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Thermoeconomic and environmental impacts of vortex generator-equipped multi-drain heat recovery systems under various renewable sources

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ABSTRACT

In response to escalating energy demands, intensifying climate change concerns, and growing environmental degradation, the incorporation of renewable energy sources has gained traction across diverse sectors and regions. Concomitantly, scientists and engineers have recognized the potential of heat recovery systems in mitigating energy consumption, fostering further investigations into their practical applications. This study introduces an innovative design, integrating vortex generators into a concentric tube heat exchanger for heat recovery from a multi-drain water system that serves 48 accommodations. The design's sustainability is assessed by evaluating its economic, and environmental implications when paired with various renewable energy sources. Specifically, the aim is to quantify both cost and environmental savings engendered by implementing this design in a multi-drain application for a building with 48 accommodations.

A numerical investigation elucidates the effects of flow rate variations on heat transfer, overall heat transfer, and thermal enhancement factors. Four types of renewable energy input - solar, wind, biomass, and hydropower - along with one storage system (pumped storage) are analyzed. The study reveals that the design implementation results in an elevation of cold water temperature between 3.5 and 7.5 °C. Furthermore, daily environmental savings for solar, wind, biomass, hydropower, and pumped storage are estimated to be 0.783 €, 0.339 €, 0.141 €, 0.027 €, and 1.356 €, respectively. Conversely, daily economic savings are calculated to be 3.62 €, 2.49 €, 5.05 €, 3.62 €, and 6.70 € for each corresponding energy source. This research underscores the viability of the proposed design in fostering sustainability through both environmental preservation and economic efficiency.

1. Introduction

The development of effective energy harvesting systems is receiving a lot of attention as a result of the rising energy demand across many industries. Energy and related services are increasingly needed to support human social and economic growth, welfare, and health. All civilizations require energy services to provide fundamental human requirements such as health, lighting, cooking, space comfort, movement, and communication, as well as to function as creative processes [1,2]. Most of the energy sources are based on fossil fuels, and according to statistical studies of Our World in Data that was held in 2022, 84.3% of the energy sources are based on fossil fuels [3]. However, carbon dioxide emissions caused by fossil fuels harm our ecosystem and contribute to global climate change. During the past 150 years, fossil

fuels have increased atmospheric CO₂ levels by quantities that are contentious, problematic, and, at best estimations, the use of fossil fuels as major energy sources has resulted in environmental deterioration and ozone layer depletion [4,5]. As a result, the economic and environmental implications of fossil fuels on the functioning of a power system demand new sources of energy that are widely available, non-depleting, sustainable, and ecologically benign, and may increase power system efficiency [6].

To halt global warming, a shift to cleaner, more sustainable energy is required. Renewable energy is rapidly expanding, but it is still a long way from replacing carbon-intensive sources of energy. Even if oil output decreases shortly, fossil fuels will continue to dominate the global energy mix for many years [7]. On the other side, waste heat recovery is considered as finding a new clean source of energy, where the quantity of waste energy in many applications is significant. In

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Nomenclature			
<i>Abbreviations</i>		$T_{cw,o}$	Temperature cold water outlet
CTHE	Concentric Tube Heat Exchanger	$T_{cw,i}$	Temperature cold water inlet
DWHR	Drain Water Heat Recovery	$T_{hw,o}$	Temperature hot water outlet
ϵ	Effectiveness of heat exchanger	$T_{hw,i}$	Temperature hot water inlet
ECI	Environmental Cost Indicator	TEF	Thermal Enhancement Factor
ELCA	Environmental Life Cycle Assessment	VGs	Vortex Generators
EP	Environmental Price	<i>Units</i>	
GWP	Global Warming Potential	kWh – MJ	Energy
HE	Heat Exchanger	kg CO ₂ eq	Global Warming Potential
HRS	Heat Recovery System	kg/s	Mass flowrate
Q	Heat transfer	J/g. °C	Specific heat (C_p)
HTE	Heat Transfer Enhancement	W/m. °C	Thermal conductivity
LCA	Life Cycle Assessment	<i>Countries</i>	
Nu	Nusselt Number	CH	Switzerland
U	Overall heat transfer	<i>Prices</i>	
P	Pumping power	€	Euro
Re	Reynolds Number		
SWH	Solar Water Heating		

automobile and automotive power utilization, for example, around 64% of the energy input is wasted as thermal energy, almost 38% is squandered in the exhaust, and 6% is lost due to friction. Additionally, power plants waste 60% of their energy before adopting heat recovery. So, when waste heat can be recovered, it is seen as a potential source of power generation [8,9]. Moreover, as energy expenses continue to increase and natural resources become scarce, there is an increasing need for heat recovery systems that can effectively capture and utilize wasted energy, ultimately aiming to preserve over 90% of this energy to address environmental concerns [10]. According to previous studies, it has been noticed that when employing hybrid heat recovery systems which means integrating more than one system, the thermal recovery level exceeds 28% with a performance coefficient of up to 2.2 times traditional processes [11].

As a result, developing effective and low-cost energy recovery technologies is equally as important as developing new energy sources. Thermal energy is necessary for many architectural applications, thus it must be supplied, maintained, and used effectively to serve both the environment and the economy. The Drain Water Heat Recovery (DWHR) system is designed to recover the leftover energy from hot drain water and use it to warm the incoming cold water [12]. The household sector accounts for 26% of total energy expenditure in the United States, 37% of which is for lighting, cooling, and appliances. The remaining energy is assigned to heating, with space heating accounting for 45% and water heating accounting for 18%. Thus, residential water heating accounts for 4% of overall government energy use. The household sector contributes 29% of total energy consumption in some countries, such as the United Kingdom. This is broken down as follows: 65% for room heating and 16% for water heating [12]. Consequently, the energy required to warm water contributes to a considerable amount of the total energy consumed in a typical household.

