Green Energy and Technology

David Borge-Diez
Enrique Rosales-Asensio *Editors*

Heat Energy Recovery for Industrial Processes and Wastes

Springer

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Indexed in Scopus.

Indexed in Ei Compendex.

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ISSN 1865-3529 ISSN 1865-3537 (electronic)
Green Energy and Technology
ISBN 978-3-031-24373-8 ISBN 978-3-031-24374-5 (eBook)
https://doi.org/10.1007/978-3-031-24374-5

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

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Wastewater as a Source of Heat Energy

Dolores Hidalgo, Jesús M. Martín-Marroquín, and Juan Castro

Abstract To counteract climate change, the application of renewable energy sources and their efficient use are of crucial importance. In this context, wastewater has also gained increased attention in recent years. For decades, wastewater treatment plants have applied heat from digester gas combustion to meet internal demands. However, wastewater can be considered as a renewable heat source throughout its cycle, from production to disposal. Domestic, industrial, and commercial wastewaters retain considerable amounts of thermal energy after being discharged into the sewage system. It is possible to recover this heat through technologies such as heat pumps and exchangers and reuse it to meet heating demands, among others. This chapter provides an overview of existing opportunities for wastewater heat recovery and its potential at different scales within the sewerage system, including at the level of wastewater treatment plants. A systematic review of the benefits and challenges of wastewater heat recovery is provided, taking into account not only technical aspects, but also economic and environmental ones. This study analyzes important parameters, such as the temperature and flow dynamics of the sewage system, the impacts of heat recovery on the environment, and the legal regulations involved. The existing gaps in the field of harnessing the heat energy contained in residual effluents are also identified. The potential of wastewater to supply clean energy on a scale ranging from buildings to large communities and districts will be analyzed, assessing the role of administrations and other stakeholders in taking advantage of the full potential of this valuable renewable heat source.

1 Introduction

Today the world is facing major challenges in terms of sustainable energy sources and depletion of energy resources. These, together with the worrying climate change, have been triggered by human action throughout the industrial development of recent

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D. Borge-Diez and E. Rosales-Asensio (eds.), *Heat Energy Recovery for Industrial Processes and Wastes*, Green Energy and Technology,
https://doi.org/10.1007/978-3-031-24374-5_1

centuries, mainly sustained by conventional energy sources. There are, therefore, two concepts that motivate energy saving: global warming, the result of climate change, and sustainable development as a remedy for the depletion of resources.

The phenomenon of global warming generates more and more impact on our environment and climate. This impact has already been studied by bodies such as the Intergovernmental Panel on Climate Change (IPCC), which in 2018 produced a report analyzing the consequences of a rise in the average global temperature of the planet of 1.5 °C compared to pre-industrial levels, and determined the trajectories that greenhouse gas emissions should follow to avoid these effects [1]. Faced with the danger of "turning the Earth into a greenhouse", there are agreements and commitments, such as the Paris Agreement within the European framework, which promotes awareness and demands effective global action to reduce greenhouse gas emissions, with the goal of keeping global temperature rise well below 2 °C. Specifically, it is intended to reduce emissions by 2030 by at least 40% compared to 1990. Among these emissions, CO_2 occupies a preferential place, due to their quantity and effect.

Combustion processes are found in all types of industrial and human activity, and release large amounts of carbon dioxide into the atmosphere. The gases obtained in the combustion of fossil fuels with air contain between 4 and 16% CO_2 [2]. Some of the most polluting activities in this sense, in addition to transport, are the processes of domestic heat generation; Boilers are, today, the most common heat generation system for heating and domestic hot water (DHW). In the case of the Netherlands, for example, the domestic demand for natural gas for heating DHW reaches 385 Nm^3/year on average in each household [3]. At this point, energy saving is key to being able to reduce the use of these systems, and with it CO_2 emissions.

Reusing the energy already produced is only the first step in decoupling energy consumption from CO_2 emissions. On the other hand, energy saving is essential to guarantee sustainable development, in which the use and exploitation of energy resources do not condition the availability of energy for future generations. It is thus necessary to change an energy model that has historically been dependent on fossil fuels such as coal and oil, through the search for new resources and proper management of them. This management is where energy saving comes into play, a determining factor in improving the efficiency of processes and making the most of available resources. From this point of view, a recirculation of the energy contained in the wastewater would reduce the demand for new energy and avoid an unnecessary waste of resources. The word "residual heat" should be valued, since today waste must be considered as a source of renewable energy, which will never be lacking where there is vital activity.

2 Challenges in Waste Heat Recovery from Wastewater

Thermal energy is a form of energy that is more degraded the lower its thermal level, and it is very expensive to convert it back into useful energy, capable of being reused in other forms of energy. However, in the case of study this concept changes, because what is sought is precisely to obtain the thermal energy lost in the processes to raise the thermal level of a fluid. It is therefore not a transformation of energy, but a recovery and adequate transport of it towards a heat transfer fluid. This transmission must be done with the lowest possible losses and with reasonable efficiency. Residual heat recovery is a promising method for saving energy and caring for the environment, as has been mentioned. However, this recovery can be difficult and costly, and in any case the extent to which it is worth implementing the recovery systems and methods in each specific case must be considered. The following aspects highlight the main problems when recovering residual heat from wastewater [4]:

- The demand for recovered heat could not be continuous, but intermittent throughout the day. In general terms, it will be difficult to find a system that produces waste heat simultaneously with the demand for DHW, for example. This raises the search for residual heat storage alternatives for later use when hot water or any other energy demand is required.
- Recovered heat is a basic resource that must meet a series of sanitary requirements, so it is necessary to investigate a clean way of providing heat that does not modify the characteristics of the receiving media.

