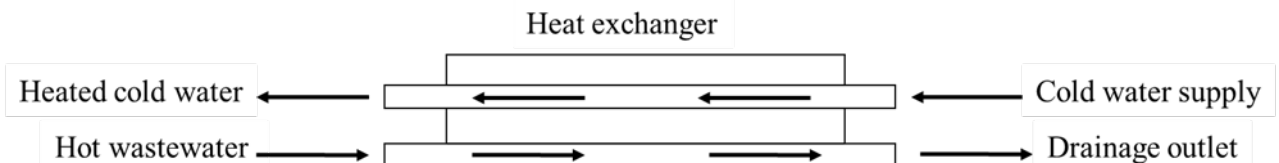


Fig. 3. Working principle of waste water heat recovery systems.

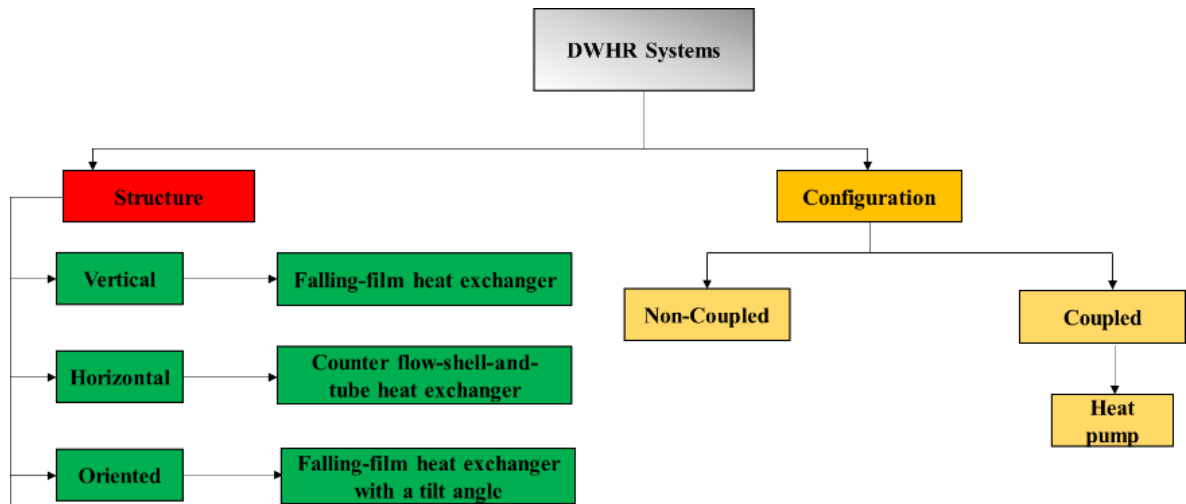


Fig. 4. Flow diagram of the classification of the WWHR system reviewed.

exchanger which represents the main component in a WWHR system. Various types of heat exchangers may be installed within systems in order to perfectly adopt the best heat transfer state. The temperature difference between the supply water and drain water will result in a heat transfer rate that will be affected by the heat transfer area and the thickness of water. Their installations in any residential building depend on several parameters, such as the building architecture and the availability in space where different types of WWHR units can be used. Copper pipes are commonly used in the WWHR system's application due to their high conductivity ensuring the best heat transfer, in addition to their ability to reduce fouling inside the pipes, hence reducing the need for periodic cleaning. [35-38].

3. Classifications of WWHR systems

Based on the literature, the heat exchanger type and structure used can be categorized according to three groups based on their structure: vertical systems (including storage tanks), horizontal systems and oriented systems. In general, the setup

of the WWHR system reviewed doesn't have any mechanical part, having a lifetime of over 30 years. Usually, studies conducted on this process take into account the structure, capacity, performance and the financial sides of waste water heat recovery treatment. Most of the publications were implemented experimentally, while some rely on numerical simulations where the analysis of these systems is concentrated on the energetical and economic sides of waste water heat recovery systems and some on their environmental benefits. In the previous decades, the work on wastewater heat recovery systems focused on giving a preliminary study on this domain. However recently, studies can be categorized according to the type of configurations used, as shown in Fig. 4. [39][40].

4. WWHR systems' applications

4.1. Non-coupled systems

Non-coupled systems use different structures of a heat exchanger to heat upcoming cold water without an additional system where they are usually connected directly with the sewage pipe lines.