Several studies show that recovering heat from drain water represents an excellent chance to decrease energy usage. For instance, Torras et al., [12] stated that drainage water constitutes a considerable amount of energy to recover, where the normal temperature of household drain water varies from 20 to 40 °C. As a consequence, domestic effluent is more suitable for heat recovery than other heat sources, where the ambient temperature of drainage water from bathtubs or washing machines is considerably high. Allowing this much energy to escape the building with warm water without collecting it is a significant energy waste. Besides, Murr et al., [13] conducted a study on using a heat exchanger to recuperate heat loss in a multi-drain application, this study

shows promising results in terms of recovering heat from multi-drainage sources. Moreover, numerous studies have been conducted to explore different methods of conserving energy in domestic water heating. These include the utilization of heat pumps, Solar Water Heating (SWH) systems, gas boilers, immersion heaters, and drain water heat recovery techniques [14–16]. Heat exchangers play a crucial role in numerous applications, including air conditioning systems, power plants, and refrigeration systems, by effectively recuperating lost heat. Their utilization has significantly enhanced both their thermodynamic efficiency and economic performance [17,18]. On the other hand, enhancing heat transfer is fundamental to improving heat recovery. There exist different passive and active methods to enhance heat transfer. Incorporating Vortex Generators (VGs) is one of the simplest methods to improve heat transfer because VGs are passive devices with high efficiency in improving heat transfer, where some studies reveal that VGs could enhance heat transfer by 40% [15,19].

The substantial thermal loss from drainage water and the high energy usage on heating domestic water, besides, the high performance of heat recovery when integrating VGs, encourage to study the effectiveness of heating recovery using VGs in a multi-drain water application. Thus, in this study, a heat exchanger design with VGs implemented in a multi-drain application is investigated. This design refers to a previous study held by Aridi et al., [17] that conducted a numerical study on different configurations of Concentric Tube Heat Exchangers (CTHE) with Vortex Generators (VGs) located in different places to enhance heat transfer at different Reynolds numbers. Another study on implementing this design in a multi-drain application coupled with four types of input energy—coal, diesel, gas, and electricity—was carried out [20]. The results show that implementing this design in a multi-drain application saves economically and environmentally and it is worth to be integrated. Thus, the objective of this article is to find how much this design could save economically and environmentally when coupled with renewable energy sources as they are widely spread and have a lower environmental impact than fossil fuels. Now, the question to answer is: is it worth integrating this design with renewable energy sources?

This study is carried out numerically by simulating the effect of the design on heat transfer, overall heat transfer, and thermal enhancement factor in a multi-drain heat recovery application. The economic and environmental aspects of the system are also evaluated to investigate its sustainability. The environmental and economic studies conducted in the research have certain limitations regarding the utilization of various renewable energy sources. Not all possible renewable energy sources

were considered or included in the analysis, this system is studied with five types of input energy solar, wind, biomass, hydropower, and pumped storage.

This research examines a novel design in a multi-drain heat recovery implementation. Its novelty resides in the following:

- Coupling two new potential concepts into one application. These new potential concepts are the use of vortex generators in heat recovery and the multi-drain heat recovery concept.
- Performing an LCA study, incorporating economic and environmental studies of the new heat recovery system.
- Comparing the economic and environmental impacts of a HRS in various renewable heating sources.
- Integrating multi-drain heat water into different renewable energy heating sources.
- Providing the renewable energy and energy management community with useful recommendations on many fronts related to advanced drain water heat recovery systems.

This applied research could lead to improved heat recovery devices in such applications by capturing a high proportion of thermal energy. It examines a novel design in a multi-drain heat recovery implementation by simulating numerically its impact on heat transfer, overall heat transfer, and thermal enhancement factor.

2. Materials and methods

2.1. Methodology

The research methodology, delineated in Fig. 1, comprises four principal components: Data collection, Numerical study, Economic analysis, and Environmental evaluation.

In the Data collection phase, a thorough review of extant literature and previous studies was conducted to accrue pertinent information and insights from established sources. The Numerical study component adopted a design from a previously published article, with the investigation primarily focused on assessing the impact of varying mass flow rates and temperatures. By modulating these variables, we achieved an extensive analysis of the system’s behavior. In this study, Ansys Fluent 2020 R2 is used to obtain the temperature outlet of the heated cold

water.

The Economic analysis involved applying complex equations to calculate costs and ascertain the payback period. This investigation furnished valuable insights into the financial ramifications associated with the studied system. Finally, the Environmental evaluation was facilitated using the openLCA software in conjunction with the Ecoinvent database. This integration enabled a comprehensive assessment of the environmental consequences and impacts associated with the system under scrutiny.

In summation, the methodology employed a systematic, multifaceted approach, merging data collection, numerical analysis, economic appraisal, and environmental assessment. The implementation of these distinct elements resulted in a well-rounded understanding of the research topic.

It is crucial to acknowledge certain limitations of this study. Firstly, while the Ansys software assumes perfect insulation, realizing such insulation in practical applications may not be attainable. Furthermore, the fabrication process of the design could introduce human error, particularly in aspects related to Vortex Generators (VGs). It is also pertinent to consider that data collection regarding prices can be subject to regional variations and fluctuations influenced by supply and demand dynamics. Consequently, the final cost estimation cannot be deemed as entirely accurate.

2.2. System description

The system description is classified into two parts: a description of the CTHE design with the VGs, and a description of the application study.

The design incorporated a CTHE of tube length, inner tube diameter, and an outer tube diameter of 2 m, 0.04 m, and 0.08 m, respectively. As for the heat transfer enhancement method, 10 rows of VGs distributed along the entire tube length are implemented, with a spacing of 180 mm between the VG rows, as depicted in Fig. 2. The flow rates for hot water were determined based on previous studies, covering a range of 0.1, 0.2, 0.25, 0.3, 0.4, and 0.5 kg/s, while the mass flow rate of cold water was fixed at 0.2 kg/s. The inlet water temperatures for the annular and tube were set at 293 K (20 °C) and 323 K (50 °C), respectively.