It will be necessary to take into account some aspects when recovering heat, especially if the thermal effluent comes from wastewater. The dirt that these bring with them negatively affects the exchange devices for multiple reasons:

- Dirt tends to settle and collapse the ducts through which the residual water circulates, reducing the passage section of the hot flow through the recovery device.
- The dirt not only obstructs the passage of the residual water flow, but also supposes an additional thermal resistance, causing the heat transfer coefficient of the exchange device to decrease.
- If the device gets dirty, it is necessary to carry out regular and costly maintenance and cleaning work, since the stoppage of the system can entail significant additional costs.

Once the main problems in the recovery of residual thermal effluents have been exposed, a review of the solutions adopted to solve them is carried out below.

The main lines of work that will be focused on in this section are the recovery of heat from the gray water network and the recovery of heat from the refrigeration cycles used in air conditioning of buildings. In both cases there is a flow of heat to the outside of the building with the possibility of recovery. There are various devices capable of recirculating residual heat. The most mentioned stand out for their simplicity, their good behavior, or for being integrated into an existing installation.

The essential element in any recovery process is the heat exchanger. Culha et al. [5] conducted an exhaustive review of wastewater heat exchangers. These authors presented a classification of the different configurations that it can take, as well as possibilities for its location and the design and construction process. The location of the exchanger with respect to the consumption point is a relevant aspect due to the

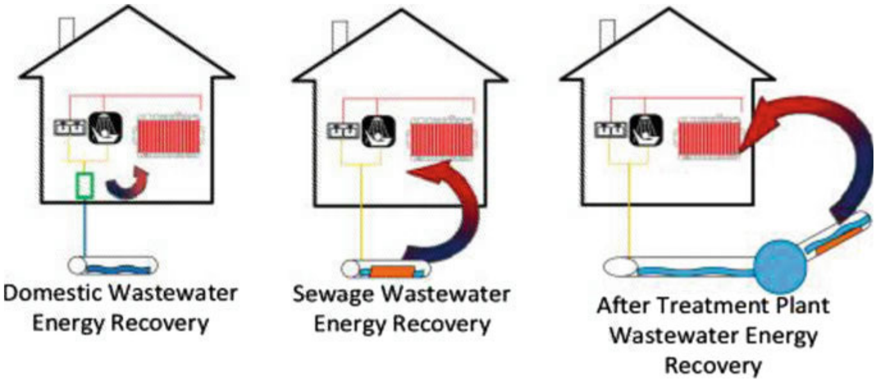

Fig. 1 Possibilities of implementation of the wastewater heat exchanger. Adapted from Culha et al. [5]

existing heat losses during the fluid path. The device can be inside the building or in its vicinity, being restricted to a domestic level; outside the building, that is, in the sewage system, being able to continuously recover more heat from various buildings; and it can even be located after a wastewater treatment plant, taking advantage of the heat with which the treatment effluents come out, although very far from the DHW supply point (Fig. 1). As for the most common configurations, in the event that the exchanger is in the sewage system, these authors indicated three types: the external ones, which work through bypass systems; the integrated ones that adapt to the shape of the sewerage network; or the modular ones, which can be installed later in the waste disposal network.

There are also studies about those exchangers designed to recover heat in situ in the drain. The research carried out with "Heat Pipe" technology in the recovery of heat from wastewater deserves a special mention. Heat pipes are devices in the form of a sealed and vacuum tube, which house a fluid inside whose function is to transport heat from one end to the other through successive phase changes (Fig. 2). The return of the fluid can be produced by capillarity, in the case of horizontal or inclined heat pipes; or by the effect of gravity, as in the case of thermosyphons. Thermosyphons have been studied as a powerful possibility for energy recovery from wastewater, due to their ability to transport heat between small temperature gradients [6].

The heat pipe is capable of transporting the heat from the wastewater to the DHW, through the evaporation and condensation of the internal refrigerant. Burlacu et al. [7] proposed a cylindrical battery of heat pipes with baffles, in which a maximum thermal jump of 49.6 °C was achieved in the DHW. The introduction of paraffin and phase change materials in the surroundings of the condensation zone made it possible to store the heat released in response to the non-simultaneous flow of wastewater and DHW demanded [8]. Vizitiu et al. [9] developed a prismatic battery performing an analysis using computational fluid dynamics (CFD), and achieving a thermal jump of 33.6 °C. Likewise, other simpler designs [10] put the wastewater and the heat pipes in direct contact, achieving a thermal jump of 28.4 °C in the DHW.

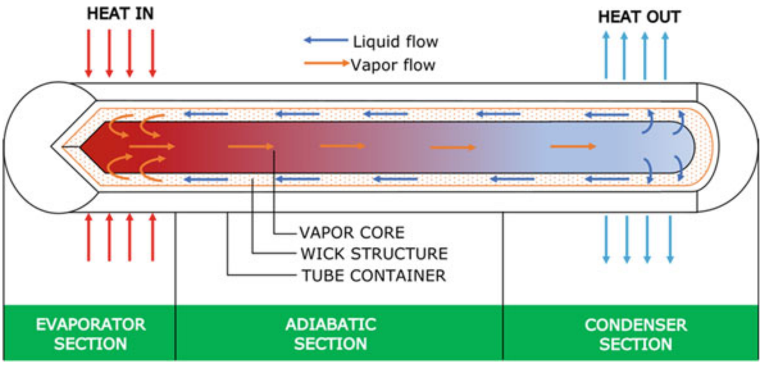

Fig. 2 Heat pipe diagram showing heat flow

Finally, the use of heat exchangers in the field of heat recovery is not limited to the exchange between wastewater and DHW, but rather constitute an essential element in any system where energy inputs and outputs are produced, and key when it comes to recirculate residual thermal effluents. This is the case in the refrigeration cycles and heat pumps of air conditioning installations, an important source of residual thermal energy. In them, the exchangers can be direct, if they transfer heat directly from the residual water to the refrigerant (that is, they act as an evaporator), or indirect, if there is an intermediate water circuit between the residual water and the evaporator. A common classification of these exchangers can be seen in Fig. 3.