4.1.1. Vertical systems

This type is commonly used and is characterized by a gravity film heat exchanger as shown in Fig. 5. The system consists of a main inner pipe with a spiral coil wrapped around it, that has a higher heat transfer area compared to a straight pipe. The heat transfer in this type of heat exchanger is affected by the geometry of the design, including the

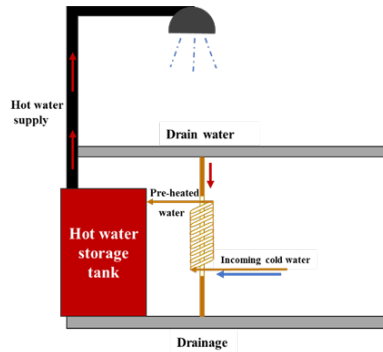


Fig. 5. Schematic of a vertical WWHR system assisted in a shower drain.

number of coil loops. The hot water flows (inside buildings temperature can be above 60 °C) at the top of the main pipe and adheres to the inlet walls. Cold water is supplied to the spiral coil where extracting heat from hot water starts until leaving the system at the top of the unit with warm water [41–43]. Some recent studies on single systems using vertical heat exchangers are presented in Table 1 giving the most important results from those studies.

Another installation scenario that can be used based on vertical systems relies on using a storage tank where the use of the WWHR system is to heat or preheat the water before being stored before being heated up to match the building requirements using means like heat pumps (see Fig. 6.) [44][45]. These studies have shown their economic and environmental benefits in some cases, in addition to their promising performance. The challenge behind WWHR systems is sometimes the low temperature and the fact that part of the drain water heat is wasted inside or outside the system’s envelope. With this in mind, the boiler/electric heater has to be installed just after the recovery system for better performance.

Table 1. Recent studies on single systems with a vertical heat exchanger

Ref.	Methodology	Approach	Main findings
[41]	Experimental	Effect of inlet temperature on system’s effectiveness.	Regardless of the geometry, any increase in main and drain sides’ temperatures will increase the effectiveness.
[42]	Experimental, Numerical	Analysis based on preheating water step.	Preheating water is considered to be beneficial financially. Its effectiveness increases with shower length and water consumption.
[43]	Experimental	Parametric analysis based on experimental setup.	Effectiveness increases with boiler output temperature.
[44]	Experimental	Hot water is discharged into a cylindrical tank with a spiral tube that carrying the cold water.	High temperature is available due to limited mixing between cold and hot flows, leading to better heat recovery.
[45]	Experimental, Numerical	The tank is charged with hot water coming from hot water tank.	The maximum heat transfer occurred at the lower flow rates. The capacity to recover about 34% to 60% from the available energy in the drain water.
[46]	Experimental, Numerical	A drain water heat recovery storage unit based on PCM plates.	A maximum of 800 kJ of heat can be removed from the drain source where 50% of the thermal energy can be provided for the next stage of a washing machine.
[47]	Experimental	Comparison between solar water heat and drain heat recovery system.	The drain water heat recovery system is much costlier effective than SWH in saving energy.
[48]	Experimental	Performance study based on flow rates and wetting sides.	The effectiveness of the heat exchanger drops with the increase of flow rates.

[49]	Experimental, Numerical	Parametric analysis of a multi-drain heat recovery system for heating/preheating cold water.	A case study in Lebanon for a drain temperature of 25°C showed, the energy used is reduced from 102.2 kWh to 410.9 kWh monthly. The increase in money saving is from 13.3 \$ to 53.4 \$. The monthly emissions reduction is increased from 72.5 kg to 291.7 kg.
[50]	Experimental	Performance of falling film DWHR system based on heat exchanger effectiveness and side wetting.	In partial wetting conditions, a reduction of about 28% in effectiveness would occur.
[51]	Experimental	The impact of having unequal flow rates on main and drain sides inside falling film heat exchanger.	Flow rates can highly affect the performance of the DWHR system and any change in inlet flow rates can also affect the performance regardless of other design parameters.

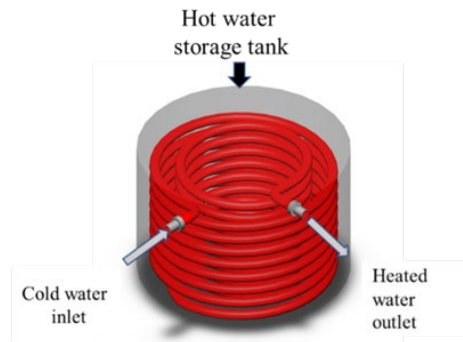


Fig. 6. Storage tank heat exchanger.

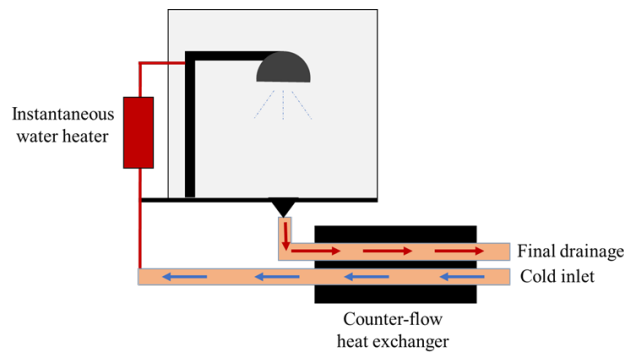


Fig. 7. Schematic of a simple single-pass horizontal installation of WWHR unit.