As for the application study, Fig. 3 presents a schematic illustration of the application study. Waste heat water exits each accommodation

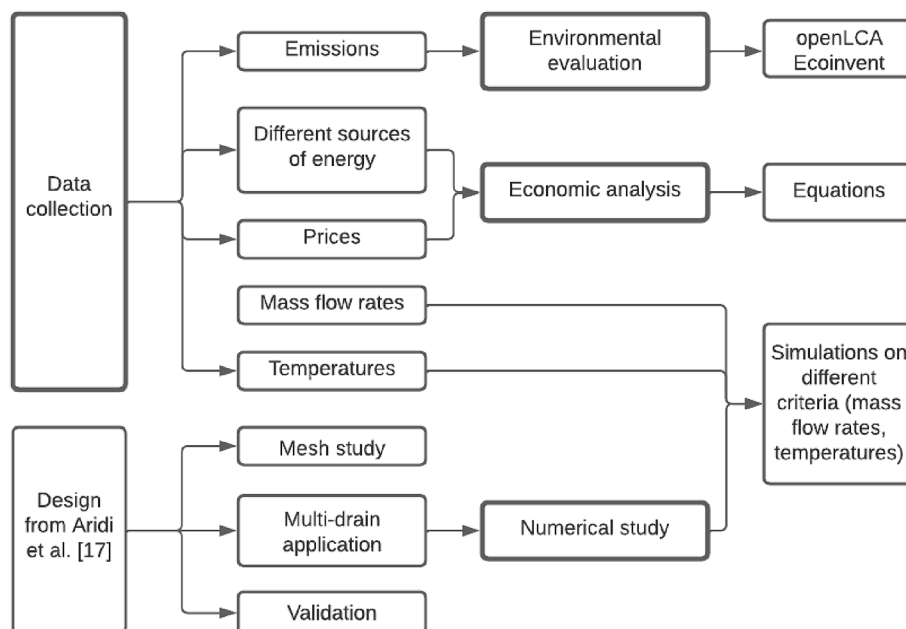


Fig. 1. Methodology of the work.

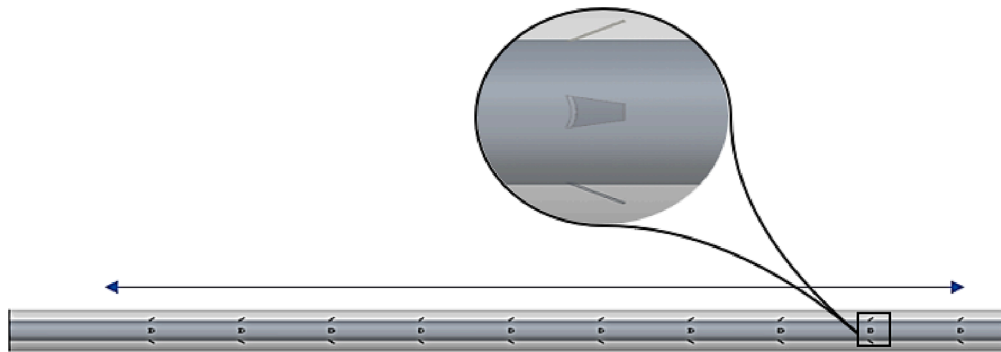


Fig. 2. VGs distribution along the tube.

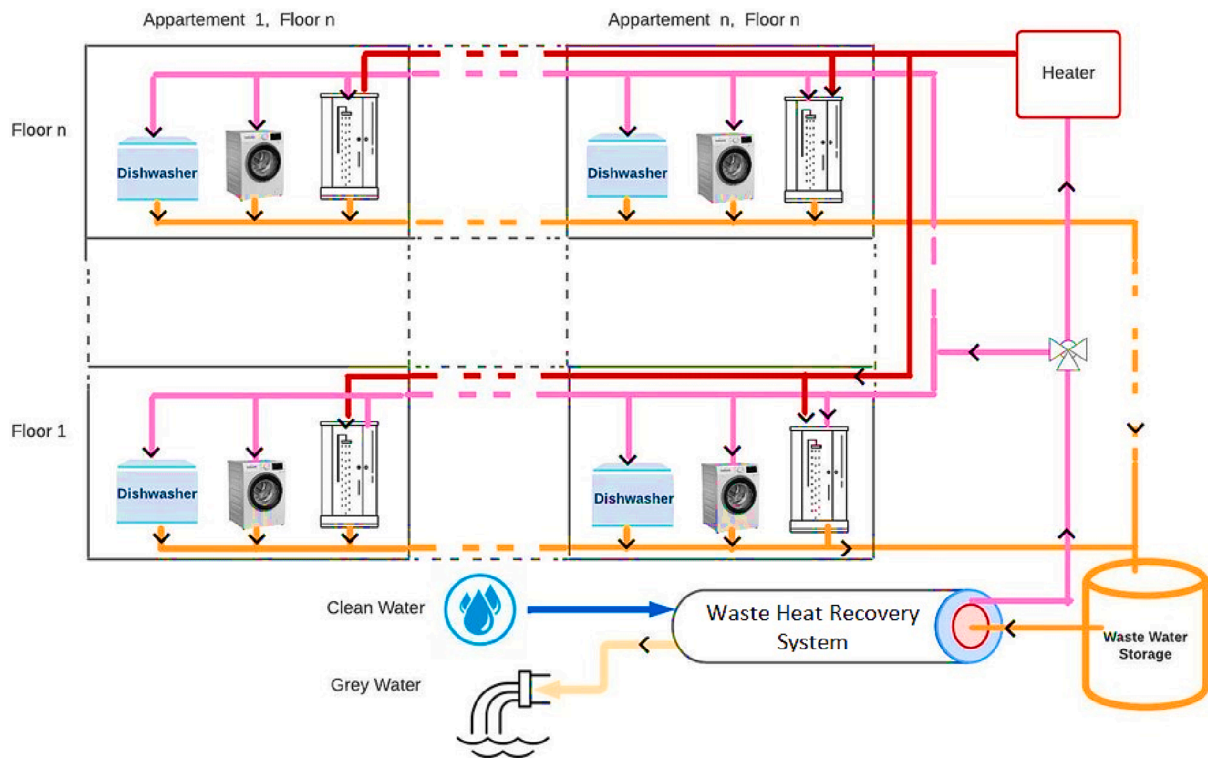


Fig. 3. Schematic drawing of the building with the heat recovery system.

into a water storage tank connected to the heat recovery system (HRS). Simultaneously, cold water enters the annulus, and heat transfer occurs between the wastewater and cold water within the HRS. As a result, the inlet cold water temperature increases by a specific amount, as determined through simulation using Ansys, which is presented in the following section.