On the other hand, among the different ways of extracting heat from a thermal effluent, heat pumps are a veteran technology, since they have been used to extract heat from wastewater since the 1980s, in centralized systems throughout Germany, Sweden and the Scandinavian countries. Among the different possibilities of recovery

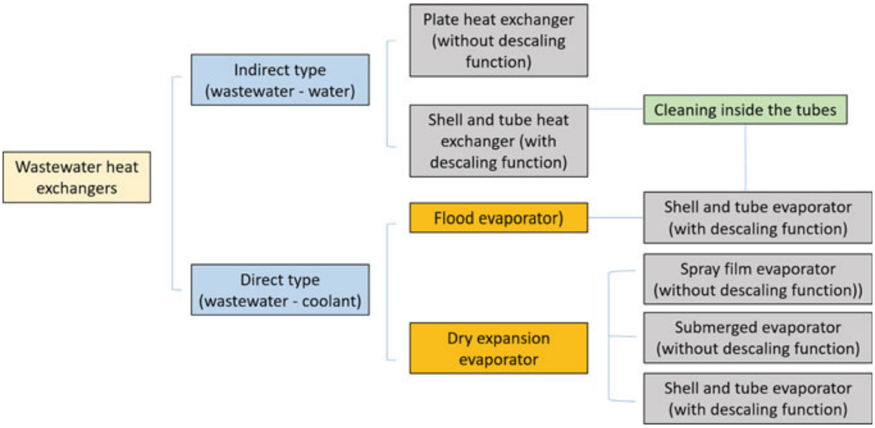

Fig. 3 Classification of exchangers used in heat pumps with wastewater. Adapted from Iglesias [4]

and applications that can be given by means of heat pumps, the main ones are the following:

– Heat pump systems with source in wastewater. Hepbasli et al. [10] conducted an extensive review of these systems. The options are: (1) Extract heat from the wastewater to transfer it to the DHW; (2) Extract heat from wastewater to transfer it to the air conditioning system (heating) or other systems that require heat.
– Heat pump systems with a source of another thermal energy carrier agent, such as the chillers of an air conditioning system, which extract heat from the glycol water (to cool it and send it to the cold demand points), and recirculate this heat in order to heat DHW.

The standard configuration of heat pumps puts the wastewater in contact with the evaporator, and the DHW with the condenser [11]. Authors such as Li and Li [12], introduce a four-way valve that allows the refrigeration cycle to be inverted, and describe the plate and spray exchangers used. It is usual to introduce one more stage through an indirect exchanger, as Zhao et al. [13] to heat DHW, although sometimes the heat from wastewater is used for air conditioning purposes [14].

As mentioned in the previous classification of heat pumps, the application does not always have to be DHW heating. Farman and Gillich [15] applied the recovery to the district heating and cooling system of a city. Other authors apply the recovered heat to the biological treatment of sewage to give rise to purified water [16]. Finally, there are studies focused on the integration of systems, combining all the exposed alternatives. For example, systems have been proposed in which a single heat pump allows the extraction of thermal energy from different sources, as proposed by Ni et al. [17], who extract heat from residual water and from the condenser of air conditioners. There are other systems that take full advantage of the wastewater, and use it for a multifunctional purpose, such as heating water and air conditioning simultaneously [18]. Some even combine wastewater recovery heat with other systems for generating and capturing thermal energy, such as the electric resistance heater or the solar collector [19].

Research in this field has also focused on the possibilities to solve the problem of fouling in the exchanger ducts. Most of these problems are due to the sedimentation of suspended particles. In this line, Ni et al. [17] tried to characterize the critical size of these deposited particles, determining that all were below 4 mm. However, Song et al. [17] explain how the problem of dirt not only involves sedimentation, but also biofouling, as wastewater is an aqueous medium rich in nutrients and conducive to the proliferation of microorganisms, which accumulated form biofilms capable of reducing by 50% heat transfer. In the same article, a convective analysis is carried out that will be used later in this work to characterize the thermal resistance due to fouling. Some cleaning systems are included in the heat exchanger itself, such as the shell and tube evaporator presented by Shen et al. [20] and others are added to the installation in the step prior to heat exchange, as is the case with systems such as the automatic anti-clogging equipment presented by Liu et al. [21], or the reflux function sewage hydrocyclone developed by Ni et al. [22].

3 Technologies for the Recovery of Heat from Residual Effluents

In most processes, both domestic and industrial, much of the energy that enters the process comes out in the form of effluents with high thermal energy. Being able to recover this type of energy is essential, as described in the previous section, to improve the total performance of the activity. For years, the recovery of surplus heat from processes, mainly industrial ones, but also from those that take place in residential buildings, for example, has been studied and analyzed to seek continuous improvement of the technologies involved [23]. These technologies can be categorized as passive technologies or active heat recovery technologies, according the classification showed in Fig. 4. In passive technologies, the equipment transfers thermal energy at the same or lower temperature. This type of technology includes the use of heat exchangers to provide heat to another current and the use of thermal storage equipment, which allows the heat generator source to be decoupled from the receiver. Active technologies for heat recovery transform thermal energy into another type of energy, or increase its temperature. In this section, the use of thermal energy to produce electricity will be analyzed as an active technology.