Table 2. Studies on single systems using horizontal heat exchanger.

Ref.	Methodology	Approach	Main findings
[52]	Experimental	Study based on shower time, water flow and inlet temperature on energy savings.	Saved energy reached is up to 15% which is an increase from 104 MWh to 406 MWh, with a drainage pipe of 50mm diameter and 1.5m counter flow heat exchanger long
[53]	Experimental, Numerical	A study on a copper pipe inserted inside a drainage plastic pipe.	The full implementation of the DWHR in every household in Ireland could amount to a

			national saving of 808 GWh for one shower per home. Which accounts for a reduction of over 400,000 tons of CO ₂ . The effectiveness reaching 45% increased with increasing the loops of the system, thinner cold-water pipe, and low flow rates of drain water.
[54]	Experimental	Study of effectiveness for two horizontal DWHR systems: brand new baffled heat exchanger and a normal heat exchanger	Based on lab conditions, the baffled heat exchanger is of higher effectiveness value than the normal one.

4.1.2. Horizontal systems

Residential buildings in some cases may not have enough space to install a vertical unit below shower trays. Horizontal WWHR systems may be sufficient where it can be installed also in different public sectors. These systems use a simple single pass counter flow heat exchanger connected directly to a water heater, as shown in Fig. 7. It is clear that in the vertical unit the water will flow around the whole boundary of the pipe, ensuring a high conductive efficiency. In the horizontal system, the water flows at the bottom of the pipe, reducing the heat transfer rates. This system is rarely used since in some cases its efficiency is considered limited compared to a vertical system. Some studies on horizontal systems are shown in Table 2. [55][56]. When comparing between the aforementioned setups, it can be shown that the effectiveness of the heat exchanger used can reach up to 50% and 60% for horizontal and vertical installations in some cases respectively. This difference is due to the fact that vertically installed heat exchangers can ensure heat transfer across the whole boundary of the pipe system, while the horizontal setup uses only a specific part of the pipe for heat transfer. In addition, the overall efficiency of the system is mainly affected by factors like: showering time, cold water temperature, flowrates, fouling effect, flow regime inside pipes and the temperature between the shower head and the drain point, where these factors differ between studies.

4.1.3. Inclined systems

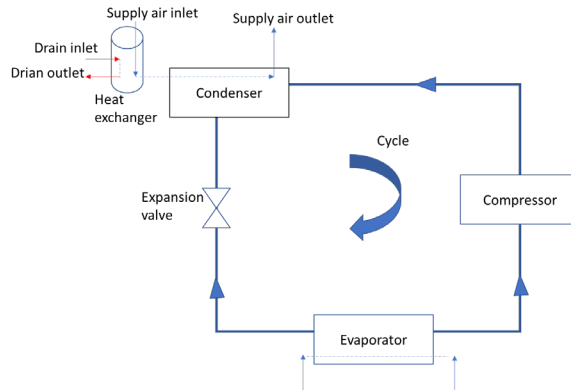
In designing some buildings, a tilt angle between the drain system heat exchanger and the vertical line should be considered. The function of this inclined type of heat exchanger is similar to the vertical system. However, while measuring the change of effectiveness compared to a vertical system, it is shown that it started with a reduction of 4% with a tilt angle 2° caused by a non-uniform flow [57].

4.2. Coupled systems with heat pumps

Hybridization between WWHR systems and other energy applications is a promising approach. Very few studies combined the WWHR system with solar domestic water heaters for better efficiencies [58][59]. However, the main focus is coupling the WWHR system with a heat pump [60][61]. It is well known that a heat pump is a device that performs a fully reversible cycle which transfers energy from one medium to another under the basis of a circulating fluid called refrigerant [62-64]. It has three thermal energy sources: air, ground and water [65-68]. The use of wastewater source heat pumps has been increased due to their energy-savings properties and performance [69-72]. Installation of urban sewage source heat pumps has been considerably increased [73-75]. Table 3 provides some recent studies on the available applications using heat pumps.

Few are the papers that clearly studied the hybridization between heat pumps and WWHR system. Coupling between the heat pump and the heat recovery system works as an enhancement of the heat pump's performance, a heat source for the evaporator or as a booster for the heat recovery system. Such objectives can lead to better satisfying the heating and hot water demands inside residential buildings. In other words, the heat recovered here can be assessed

Fig. 8. Coupling between heat pump system and drain water heat recovery system



easily relying on an enhanced heat recovery ratio which is convenient for a better supply demand formula. Fig. 8 shows an example of a coupling between wastewater heat recovery system and w heat pump system. This drain system can be attached also to the evaporator.