Simulations were conducted for various flow rates during both summer and winter to explore how flow rate variation impacts heat transfer under different climatic conditions. The inlet cold water temperature is lower in winter than in summer, and the hot water temperature required by users is higher in winter than in summer, resulting in outcomes influenced by the weather. Consequently, the cold and hot water inlets were set at 283 K (10 °C) and 333 K (60 °C) in winter, and 293 K (20 °C) and 313 K (40 °C) in summer, respectively. The flow rates investigated ranged from 0.1 to 0.5 kg/s.

In this study, the focus is on a building consisting of 48 accommodations, and the water used for washing machines, dishwashers, and showers in each house per week is analyzed. Fig. 4 illustrates the water quantity used for each piece of equipment in the 48 accommodations.

The volume of water used is calculated, and the duration of each process is determined to understand the daily water usage for each piece of equipment. The mass flow rates and consumption values for the machines are obtained from previous studies and statistical reports conducted for various numbers of accommodations [21–23].

The calculations indicate that water consumption amounts to 21.7 h per day, indicating nearly continuous flow. However, to ensure a continuous flow of heated water, the investigated innovative design is connected to a building with 48 accommodations, enabling a consistent flow of grey hot water, also known as wastewater. An insulated tank is used to store the grey hot water during periods of high flow rates, ensuring a steady flow rate over time. Based on the literature review, the average flow rate for a building comprising 48 accommodations throughout the day is determined to be 0.25 kg/s [21,24]. However, the range of flow rates will be studied as the flow rate can be changed according to the application and water consumption (0.5, 0.4, 0.3, 0.25, 0.2, and 0.1 kg/s). Consequently, this study will simulate the average flow rate during the summer and winter seasons to evaluate the heat transfer capabilities of this design.

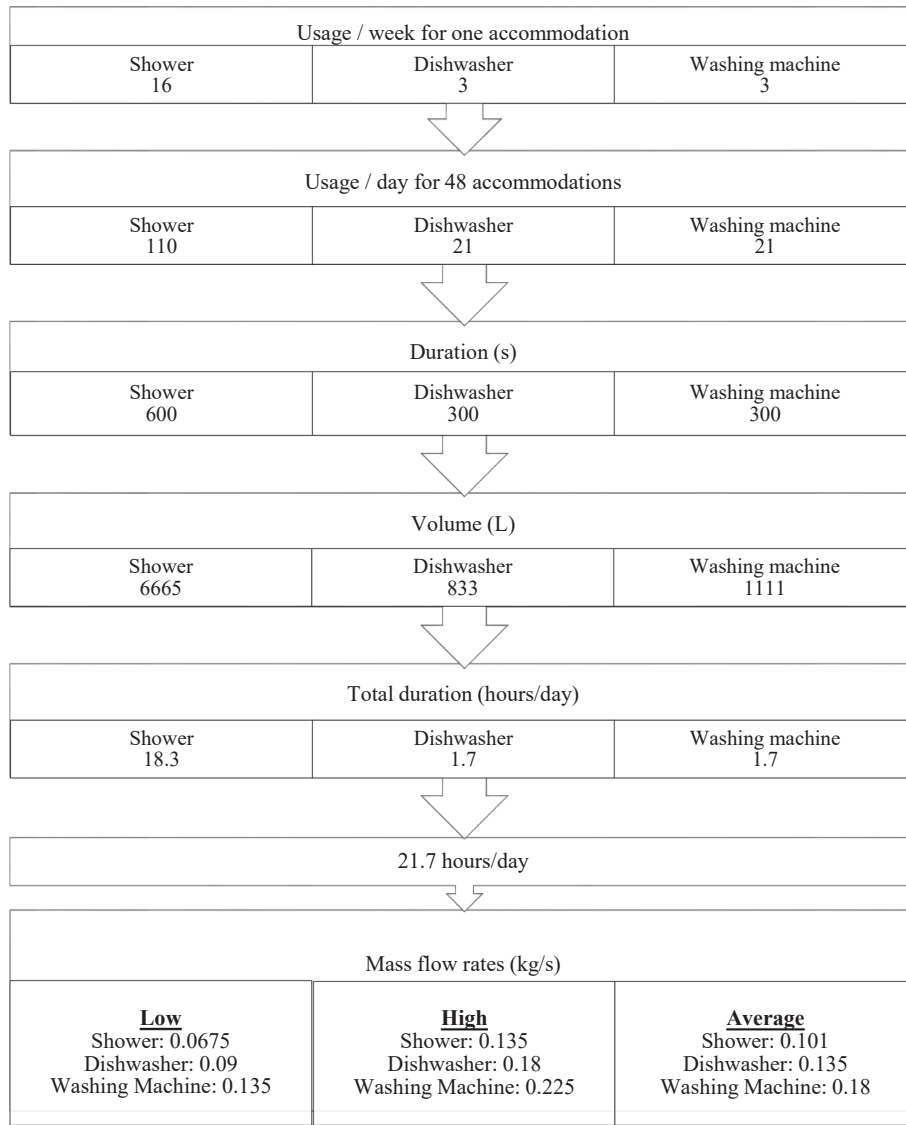


Fig. 4. Mass flow rates and average usage of shower, dishwasher, and washing machine.