A heat exchanger is an equipment designed to transfer energy, in the form of heat, between two or more fluids with different temperatures. These equipments are widely used for applications that involve increasing or decreasing the temperature of any fluid stream. In some of this equipment, the fluids involved in the process are

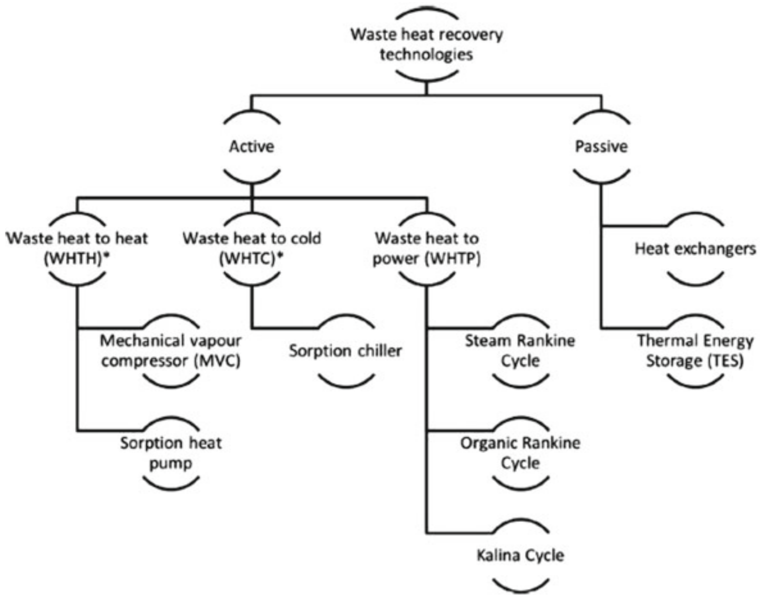

Fig. 4 Technologies for heat recovery. Adapted from Loma [24]

in direct contact with each other. In other exchangers there is no contact between the fluids, so the heat transfer between them occurs through a surface called heat transfer surface, these teams are called indirect contact exchangers. There are two main types of indirect contact exchangers, those called direct transfer or recuperators and those called indirect transfer or regenerators. In the recuperators, the fluids go through the equipment with a continuous flow and the transfer is carried out through a fixed separation surface. In regenerators, heat transfer is carried out through a matrix through which the different currents circulate alternately, giving heat to the matrix in one case and absorbing heat from the matrix in another. Heat exchangers can be classified according to their heat transfer process, the number of fluids involved in the process, their function in the process, flow arrangement, heat transfer mechanism, or their construction structure [25].

Tubular heat exchangers are generally built using tubes with circular sections through which one of the fluids passes, although they can also be designed with cross sections that differ from circular, mostly elliptical and rectangular [26]. There is great design flexibility for this equipment, because the flow passage area, and therefore the heat transfer surface, can easily vary by changing the diameter of the tubes, the length and the arrangement of the set of tubes that make up the team. The design of the tubular exchangers can be adapted to any temperature and pressure of operation, the only existing limitation is the material of construction of the equipment and certain considerations of the system. Their high flexibility also makes them suitable for being designed for special operating conditions: corrosive fluids, with high viscosity, radioactive, etc. The main types of tubular exchangers are: shell-and-tube exchangers, double pipe exchangers, spiral exchangers and coils. Shell-and-tube exchangers are usually the most used, because it is possible to adapt them to a large number of processes thanks to their wide flexibility regarding pressure and temperature ranges, something that greatly determines the choice of the type of exchanger for each process. Shell-and-tube exchangers are mostly made up of a bank of tubes mounted inside a cylindrical shell. The use and design of this equipment for decades has led to the existence of well-established design criteria and a specific notation, developed by the Tubular Exchanger Manufacturers Association [27], for the denomination of the equipment according to its constructive parts. Using this notation each shell-and-tube exchanger can be defined using three letters that correspond to its front header type, shell type, and rear header type. On the other hand, double pipe exchangers are very basic equipment. Its main structure consists of two concentric tubes, mounted one inside the other, through which the two fluids between which heat is to be exchanged flow (Fig. 5). They are often used for applications where one or both fluids are at high pressure and for small capacities. These equipments have the advantage of having a pure countercurrent flow. The tubes in this type of equipment can be smooth or finned, in order to increase the transfer surface between the fluids. The choice between smooth or finned tubes is usually conditioned by cost. For small equipment where it is necessary to improve the transfer surface and the fluid in the inner tube has a relatively high transfer coefficient, the choice of finned tubes is usually more economical. As a general rule, these units are more economical if the external fluid transfer coefficient is less than 25% of the internal fluid coefficient.

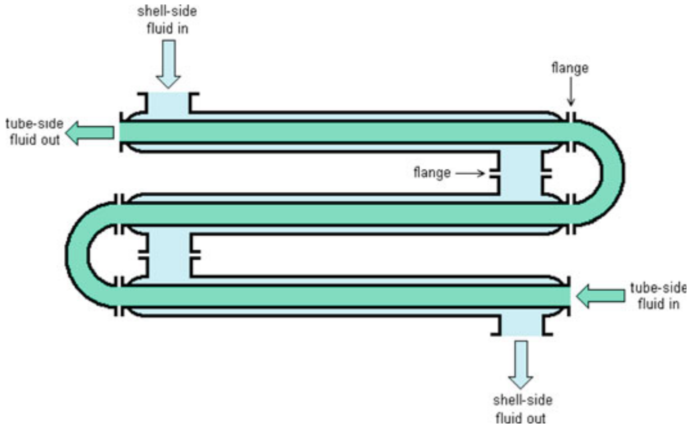

Fig. 5 Double pipe heat exchangers

Another group of exchangers are plate exchangers. This type of heat exchangers are usually made up of thin sheets, which make up the heat transfer surface. They are not usually used for high pressure or temperature differences between the fluids involved in the process. They can be classified into several groups: plate heat exchangers, spiral heat exchangers, coiled plate heat exchangers and lamella heat exchangers [28].