5. Discussion

The diversity in construction and utilization of heat recovery systems from wastewater showed the capability of these units to reduce energy consumption as well as reduce environmental pollution. Large amounts of wastewater with a high temperature and flow rate goes through sewage every year, which is a motivating element for governments to install this technology and especially from shower where it consumes the highest amount of energy. Different concluding remarks were noticed throughout this review:

- 1- China has dominated a large number of researches in this domain and then Canada comes in second place where several studies were published in it.
- 2- The setup designs in different publications can be classified into different configurations that lie in two criteria's: single and hybrid systems. Hybrid systems may use heat pumps coupled with a heat recovery system or a solar heater. Other types of hybrid applications could be used, like a typical coupling between exhaust gas heat recovery with wastewater.
- 3- Almost all the studies implemented an experimental setup, where few studies assess their research with a numerical simulation, where a low discrepancy between numerical simulations and experimental analysis was noted among all. However, the numerical approach should be broadened since it allows deeper understanding of the heat transfer phenomena that will occur in such systems.
- 4- Various types of heat exchangers were used throughout studies where the heat transfer performance through it is dominated by the temperature difference between hot and cold flows. In most cases, a helical type of heat exchanger is used. However, a more advanced form of heat exchanger could be utilized to enhance the heat transfer is a heat exchanger coupled to phase change material which may offer a higher efficiency.

Table 3. Studies on coupled systems with heat pump

Ref.	Methodology	Heat exchanger	Approach	Main findings
[76]	Experimental, Numerical	Counter flow heat exchanger	A heat pump water heater assisted by shower wastewater with thermodynamic models.	An optimal COP of 4.97 with condenser and evaporator optimized temperatures.
[77]	Experimental	Gravity film	The performance of a vertical DWHR system with a heat pump under different drain water flows.	Sizing the recovery system is important to match the drain water profiles. For 5 apartments, the available energy recovered from drain is 23.3 kWh.

[78]	Experimental, Numerical	Gravity film	Performance of vertical DWHR with heat pump	The heat recovery is affected by the contact heat resistance between the inner and outer pipe of the heat exchanger reaching 25%. Flow rate and inlet temperature affect the effectiveness and the heat recovery ratio respectively. Under the given condition, the heat recovery ratio ranges between 32 and 50%.
[79]	Experimental	NA	A novel heat pump water heater for shower assisted with shower drain water. A waste heat extraction device with water pre-heater was installed.	Water pre-heated loops showed a better performance where more waste heat in the SDW could be recovered with a COP increased from 2.19 to 3.21. The energy consumption of the system increased by increasing the water flow rates and shower temperature. The design can save 70% energy compared to an electrical water heater. Where, the total energy saving was is 659 kW h/year, and with a saving of ¥336 per year.
[80]	Numerical, Experimental	Gravity film	The performance of drain heat recovery system for enhancing the performance of a heat pump under several scenarios	The COP can be increased by increasing the air supply temperature and the flow rate of the drain. The scenario using a condenser and evaporator with the heat recovery system is the most likely to improve the heat pump's performance. The saved money is up to 47\$/month. The amount of reduced energy is 365 kWh. And the amount of CO ₂ reduction is increased from 82 to 259kg as the drain water inlet temperature increases from 20°C to 50°C.

5- In most cases, the wastewater source is a shower, which is due to the fact that this source is available in all residential zones. Nevertheless, other typical residential applications that provide hot waste water could be used as a heat source where they are yet investigated.

6- The performance of different trends on experimental setups and numerical studies lies in the fact that the flow rates and temperature difference between cold and hot flows has a significant effect on the heat recovery efficiency. While, losses like conduction and convection through the walls of WWHR system have a slight effect on its potential.

7- Barriers

a- Technical Barriers

- Fouling

Almost all types of wastewater may contain bio-substances which will lead to de-fouling within the surface of a heat exchanger in a biological growth form. These precipitations will affect in reducing heat transfer efficiency. Nonetheless, in order to minimize bio-fouling growth, different cleaning systems should be installed inside WWHR system tubes.

- Contamination

The majority of works were compiled that wastewater in some cases may be contaminated, so untreated sewage water may cause a serious problem like fouling in the unit, which will reduce the potential of recovering heat for long term usage.

- Pressure Drop

Increasing the cold flow temperature will decrease system efficiency where special attention should be given to the pressure drop inside the cold pipe in a way increasing the effectiveness of the unit.

- b- Social Barriers

Management systems and high-tech buildings can be built by a limited number of countries which have sufficient economic and social capacities, thus helping to develop and support this technology worldwide. Meanwhile, different social or scientific organizations should be taking this technology into consideration in their awareness campaigns in coordination with the governments and ministries in order to ensure financial support and a full knowledge of these systems and help to facilitate and improve the lives of citizens.