Thus, to examine the impact of varying flow rates on heat transfer under different climatic conditions, the simulation will be conducted during both winter and summer seasons. The temperature of the inlet cold water during winter is lower compared to that in summer, while the required temperature of the hot water by the users is higher in winter. This weather dependency necessitates considering different temperature settings for accurate results. For the winter simulations, the inlet cold water temperature is set to 283 K (9.85 °C), while the inlet hot water temperature is set to 333 K (59.85 °C). In contrast, during the summer months of July and August, the inlet cold water temperature is set to 293 K (19.85 °C), and the inlet hot water temperature is set to 313 K (39.85 °C). A detailed overview of the flow rates that will be simulated throughout the study.

2.3. Mesh sensitivity study

This study employs a polyhedral mesh, as depicted in Fig. 5, which visualizes the simulation process. Initially, the design is delineated, and a refined mesh is incorporated. The index “i” signifies the study number; for instance, in Study 1, the initial mesh comprises 2,089,201 elements at a specified element size. Thus, “i” denotes the first study. If the conditions are not met, the index “i” increments to 2, indicating the

transition to the second study and continues similarly.

After meshing and simulation, the y^+ value is evaluated, and the error percentage is compared with the preceding study. This comparison is initiated post the second study. If the pre-established conditions are fulfilled, suggesting the reliability of the applied sizes, they are utilized for further analysis. Conversely, if the conditions are unfulfilled, the mesh study requires repetition. In this investigation, the conditions were satisfied with 7,020,216 elements, an error of 1%, and a y^+ value of less than 1.

2.4. Governing equations

Now, to study the behavior of the flow some parameters should be calculated, which are presented by the equation (1) to (9):

Overall heat transfer: In the CTHE, the overall heat transfer coefficient is computed by just taking into account the convection resistance, ignoring the wall thermal resistance resulting from conduction [25]:

$$U = \frac{1}{\frac{1}{h_{hw}} + \frac{1}{h_{cw}}} \quad (1)$$

where the heat convection coefficient of the flow in the annular is denoted by h_{cw} and is the heat convection coefficient of the flow in the

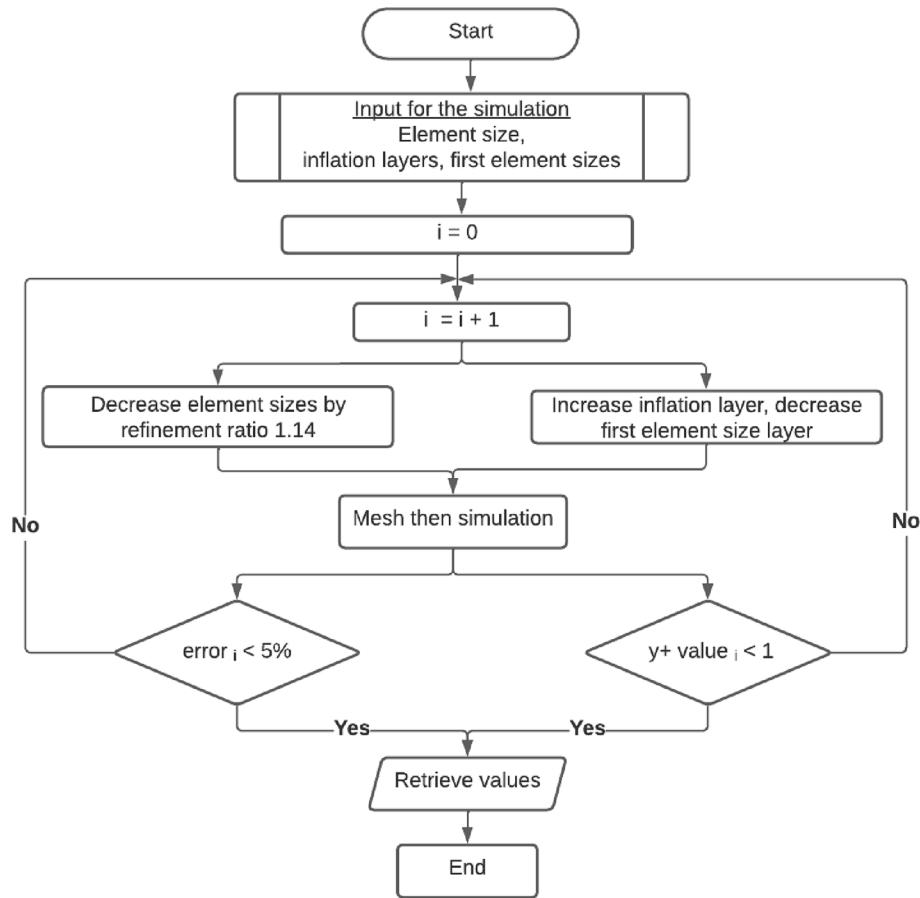


Fig. 5. Algorithmic chart of the mesh study and $y +$ value.

tube is denoted by h_{hw} . The heat transfer coefficient is a measure of the rate at which heat is transferred between a solid surface and a fluid (liquid or gas) through convection as illustrated in equations (6) and (7). It quantifies the effectiveness of heat transfer and is expressed in units of watts per square meter per Kelvin ($W/m^2 \cdot K$).

Nusselt number: The global Nusselt numbers, which are determined based on the tube side and the annular side Nu_{annular} , are computed to evaluate the improvement in heat transport and are given by [25]:

$$Nu_{cw} = \frac{h_{cw} \cdot (D_o - D_i)}{k} \quad (2)$$

$$Nu_{hw} = \frac{h_{hw} \cdot D_i}{k} \quad (3)$$

where the heat convection coefficient of the flow of cold water is denoted by h_{cw} and the heat convection coefficient of the flow of hot water is denoted by h_{hw} is. The diameter of the inner tube is represented by D_i and the diameter of the outer tube is represented by D_o , and k is the heat conductivity.