In plate heat exchangers, the fluids are separated by rectangular plates mounted on a frame. Generally, the plates have a corrugated design in order to increase the transfer surface between the fluids. The fluids enter through the ends of the plates, passing through them alternately, so that a section containing hot fluid is always in contact with one containing cold fluid. They are equipment that have a large contact surface in a small space. Within this group of exchangers, one can differentiate between those that use gaskets between the plates and those that use plates welded together. Plate heat exchangers that use gaskets have a very flexible design, which can be adapted from a standard design, so they can be produced in series. For common designs, the plates are made of stainless steel, but another commonly used material is titanium and they could be made of other materials if necessary. The gaskets between the plates, which are the main limitation in this equipment, are generally made of ethylene propylene rubber or nitrile elastomer, but there are a wide variety of materials that can be used for this purpose and they should be chosen considering the fluids in mind with which the equipment will work. One of the greatest advantages of this type of equipment is the possibility of increasing its size, simply by adding more plates to the equipment, which entails a small cost. The equipment in which the plates are welded together solve the problems that may arise from the use of gaskets. With welded plates, it is possible to work at a pressure of 60 bar inside the equipment, although there is a limitation when working with a pressure difference between the two fluids greater than 30 bar. The disadvantage with respect to the use of joints in this type of equipment is its higher price and the added difficulty of cleaning the equipment, requiring chemical cleaning.

The basic structure of spiral exchangers consists of two metal sheets joined together, leaving an interior space for a fluid to circulate, and rolled around an axis, forming a series of spiral passages through which the fluids involved in the heat exchange will circulate, thus achieving a large transfer surface in a small space. In the countercurrent design of this type of equipment, the hot fluid enters through the central part of the equipment and exits through the outside, while the cold fluid travels in reverse, enters through the periphery of the equipment and flows towards the center, where he ends up leaving the team. There are alternative designs that can be used for the condensation or evaporation of fluids. The heat transfer coefficient in this equipment is lower than in a plate equipment if the plates that make it up are not corrugated, but this coefficient is greater than in a shell-tube equipment, so the required transfer area compared to a shell-with-tube unit is about 20% less. As main advantages, it can be highlighted that this equipment can work with fluids with high viscosity, with suspended particles, with sludge and with dirty fluids. The fouling of this equipment is less than in a shell-tube exchanger. They are compact units and do not present differential expansion problems. The main disadvantage is the need, generally, to use a chemical cleaning in the equipment and the difficulty when it comes to repairs due to its construction characteristics.

Plate heat exchangers with coils or plate coils, are made up of a series of plates with a coil inside, through which one of the fluids flows, and these plates are submerged in a tank in which the other fluid is found. As main advantages we can highlight the high control that can be had on the transfer of heat and temperature within the equipment and the few maintenance problems, contamination between fluids and cleaning that they originate. Their use is limited and for the most part they are used in cryogenic processes, the food industry and the pharmaceutical industry. "Lamella" heat exchangers are hybrids between plate heat exchangers and shell-tube heat exchangers. In this type of design, the tubes are replaced by a series of plates and inserted into a casing similar to those of the casing-tube, fixing only one of the ends to allow expansion. They are very specific equipment and whose design is carried out by suppliers.

Another group are the extended surface exchangers. In the tubular and plate type exchangers, already described, the heat transfer surface with respect to the volume occupied by the equipment is generally less than 700 m^2/m^3. On many occasions, a high effectiveness is needed in the equipment, having a limitation regarding the size of the equipment, which makes it necessary to increase its compactness (the transfer surface with respect to the occupied volume). A large transfer surface may also be necessary if one of the fluids involved in heat transfer has a low transfer coefficient. This increase in the transfer surface can be achieved by adding fins to the primary surfaces of the equipment, from which the two types of exchangers that will be detailed below arise: plate-fin exchangers and tube-fin exchangers. Plate-fin heat exchangers are made up of a series of parallel plates between which fins are placed, on whose edges side bars are installed to increase the transfer surface. The currents involved in the transfer process alternately pass between the plates. Aluminum is usually used as a construction material. These equipments are generally designed to work at moderate pressures (<7 bar), although there are equipments that can operate above 80 bar. The temperature limitation is imposed by the method used to join the equipment components and by the materials used for its construction. There are equipments capable of working at temperatures of up to 840 °C. This type of exchangers can be built with a high compactness, up to 5900 m^2/m^3, and there is total freedom when selecting the surface of the fin, being able to adapt to the fluid that will circulate on each side of the equipment. The main problem with this equipment is fouling, which is why it is usually used to work with clean fluids and it is advisable to place filters at the fluid inlet to prevent blockage of the passage channels due to particles. On the other hand, tube-fin exchangers can be classified as conventional or specialized. In a conventional tube-fin exchanger, the transfer between the two fluids is carried out through the tube wall by conduction and through the heat transfer surface by convection. In exchangers commonly called "heat pipes", which are a type of fin tube exchanger known as specialized, heat transfer takes place through the separation wall between the fluids by conduction and phase change. In gas–liquid exchangers, the transfer coefficient on the liquid side is usually greater than on the gas side, so fins can be used on the gas side to increase the exchange area, and if the pressure is high in one of the fluids, it is usually economical to use tubing. The fins are usually located on the outside of the tubes, but in some applications it may be interesting to fin the inside. This equipment can work at high pressures on the side of the tubes and the working temperature in the equipment is limited by the construction materials and the joining method between the parts of the equipment. It can reach a compactness of about 3300 m^2/m^3.

As mentioned above, another type of exchangers are those of indirect transfer or regenerators. The regenerators operate transiently. Its operating principle consists of passing a fluid current through a matrix of solid material, in which heat is stored, and then passing the cold fluid current. The most common are fixed matrix regenerators and rotary regenerators [29]. Fixed matrix regenerators consist of a fixed solid matrix through which currents alternately pass. In order to make this heat transfer process continuous, this equipment is usually assembled using a system of valves and pipes to vary the path of the fluids. In rotary regenerators, the solid matrix rotates around an axis. The fluid currents pass through the equipment parallel to the axis, normally countercurrent, passing through different sectors of the matrix. When a sector is crossed by the current of hot fluid, it stores heat and the rotational movement of the equipment causes that same sector to come into contact with the cold fluid, giving it the stored heat. Due to the construction structure of the equipment, it is a complicated task to prevent leakage from one stream to another. If it is necessary that one of the fluids is not contaminated with the other, it would operate with a higher pressure in the air current, in this way if there is any leak in the equipment it would be from the air current in the exhaust gases. As advantages, they are more compact than recuperators, providing more exchange surface in less space, and the cost per unit of exchange surface is usually considerably lower than in a recuperator. The biggest drawback would be the unavoidable entrainment of a small fraction of fluid, trapped inside the matrix, by the other stream.