- c- Economic Barriers

The WWHR system's expenses and maintenance costs are considered high especially when dealing with complicated systems that are coupled with heat pumps or solar systems. This economic problem is contracting the use of this technology since it would not be available for all society levels.

6. Conclusions and future perspectives

Waste water heat recovery can be considered as an indirect renewable energy source. It is not only a bounteous source of heat, but it is also available in each house. What's more, due to its thermal characteristics, it can be easily extracted and reutilized in other applications. The present paper conducted an inclusive review on the available (WWHRs)s, highlighting their potential in the field of energy efficiency and energy saving. The studies are presented according to their timeline of publication and categorized based on their type of installation.

From a practical point of view, the heat exchanger is the core of (WWHRs)s, where it can greatly influence its performance. A counter flow heat exchanger is usually used since it allows better heat transfer. (WWHRs)s can be classified within three main configurations: vertical including storage tank based systems, horizontal and oriented. Moreover, the recovery systems are categorized within two categories: Single systems and Hybrid systems. Single systems mainly rely on the heat transfer process. While the hybrid type uses a heat pump or a solar system coupled with a WWHRs.

Nevertheless, the main parameters that affect the heat performance of (WWHRs)s are: viscosity of water, hot and cold temperatures, ambient temperature and flow rates. It has been remarked that the effectiveness of (WWHRs)s is higher when coupled to a heat pump where the COP may exceed 6 in some configurations. It was also noticed that increasing the hot flow rate and temperature would increase both effectiveness and efficiency of the system. Economically, the average payback period for single systems is seven years whereas for hybrid systems it is five years. Furthermore, several obstacles should be taken into consideration in order to preserve the performance of (WWHRs)s, such as fouling, contamination and pressure drop.

References

- [1] Zhou, Moncaster, O'Neil, Reiner, Wang and Guthrie. (2022) "Modelling future trends of annual embodied energy of urban residential building stock in China." *Energy Policy* 165 (2022): 112932.
- [2] Rivera, Maclean and McCabe. (2021) "Implications of passive energy efficiency measures on life cycle greenhouse gas emissions of high-rise residential building envelopes." *Energy and Buildings* 249 (2021):111-202.
- [3] Lyu, Li, Shi, Wang and Haung. (2011) "A general method to evaluate the applicability of natural energy for building cooling and heating: Revised degree hours." *Energy and Buildings* 250 (2021):111-127.
- [4] Tyagi, Chopra, Kalidasan, Chauhan, Stritih, Anand, Pandey, Sari and Kothari. (2021nm0) "Phase change material based advance solar thermal energy storage systems for building heating and cooling applications: A prospective research approach." *Sustainable Energy Technologies and Assessments* 47 (2021): 101-318.
- [5] Yang, Li, Wang, Huang and Peng. (2015) "Testing for Energy Recovery Ventilators and Energy Saving Analysis with Air-Conditioning Systems." *Procedia Engineering* 121 (2015): 438 – 445.
- [6] Ilie, Dumitrescu, Girip, Cublesan. (2017) "Study on technical and economical solutions for improving air conditioning efficiency in building sector." *Energy Procedia* 112 (2017):537 – 544