Heat Transfer: The following factors are provided to determine the heat transfer rates between hot and cold water [25]:

$$q_{cw} = \dot{m}_{cw} \cdot Cp \cdot (T_{cw,o} - T_{cw,i}) \quad (4)$$

$$q_{hw} = \dot{m}_{hw} \cdot Cp \cdot (T_{hw,i} - T_{hw,o}) \quad (5)$$

where the heat transfer of the cold water is denoted by q_{cw} , the heat transfer of the hot water is denoted by q_{hw} , \dot{m} represents the mass flow rate, Cp represents water's specific heat capacity, the temperature of cold water at the inlet is presented by $T_{cw,i}$, the temperature of cold water at the outlet is denoted by $T_{cw,o}$, the temperature of hot water at the inlet is

presented by $T_{hw,i}$ and the temperature of hot water at the outlet is presented by $T_{hw,o}$. Here, the cold water absorbs almost all the heat that the hot water is transferring, causing $q_{cw} = q_{hw}$.

The coefficients of heat transfer convection for the hot water/cold water common wall contact can be obtained by [25]:

$$h_{hw} = \frac{q_{hw}}{\pi \cdot D_i \cdot L \cdot (\bar{T}_{hw} - \bar{T}_w)} \quad (6)$$

$$h_{cw} = \frac{q_{cw}}{\pi \cdot D_i \cdot L \cdot (\bar{T}_w - \bar{T}_{cw})} \quad (7)$$

where the average temperature of the wall interface between the hot tube and cold annular \bar{T}_w , the arithmetic mean temperature of the hot water between the inlet and the outlet of the tube \bar{T}_{hw} and the arithmetic mean temperature between the inlet and outlet of the annular side \bar{T}_{cw} are presented by $(\frac{T_{hw,i} + T_{hw,o}}{2})$ and $(\frac{T_{cw,i} + T_{cw,o}}{2})$ respectively, L and D_i are the length and the inner diameter of the tube respectively.

Thermal Enhancement Factor (TEF): TEF measures the improvement in heat transfer that results from a rise in pumping power, which is the input power used for operating the flow when VGs are added. The heat transfer ratio and pumping power ratio represent the TEF:

$$TEF = \frac{q/q_0}{P/P_0} \quad (8)$$

where the heat transfer with the presence of VGs is denoted by q and the heat transfer with the absence of VGs is represented by q_0 is, thus q/q_0 shows the improvement of heat transfer in the case with VGs to the case with no VGs.

The pumping power ratio [25] is the fraction of the pumping power for the case with VG to the case with no VGs:

$$\frac{P}{P_0} = \frac{(\Delta P_{hw} \cdot \dot{m}_{hw} + \Delta P_{cw} \cdot \dot{m}_{cw})}{(\Delta P_{hw,0} \cdot \dot{m}_{hw,0} + \Delta P_{cw,0} \cdot \dot{m}_{cw,0})} \quad (9)$$

where the input pumping power to obtain a specific Re number in each case is denoted by P , and the input pumping power for the empty case (the case with no VGs) is presented by P_0 .

The effectiveness of a heat exchanger (ϵ) refers to the ability of the HE to efficiently transfer heat between two streams. It is denoted by the following equation:

$$\epsilon = \frac{Q}{Q_{max}} \quad (10)$$

$$\epsilon = (1 - \exp(-NTU(1 - Cr))) \quad (11)$$

where Q is the actual heat transfer rate achieved by the HE, and Q_{max} is the maximum possible heat transfer rate that could occur in an ideal scenario.

NTU is the Number of Transfer Units, Cr is the heat capacity rate ratio $\frac{C_{min}}{C_{max}}$, where C_{min} is the minimum heat capacity rate of the two fluid streams and C_{max} is the maximum heat capacity rate.

The NTU is a dimensionless parameter that represents the combined effect of heat transfer surface area, flow rates, and heat capacity rates. It is calculated as:

$$NTU = \frac{UA}{C_{min}} \quad (12)$$

3. Results and discussion

3.1. Numerical results

Following the implementation of simulations using the range of mass flow rates outlined in Fig. 4 in Ansys, various parameters were calculated to analyze the heat transfer for each case. Fig. 6 illustrates the temperature distribution along the Concentric Tube Heat Exchanger (CTHE) during both the winter and summer seasons. The mass flow rate of the cold water is held constant at 0.25 kg/s, which is the average mass flow rate obtained from Fig. 6. However, the mass flow rates of the hot water range from 0.1 to 0.5 kg/s.

Notably, at the highest hot water flow rate, the temperature of the heated water reaches 290.53 K, resulting in a significant increase of

7.53 K. For the cases with hot water mass flow rates of 0.4, 0.3, 0.2, and 0.1 kg/s, the corresponding temperature increases are calculated as 6.82, 5.97, 5.49, 4.97, and 3.60 K, respectively. During the summer season, although there is an increase in temperature, it is less pronounced compared to winter. The temperature differences reach up to 4.6 K, and the temperatures of the cold-water inlet for flow rates of 0.5, 0.4, 0.3, 0.2, and 0.1 kg/s are measured as 295.2, 296.0, 296.4, 296.6, and 297.1 K, respectively.

Fig. 7 shows the values of the main parameters that indicate the behavior of the flow.

The results indicate that as the flow rate increases, heat transfer rate (q), overall heat transfer coefficient (U), temperature difference (ΔT), and thermal enhancement factor (TEF) all increase. These factors exhibit promising performance in both seasons, with winter results surpassing those in summer due to the greater temperature difference between the hot and cold-water inlets. Although the temperature difference is smaller in summer, the outcomes remain acceptable, as the inlet cold water is preheated by up to 4.6 °C. In winter, the temperature difference reaches up to 7.5 °C, signifying energy savings equivalent to the temperature difference.

Regarding TEF, the results reveal that the TEF in both seasons is approximately 2.3, which implies that the heat transfer enhancement relative to the pumping power driving the flow is more than twice the case without vortex generators (VGs).