4 Methodology to Determine the Potential for Heat Recovery in an Effluent

The methodology that is usually used to determine the heat recovery potential of a residual effluent with a certain energy level is presented in this section. When an industry or building is analyzed to determine the potential to recover waste heat, a distinction must be made between what is considered theoretical potential, technical potential and economic potential. The theoretical potential focuses on the physical limitations that the process may present, this refers to whether, for example, heat is emitted at a temperature higher than that of the environment. This means that the heat that is emitted in the form of radiation has theoretical recovery potential, but the method to extract this heat or its possible use is not taken into account. The technical potential refers to the technical capacity that exists to capture these residual heat sources that may exist and take advantage of them. This potential depends on the technology that is decided to be chosen for heat recovery, since these technologies may have limitations, such as a minimum temperature or the need for space, this section may change over time as the state of the art of heat recovery technology changes, and it also depends on the demand for energy, since there can be a hypothetical situation of having a technology capable of recovering residual heat but not being able to take advantage of this energy [30]. The economic potential dictates whether it is economically feasible to use that technology to recover waste heat. Starting from a technology and an application that are technologically viable, an economic analysis is required to evaluate the impact that the implementation of this technology would have with respect to the initial state.

The first step to determine the recovery potential in an effluent is, obviously, the study of the process. Each process has different threads involved with specific equipment that performs a certain task. To determine if heat recovery in industry, for example, is possible from a theoretical point of view, it is necessary to know the entire process and identify the points where energy is lost in the form of residual effluents. Generally, the process with the highest thermal demand will be the one with the greatest potential for energy recovery.

Once the process has been analyzed and a residual effluent that could be used to recover energy has been identified, it is necessary to know the parameters of the effluent in question. In addition to knowing the temperature and flow rate of the effluent, which can be measured directly, it is important to know the temperature and flow profiles. An effluent with a stable flow rate and temperature, with little variability or known variability, will be a better candidate to carry out an analysis on the possibility of energy recovery in it. These factors usually depend on the process load, the hours of operation of the process per day, the necessary stops for maintenance, the variability in fuel consumption due to process specifications or the variability in the composition of these fuels. Other factors to take into account is the composition of the effluent to be recovered, e.g. an effluent with high concentrations of sulfur will not entail the technical considerations that one that does not present this component. It is also important to know parameters such as the viscosity of the fluid, and whether it carries many solids in suspension. This database becomes important when it is required to record fuel consumption, air flows for combustion, inlet and outlet temperatures of gases and fluids involved during a representative period of time to determine the usual working conditions of the equipment.

For a given process that involves residual effluents with the potential to be used in a heat recovery process, there may be many technical alternatives to carry out this operation. This chapter names some of the most important technologies when it comes to heat recovery in effluents, whether they are passive techniques, such as the use of heat exchangers directly as preheaters or economizers in a boiler or thermal storage, or active techniques, such as cycles for transforming waste heat into power, but for the selection of a certain recovery technology it is necessary to assess the needs of the process studied, whether they are needs for process water, steam, thermal or electrical energy. Once the available technologies and the needs that can be covered with these technologies are known, a selection of one or several technologies can be made to analyze their impact on the process being studied, carrying out a basic engineering in which all the modifications that would have to be made and the necessary equipment to implement the heat recovery technology in order to subsequently determine its economic potential are determined.

Finally, to determine the feasibility of a project for the installation of equipment that allows the recovery of heat from an effluent, it is essential to carry out an economic evaluation of the project. This economic evaluation will determine how viable is the implantation of the equipment that has the purpose of bringing a benefit to the industry with respect to its previous state. This evaluation also allows decisions to be made regarding how to finance the project, if an external investor is necessary or if it is possible to take full charge of the project from the company that owns the residual effluent. For this type of analysis it is necessary to know data such as the investment to be made, installation and start-up costs, maintenance costs, operating costs, etc. In addition to the project's own data, data such as inflation rates or changes in interest rates are also necessary. To carry out this analysis, concepts such as payback, net present value or internal rate of return must be applied [31].

5 Possible Options of Heat Recovery from Wastewater

According to Nagpal et al. [32], there are four main possible locations within the sewer system for energy recovery from wastewater, schematized in Fig. 6: at the component level; at building level; in the sewer pipe network, and from wastewater treatment plant.

At the component level, heat can be recovered from wastewater directly after it is produced in specific activities related to a single component (e.g. showering or cooking). The heat is extracted by a heat exchanger directly after the component used in the activity. The recovered heat can be used to preheat the incoming cold water, or it can be used in conjunction with a heat pump for other purposes. Heat recovery from shower water is the most common practical application at this level.

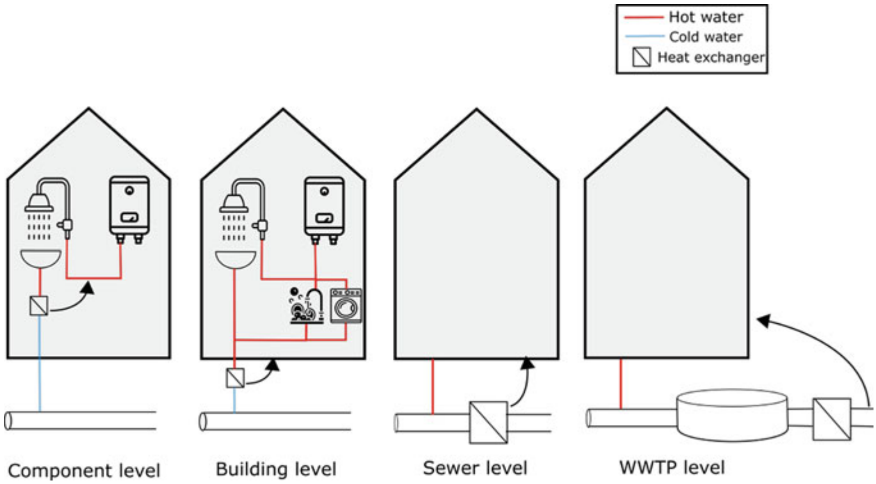

Fig. 6 Strategic points for heat recovery from wastewater. Adapted from Schmid [33]