- [7] Slys, Kordana. (2014) “Financial analysis of the implementation of a Drain Water Heat Recovery unit in residential housing. *Energy Buildings* 71 (2014):1–11.
- [8] Boait, Dixon, Fan and Stafford. (2012) “Production efficiency of hot water for domestic use.” *Energy Buildings* 54 (2012):160–168.
- [9] Kuskaya. (2022) “Residential solar energy consumption and greenhouse gas nexus: Evidence from Morlet wavelet transforms.” *Renewable Energy*.
- [10] Ma, Li, Gu, Weng, Peng and Xiao. (2022) “Solar energy harvesting pavements on the road: comparative study and performance assessment.” *Sustainable cities and society* 81 (2022): 103868.
- [11] Zhou, Lu, Liu, Chang and Wang. (2017) “Harvesting wind energy in low-rise residential buildings: Design and optimization of building forms.” *Journal of Cleaner Production* 167 (2017): 306-316.
- [12] Ge, Shen, Zhao and Lv. (2022) “Energy production features of rooftop hybrid photovoltaic–wind system and matching analysis with building energy use.” *Energy Conversion and Management* 258 (2022): 115-485.
- [13] Neves, Cho and Zhang. (2021) “State of the nation: Customizing energy and finances for geothermal technology in the United States residential sector.” *Renewable and Sustainable Energy Reviews* 137 (2021): 110-463.
- [14] Liu, Zhang, Xu, Yang, Liu and Jin. (2020) “Suitability and feasibility study on the application of groundwater source heat pump (GWSHP) system in residential buildings for different climate zones in China.” *Energy Reports* (2020): 2587-2603.
- [15] Brandi, Gallo and Capozzoli. (2022) “A predictive and adaptive control strategy to optimize the management of integrated energy systems in buildings.” *Energy Reports* (2022): 1550-1567.
- [16] Barreto, Qu, Wang, Iten and Riffat. (2022) “An innovative window heat recovery (WHR) system with heat pipe technology: Analytical, CFD, experimental analysis and building retrofit performance.” *Energy Reports* 8 (2022): 3289-3305.
- [17] Alhajri, Gadalla and Elazab. (2021) “A conceptual efficient design of energy recovery systems using a new energy-area key parameter.” *Energy Reports* 7 (2021): 1079-1090.
- [18] Xu, Cui, Wang and Wang. (2021) “Simulation study on exhaust turbine power generation for waste heat recovery from exhaust of a diesel engine.” *Energy Reports* 7 (2021): 8378-8389.
- [19] Zhang, Zhao, Lu, Ni and Li. (2017) “Waste energy recovery and energy efficiency improvement in China’s iron and steel industry.” *Applied Energy* 191 (2017): 502–520.
- [20] Bumete, Mariasiu, Depcik, Barabas and Moldovanu. (2022) “Review of thermoelectric generation for internal combustion engine waste heat recovery.” *Progress in Energy and Combustion Science* 91 (2022): 101-009.
- [21] Salek, Babaie, Naserian and Ahmadi. (2022) “Power enhancement of a turbo-charged industrial diesel engine by using of a waste heat recovery system based on inverted Brayton and organic Rankine cycles.” *Fuel* 322 (2022): 124-036.
- [22] Shahzad, Ding, Xuan, Gao and Chen. (2022) “Performance analysis of a novel double stage multifunctional open absorption heat pump system: An industrial moist flue gas heat recovery application.” *Energy Conversion and Management* 254 (2022): 115-224.
- [23] Ge and Lang. (2022) “Alloy selections in high-temperature metal hydride heat pump systems for industrial waste heat recovery.” *Energy Reports* (2022): 3649-3660.
- [24] Khalil and Hassan. (2020) “Enhancement of waste heat recovery from vertical chimney via thermoelectric generators by heat spreader.” *Process Safety and Environmental Protection* 140 (2020): 314-329.
- [25] Khalil and Hassan. (2019) “3D study of the impact of aspect ratio and tilt angle on the thermoelectric generator power for waste heat recovery from a chimney.” *Journal of Power Sources* 418 (2019): 98-111.
- [26] Sukarno, Putra and Ibnu Hakim. (2021) “Non-dimensional analysis for heat pipe characteristics in the heat pipe heat exchanger as energy recovery device in the HVAC systems.” *Thermal Science and Engineering Progress* 26 (2021): 101-112.
- [27] Ramadan, Gad El Rab and Khaled. (2015) “Parametric analysis of air–water heat recovery concept applied to HVAC systems: Effect of mass flow rates.” *Case Studies in Thermal Engineering* 6 (2015): 61-68.
- [28] Garayo, Martinez and Astrain. (2022) “Optimal combination of an air-to-air thermoelectric heat pump with a heat recovery system to HVAC a passive house dwelling.” *Applied Energy* (2022): 118-443.
- [29] Frijns, Hofman and Nederlof. (2013) “The potential of (waste) water as energy carrier.” *Energy Conversion Management* 65 (2013):357–63.
- [30] Schmid. (2009) “Sewage Water: interesting heat source for. Swiss Energy Agency Infrastruct Plants.” (2009).
- [31] Hofman, Hofman–Caris, Nederlof, Frijns and Van Loosdrecht. (2011) “Water and energy as inseparable twins for sustainable solutions.” *Water Science and Technology* 63 (2011): 88–92.
- [32] Pomianowski, Johra, Marszal-Pomianowska and Zhang. (2020) “Sustainable and energy-efficient domestic hot water systems: A review.” *Renewable and Sustainable Energy Reviews* 128 (2020):109900.
- [33] Kretschmer, Simperler and Ertl. (2016) “Analysing wastewater temperature development in a sewer system as a basis for the evaluation of wastewater heat recovery potentials.” *Energy Buildings* 128 (2016):639–48.
- [34] Prado and Gonçalves. (1998) “Water heating through electric shower and energy demand.” *Energy Buildings* 29 (1998):77–82.
- [35] Peereboo and Peereboom. (1998) “Recovering heat from shower water in dwellings.” (1998).
- [36] Ip and She. “Waste heat recovery from showers: case study of a university sport facility in the UK.” *Water Efficiency Conference* (2016).
- [37] Wong, Mui and Guan. “Shower water heat recovery in high-rise residential buildings of Hong Kong.” *Applied Energy* 87 (2010):703–9.
- [38] Zaloum, Lafrance and Gusdorf. “Drain water heat recovery characterization and modeling.” *National Resources Canada* (2007): 0–42.
- [39] Lindley and Orourke. (1981) “Future building package: Is domestic heat recovery really necessary?” *Heat Recovery Systems* 1 (1981):167-179.
- [40] Gonzalez, Tabares, Alvarez and Viar. (2001) “Feasibility study for the installation of HVAC for a spa by means of energy recovery from thermal water—Part I: Analysis of conditions.” *Renewable Energy* 23 (2001): 123–134.