The results of this study are compared with previously published research that examined the effectiveness of heat exchangers in various applications. The comparison is presented in Table 1, which illustrates the impact of heat exchangers in different studies, including this study. The effectiveness of heat exchange is varying from 0.15 to 0.26 across all cases, with variations primarily arising from differences in the application, heat exchanger dimensions, and boundary conditions (mass flow rates, temperatures of cold and hot water, and working fluid ...).

Another factor contributing to the variations in effectiveness is the method employed to enhance heat transfer within the heat exchanger. For instance, in the study first study, a coil tube heat exchanger was utilized, where the heat transfer enhancement Method (HTEM) was achieved through the introduction of coil tubes that generated Dean vortices, thus improving heat transfer efficiency. In the second study, a corrugated tube was used with varying mass flow rates at the same temperature. In the third study, the effectiveness of the heat exchanger was relatively low, this can be attributed to the working fluid used (ethanol). However, in the fourth study, heat transfer enhancement is achieved using trapezoidal-shaped vortex VGs, which also contribute to enhancing heat transfer. As noticed from Table 1, there exists a slight difference in the effectiveness of the HE, this is due to several factors

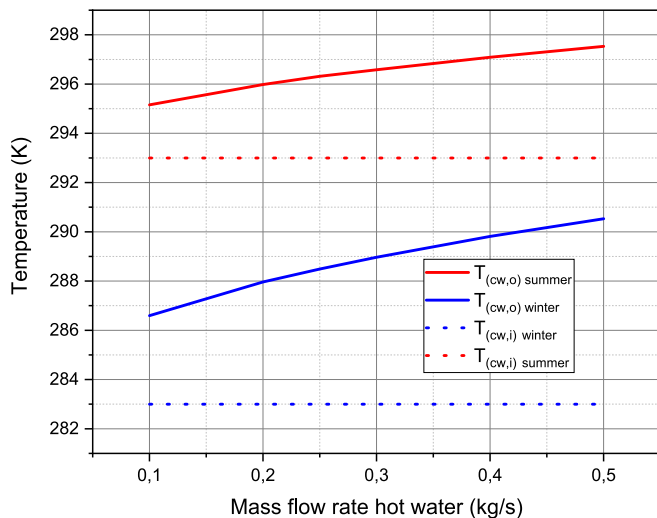


Fig. 6. The temperature of the cold-water outlet in winter and summer at different mass flow rates of the hot water.

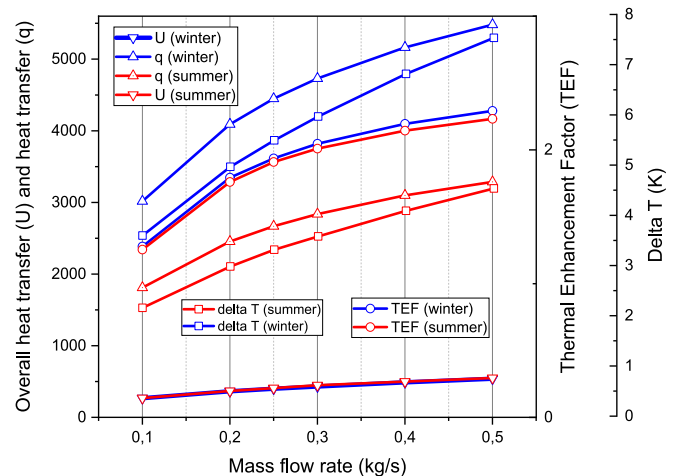


Fig. 7. Overall heat transfer, heat transfer, TEF, and delta temperature in winter and summer vs mass flow rate of hot water.

Table 1
Comparison between the effectiveness obtained in this study with other published work.

Study	HE types	HTEM	Conditions	Effectiveness
1 Murr et al., [13], 2020	Counter flow coil tube HE	Coil tube	At a hot temperature of 65 °C	0.26
			At a hot temperature of 45 °C	0.23
			At a hot temperature of 25 °C	0.19
2 Kumar et al., [27], 2020	Counter flow CTHE	Corrugated/ curved tubing	$T_h = 47$ °C, $\dot{m}_c = 3/60$ kg/s, and $\dot{m}_h = 2/60$ kg/s.	0.15
			$T_h = 47$ °C, $\dot{m}_c = 2/60$ kg/s, and $\dot{m}_h = 1/60$ kg/s.	0.21
3 Ramkumar et al., [28], 2021	Concentric tube - heat pipe - heat exchanger	Heat pipe	At a hot temperature of 65 °C methanol working fluid	0.21
4 Present study	Counterflow CTHE	VGs	At a hot temperature of 50 °C	0.25

such as the presence of different enhancement heat transfer methods, different geometry, and boundary conditions. However, it is noteworthy that the design under investigation in this study demonstrates promising potential, achieving equivalent effectiveness to coil tube heat exchangers, which are renowned for their high efficiency [26]. Additionally, this design exhibits lower pumping power requirements compared to other systems, boasting a thermal enhancement ratio of 1.8. This ratio signifies the heat transfer ratio over the required pumping power [17]. Consequently, these findings suggest a favorable outlook for this design in the future.

3.2. Economic study

To study the effectiveness of the system two main studies should be considered: economic and environmental. To consider that the system is sustainable, it should have a low impact on the three categories. In this part, the economic study will be held for the five sources of heating energy: solar, wind, biomass, hydropower, and pumped storage. Table 2 shows the levelized cost of electricity (LCOE), which is the amount at which generated energy should be distributed for the system to break even after its lifetime. The economic cost saved by the DHRS, and the prices for solar, wind, biomass, and hydropower are taken from [29], for the pumped storage the price is taken from [30].

It is noticed that the prices saved by the DWHRs are significant, where the saved money reached up to 6.70 €/day for pumped storage, and the savings for other systems are 3.62, 2.49, 5.05, and 3.62 €/day for solar, wind, biomass, and hydropower respectively for a temperature difference of 7.5 °C. Now, although the price of wind is the lowest, however, this cost is per day, so it makes a difference over time. Moreover, the cost of the energy saved from expensive energy sources is more than the cheap energy source, in other words, the higher cost of the energy sources the more savings the system will provide.