This application has the advantage of a continuous and simultaneous backflow of wastewater and incoming cold water supply for use in the shower. Therefore, the heat recovered here can be achieved with high effectiveness and there is no time lag between the availability of waste heat and the heat demand for the shower, which eliminates the need for heat storage and the resulting losses [34]. In real applications, heat exchangers are placed under the shower tray in either horizontal or vertical orientation. In the vertical configuration, the wastewater is discharged as a falling film flow, whereas in the horizontal orientation, the water flows through the bottom of the pipe. Therefore, the effective surface area over which heat is exchanged is larger in the vertical orientation, leading to higher efficiency [35]. Apart from the shower systems, wastewater heat can be recovered from other components, such as washing machines and dishwashers.

At the building level, heat recovered from the general wastewater discharge of an entire building is considered. The flow and temperature characteristics of the wastewater from this discharge depend on the type of building and its location. Wastewater in domestic buildings can maintain a temperature of 10–25 °C during the year [36]. Energy savings from heat recovery at the building level can be higher compared to the individual component level due to the larger volume of wastewater and the accumulation of multiple hot water activities [37]. However, discharge at building level also includes cold wastewater in the mix, reducing energy potential. At this level, to perform heat recovery, it is recommended that the wastewater is collected in a common holding tank and the heat recovered using a heat exchanger [38] or water source heat pump [36]. Other aspects are also key when considering wastewater heat recovery at the building level. The information on the amount of heat in the wastewater and its variation throughout the seasons depending on the location of the building is a crucial gap to identify the heat inputs in the system.

Also, the often mismatched issue of distance between the waste heat source and the existing heating installation or incoming cold water in a building can be barriers to implementation [37]. Another problem mentioned by Spriet and McNabola [36] is that the studies often consider an instantaneous consumption of residual heat and do not take into account the actual consumption.

Heat recovery from raw sewage in the public sewer pipe network is a promising source of energy. The flow of wastewater in sewer pipe systems is abundant and continuous throughout the year, with an annual temperature of 10–20 °C, making wastewater from sewer pipes an ideal source of heating or cooling for heat pumps. There are two possible ways of heat recovery from the sewer pipe system. The first is to install a heat exchanger in the pipe bed and use a heat pump to pump this energy to a district heating system. The second option is to install an external heat exchanger above ground level. To do this, a part of the sewage water flows into a filter to retain coarse solids and the previously filtered wastewater is pumped to the above-ground heat exchanger. The heat exchanger is further connected to a heat pump evaporator. Both types of installations have been in operation for many years in several European countries such as Switzerland, Norway [33] and Sweden [39] with thermal power of the installations ranging from 10 kW to 20 MW.

Another critical point for the recovery of energy from wastewater is the treatment plants. In these facilities there are three possible points of heat recovery: from raw wastewater as it arrives at the plant (Fig. 7), from partially treated water, and from the effluent discharge point after treatment (Fig. 8). Heat recovery from raw sewage is similar to heat recovery within the sewer pipe system mentioned in the previous paragraph. At the treatment plant, the influent temperature and available energy are higher, offering the greatest potential for heat recovery [40]. However, the quality of the water is worse, which creates significant technical challenges to exploit it. As we progress through the treatment stages, the temperature of the water, as a general rule, decreases (unless biological processes are used), but its quality increases, thus facilitating the heat recovery process. Wastewater treatment plants process and treat large amounts of sewage water and then discharge it daily into nearby bodies of water. This treated water temperature is stable and has low daily variations compared to the influent temperature. The potential for heat recovery in wastewater just at the outlet of the treatment plant is greater than that of downstream water, since it can be cooled [33]. The treated water also has the advantage that it generates less biofouling and, with it, less interference of solid matter with the heat exchanger, which improves the efficiency of heat transfer. However, since heat consumers are not usually located near sewage treatment plants, a major disadvantage of this energy recovery option is that the heat supply must be transported long distances, leading to high losses. One option is to reuse that heat in the treatment facility itself, where energy consumption is high. On the other hand, treatment plants have a significant amount of energy from other processes such as the generation of electricity from the biogas produced in anaerobic digestion. Therefore, treatment plants can be considered as islands of energy that can supply energy to local networks (heat and electricity) [22]. An important limitation for the use of recovered heat is that there must be a local district heating network

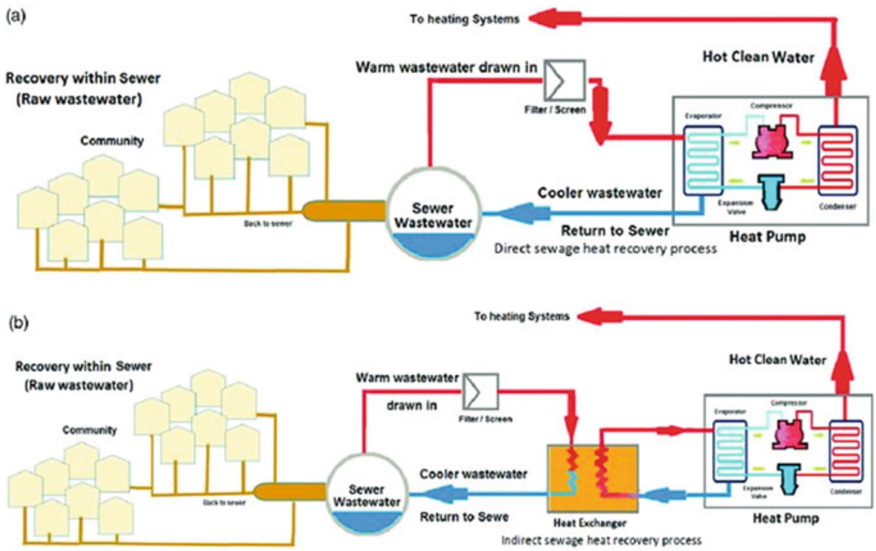

Fig. 7 Direct (**a**) and indirect (**b**) wastewater heat recovery process from the sewer network before a wastewater treatment plant. Farman Ali and Gillich [41]