- [41] Manouchehri and Collins. (2016) "An experimental analysis of the impact of temperature on falling film drain water heat recovery system effectiveness." *Energy Buildings* 130 (2016):1–7.
- [42] Slys and Kordana. (2014) "Financial analysis of the implementation of a Drain Water Heat Recovery unit in residential housing." *Energy Buildings* 71 (2014):1–11.
- [43] Ramadan, Iemenand, and Khaled. (2016) "Recovering heat from hot drain water—Experimental evaluation, parametric analysis and new calculation procedure." *Energy Buildings* 128 (2016):575–582.
- [44] De Paepe, Theuns, Lenaers and Van Loon. (2003) "Heat recovery system for dishwashers." *Applied Thermal Engineering* 23 (2003):743–756.
- [45] Torras, Oliet, Rigola and Oliva. (2016) "Drain water heat recovery storage-type unit for residential housing." *Applied Thermal Engineering* 103 (2016):670–683.
- [46] Ruiz, Rigola, Oliet and Oliva. (2016) "Analysis and design of a drain water heat recovery storage unit based on PCM plates." *Applied Energy* 179 (2016):1006–1019.
- [47] Leidl and Lubitz. (2009) "Comparing domestic water heating technologies." *Technology in Society* 31(2009): 244–256.
- [48] Beentjes, Manouchehri, and Collins. (2014) "An investigation of drain-side wetting on the performance of falling film drain water heat recovery systems." *Energy and Buildings* 82 (2014): 660–667.
- [49] Murr, Khaled, Faraj, Harika and Abdulhay. (2020) "Multi drain heat recovery system – Thermal modeling, parametric analysis, and case study." *Energy and Buildings* 228 (2020): 110–447.
- [50] Salama and Sharqawy. (2020) "Experimental investigation of the performance of a falling-film drain water heat recovery system." *Applied Thermal Engineering* 179 (2020): 115–712.
- [51] Manouchehri and Collins. (2018) "An experimental analysis of the impact of unequal flow on falling film drain water heat recovery system performance." *Energy and Buildings* 165 (2018): 150–159.
- [52] Wong, Mui and Guan. (2010) "Shower water heat recovery in high-rise residential buildings of Hong Kong." *Applied Energy* 87 (2010): 703–709.
- [53] McNabola and Shields. (2013) "Efficient drain water heat recovery in horizontal domestic shower drains." *Energy and Buildings* 59 (2013): 44–49.
- [54] Pochwat, Kordana, starzec and Slys. (2019) "Comparison of two-prototype near-horizontal Drain Water Heat Recovery units on the basis of effectiveness." *Energy* 173 (2019): 1196–1207.
- [55] Peereboom and Visser. (1998) "Peereboom Recovering heat from shower water in dwellings." (1998).
- [56] Ip and She. (2016) "Waste heat recovery from showers: case study of a university sport facility in the UK." *Water Efficiency Conference* (2016).
- [57] Manouchehri, Banister and Collins. "Impact of small tilt angles on the performance of falling film drain water heat recovery systems." *Energy and Buildings* 102 (2015):181–186.
- [58] Tanha, Fung and Kumar. (2015) "Performance of two domestic solar water heaters with drain water heat recovery units: Simulation and experimental investigation." *Applied Thermal Engineering* 90 (2015): 444–459.
- [59] Liu, Fu and Jiang. (2010) "Application of an exhaust heat recovery system for domestic hot water." *Energy* 35 (2010):1476–81.
- [60] Baek, Shin and Yoon. (2005) "A study on the design and analysis of a heat pump heating system using wastewater as a heat source." *Solar Energy* 78 (2005):427–440.
- [61] Zhao, Fu, Zhang, Jiang, Lai. (2010) "Study of the performance of an urban original source heat pump system." *Energy Conversion and Management* 51 (2010):765–770.
- [62] Vering, Kroppa, Venzik, Streblov and Müller. (2022) "Towards an integral decision-making process applied to the refrigerant selection in heat pumps." *Renewable Energy* (2022).
- [63] Guzzardi, Costantino, Marco Azzolin, Sandro Lazzarato, and Davide Del Col. (2022) "Refrigerant mass distribution in an invertible air-to-water heat pump: effect of the airflow velocity." *International Journal of Refrigeration* (2022).
- [64] Xu, Qiangqiang, Jianghong Wu, Zhengdao Guo, Geyao Xu, Yiqun Chen, Huaiyu Yang, and Xiangjin Xue. (2022) "Experimental investigation on control strategy of electric vehicle heat pump with refrigerant injection at low temperature." *International Journal of Refrigeration* (2022).
- [65] Han, Lichao, Shuangquan Shao, Zhichao Wang, Qiang Yang, Zhaowei Xu, Jiandong Li, Xiaoxi Gou, and JinPeng Suo. (2022) "A new method for field test of the heating capacity of air source heat pumps." *Flow Measurement and Instrumentation* 85 (2022): 102–168.
- [66] Fan, Yi, Jing Li, Xudong Zhao, Steve Myers, Yuanda Cheng, Min Yu, Yousef Golizadeh Akhlaghi, XiaoLi Ma, and Sen Yu. (2022) "A proof-of-concept study of a novel ventilation heat recovery vapour injection air source heat pump." *Energy Conversion and Management* 256 (2022): 115404.
- [67] Ceglia, Francesca, Elisa Marrasso, Carlo Roselli, Maurizio Sasso, and Peter Tzscheuschler. (2022) "Exergetic and exergoeconomic analysis of an experimental Ground Source Heat Pump system coupled with a thermal storage based on Hardware in Loop." *Applied Thermal Engineering* (2022): 118559.
- [68] Jung, Yujun, Jinwoo Oh, Ukmin Han, and Hoseong Lee. (2022) "A comprehensive review of thermal potential and heat utilization for water source heat pump systems." *Energy and Buildings* (2022): 112124.
- [69] Chen, Qiong, Wenhan Wei, and Nan Li. (2022) "Techno-economic control strategy optimization for water-source heat pump coupled with ice storage district cooling system." *International Journal of Refrigeration* (2022).
- [70] Wang, Qiang, Xiaoming Zhang, Xinqi Geng, Xu Chen, and Meize Xing. (2022) "Experiments on the characteristics of a sewage water source heat pump system for heat recovery from bath waste." *Applied Thermal Engineering* 204 (2022): 117956.