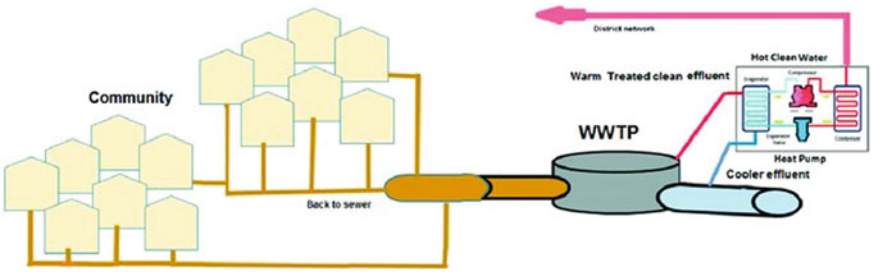

Fig. 8 Heat recovery from the wastewater effluent. Farman Ali and Gillich [41]

into which the recovered heat can be injected. Therefore, the final destination of the recovered heat will depend a lot on each specific case.

6 Heat Recovery from Wastewater: Practical Applications

The thermal energy recovered from wastewater has its main direct application in heating and cooling activities, as previously mentioned. There are several limitations in the recovery of thermal energy from effluents, the main one being the distance for the supply of heat/cold between the sources and the users, which is usually limited to a maximum of 3–5 km. On the other hand, government subsidies or tax relief (related to GHG reduction) can be an important driver to promote thermal energy recovery. In practice, there are already multiple cases around the world of applications of thermal energy from wastewater in heating and cooling, some of them are listed in Table 1.

Apart from the reuse of heat in the building or facility itself where the residual effluent is generated, a potential use of the recovered heat may be agriculture. Today, agriculture often involves the use of greenhouses [45]. Keeping greenhouses warm requires a lot of energy, and the heat recovered from effluents could be a substitute for traditional energy sources for greenhouses located near wastewater treatment plants. There is a case in Japan where this successful application is a reality [42]. Alternatively, other possible routes of application of thermal energy from wastewater could be the heating of biogas digesters or the drying of dewatered sludge [45].

Table 1 Practical applications of the thermal energy recovered from the effluent of wastewater treatment plants around the world

Country	Application	References
Norway	Heat pump air conditioning system for 28 commercial buildings with the total area of 155,000 m^2	Shen et al. [18]
Sweden	Capacity 3.3 MW, around 1,300 household equivalents	
Sweden	Heating for 5,170 buildings, centralized heating	
Russia	9.5 MW (3,800 household equivalents)	
Sweden	Heating for 95,000 residential buildings	Mikkonen et al. [27]
Norway	20 MW (8,000 households) for heating and 18 MW (7,200 households) for cooling energy	
Japan	Heating and cooling for a building with 2,270 m^2	Funamizu et al. [42]
Japan	Cooling for the Makuhari district near the plant covering an area of 850,000 m^2	
China	Heating for a district near the plant (initial area: 460,000 m^2)	Hao et al. [17]
Finland	Heat pump air conditioning system for the Turku public buildings and living areas (12,000 households)	Niemela and Saarela [43]
Finland	Heat pump air conditioning system for living areas (17,000 households)	Fortum [44]
Netherlands	Heating and cooling for 1,600 household equivalents	Neugebauer et al. [45]
Netherlands	Heating for 10,000 households	Waternetwerk [46]
Austria	Heating for the Stadtwerke Amstetten building and nearby power factory	EPHA [47]

7 Conclusions

Wastewater is a permanently available resource that contains large amounts of thermal energy that can be recovered at different points in the water cycle and utilized to reduce heating demand. Thermal energy could be extracted using either heat exchangers or a combination of heat exchangers and heat pumps. The thermal use of wastewater in sewage systems can contribute to concepts of differentiated and decentralized urban energy supply. The analysis carried out shows that heat recovery systems have significant potential for development. However, where to include the heat recovery point along the circuit that wastewater runs from its generation to its evacuation, already treated, to a water channel is a crucial element that must be assessed in each case, taking into account the conditions existing. The use of heat transported by wastewater can present drawbacks associated with existing legal regulations and the environmental awareness of the public. Therefore, generalized recommendations regarding the use of the energy contained in wastewater would be inadvisable or, in fact, impossible; consequently, it is necessary to approach each project related to the recovery of heat transported by wastewater on a case-by-case basis.

This chapter has justified the importance of energy saving, and the great potential of residual thermal effluents in energy recovery. For this, the state of the art has been reviewed, verifying that there is an extensive bibliography, studies and research in this regard, and concluding that it is a field prepared to be implemented in real cases on a large scale. But, in general, the importance of this energy vector is clearly underestimated, despite the fact that its use could increase the independence of countries from external deliveries of fossil fuels and contribute to improving the state of the natural environment. Therefore, there is a need for widespread promotion of this method of energy extraction which will result in increased awareness related to sustainable energy systems and help gain consumer approval for energy extracted from wastewater.

Acknowledgements The authors gratefully acknowledge support of this work by the European Commission through the grant agreement N.776708 (HOUSEFUL project).

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