- [71] Jung, Yujun, Joonbyum Kim, Heejoon Kim, Yujin Nam, Honghyun Cho, and Hoseong Lee. (2021) "Comprehensive multi-criteria evaluation of water source heat pump systems in terms of building type, water source, and water intake distance." *Energy and Buildings* 236 (2021): 110765.
- [72] Wang, Wenyi, Jiatong Jiang, Bin Hu, R. Z. Wang, Mingwen Luo, Guangpeng Zhang, and Bo Xiang. "Performance improvement of air-source heat pump heating system with variable water temperature difference. (2022) " *Applied Thermal Engineering* 210 (2022): 118366.
- [73] Zhang, Qunli, Zhiming Wang, Chaohui Yin, Qian Nie, and Liwen Jin. (2017) "Field test analysis of an urban sewage source heat pump system performance." *Energy Procedia* 143 (2017): 131-136.
- [74] Liu, Zhibin, Liangdong Ma, and Jili Zhang. (2014) "Application of a heat pump system using untreated urban sewage as a heat source." *Applied Thermal Engineering* 62, no. 2 (2014): 747-757.
- [75] Qunli, Zhang, Nie Qian, Liu Fang, and Yin Chaohui. (2017) "Technology and economic analysis of sewage source heat pump combined type district heating method." *Energy Procedia* 142 (2017): 1312-1318.
- [76] Chen, Liang, Guo, Cheng, Gui and Tang. (2013) "Investigation on the thermal performance and optimization of a heat pump water heater assisted by shower waste water." *Energy and Buildings* 64 (2013):172–181.
- [77] Wallin and Claesson. (2014) "Analyzing the efficiency of a heat pump assisted drain water heat recovery system that uses a vertical inline heat exchanger." *Sustainable Energy Technologies and Assessments* 8 (2014):109-119.
- [78] Wallin and Claesson. (2014) "Investigating the efficiency of a vertical inline drain water heat recovery heat exchanger in a system boosted with a heat pump." *Energy and Buildings* 80 (2014): 7–16.
- [79] Dong, Zhang, Yao, Jiang and Lei. (2015) "Experimental performance evaluation of a novel heat pump water heater assisted with shower drain water." *Applied Energy* 154 (2015): 842-850.
- [80] Ramadan, Murr, Khaled and Olabi. (2018) "Mixed numerical - Experimental approach to enhance the heat pump performance by drain water heat recovery." *Energy* (2018): 1-12.