3.3. Environmental study

Environmental Life Cycle Assessment (ELCA) has been widely used to evaluate the environmental impact and viability of products. This method is used to quantify each product's environmental effect from the start to the finish line, where some releases may be damaging to the ecosystem at each stage and each form of emission has a related cost that represents its possible damage. In this section, we will study the environmental impact of solar, wind, biomass, hydropower, and pumped storage. The rate of emission changes depending on the sort of natural

Table 2
Saved energy and prices for the heat recovery system.

Temperature difference (°C)	Q (kWh)	Price (€)				
		Solar	Wind	Biomass	Hydropower	Pumped storage
3.5	35.17	1.69	1.16	2.36	1.69	3.13
4.5	45.19	2.17	1.49	3.03	2.17	4.02
5.5	55.25	2.65	1.82	3.70	2.65	4.92
6.5	62.27	3.13	2.15	4.37	3.13	5.81
7.5	75.33	3.62	2.49	5.05	3.62	6.70

resource used. Thus, the ELCA of the five researched energy sources is performed using OpenLCA and the Ecoinvent database to assess the environmental consequences connected with all of the processes from cradle to grave [4]. Fig. 8 shows the processes and emissions of producing and using various sources of energy (solar, wind, biomass, hydropower, and pumped storage).

The environmental analysis begins with the preparation system, encompassing the materials and labor required to construct the power infrastructure. Throughout this process, emissions are released alongside power generation. Subsequently, electricity is either distributed through wires or stored in batteries, both of which also emit greenhouse gases. Ultimately, the materials used in the system reach the end of their useful life and are disposed of in landfills.

In this section, we examine the life cycle assessment (LCA) of each energy source, taking into account the emissions produced at each stage of the process. These emissions vary across activities, and each type has distinct environmental consequences. Consequently, the impact of each energy source is assessed and quantified in carbon dioxide equivalents (CO₂ eq), while the Environmental Cost Indicator (ECI) is employed to calculate the Eco-cost for each type. This LCA categorizes the studied impact groups into two sectors: (1) Abiotic Environment Influence, which concerns the general environmental impact, and (2) Potential Human Health and EcoToxicity Impacts, which relate to the impact on both human and natural resources.

After identifying the processes and emissions for each type of electricity source, the processes are obtained from the Ecoinvent database for Switzerland (CH) as follows: electricity, at wind power plant – CH; electricity, production mix photovoltaic, at the plant – CH; electricity, hydropower, at pumped storage power plant – CH; electricity, hydro-power, at power plant – CH; and electricity, wood, at distillery – CH.

Table 3 presents the results of an impact assessment of the heating system using various electricity sources, such as solar, wind, biomass, hydropower, and pumped power storage, to calculate the Environmental Cost Indicator (ECI). The ECI computes the total environmental cost by summing all categories, allowing for comparison to assess the ecological cost of each process. Moreover, the Eco-cost ECI is calculated for each energy source, with each impact category featuring a unique coefficient that combines all relevant environmental effects into a single environmental cost metric, representing the product's environmental burden.

It is observed that pumped storage exhibits the highest Global Warming Potential (GWP) and ECI, at 0.018 €/kWh, while hydropower displays the lowest ECI, at 0.00036 €/kWh, due to its straightforward process that harnesses potential energy to drive the pump. Conversely,

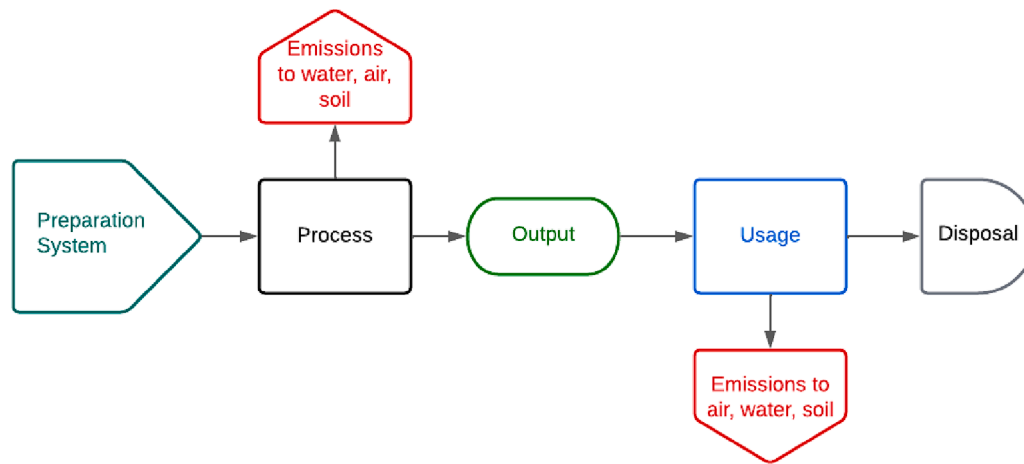


Fig. 8. Life cycle of using the heating source from cradle to grave.

Table 3
Impact analysis of 1 kWh of solar, wind, biomass, and pumped storage.

Impact categories	Unit	Solar	Wind	Biomass	Hydropower	Pumped storage
GWP100	kgCO ₂ -eq	0.021	0.00483	0.011	0.00126	0.0524
0.05 €/kgCO ₂	€	0.0011	0.000242	0.00054	0.000063	0.00262
Ozone layer depletion	kgCFC-11-eq	4×10^{-9}	0.29×10^{-9}	1.1×10^{-9}	0.0076×10^{-9}	7.06×10^{-9}
30 €/kgCFC-11-eq	€	12×10^{-8}	0.02×10^{-8}	3.4×10^{-8}	0.23×10^{-8}	21.2×10^{-8}
Human toxicity	kg _{1,4} DB-eq	0.0338	0.03	0.0045	0.00197	0.0045
0.09 €/kg _{1,4} DB-eq	€	0.003	0.0027	0.00041	0.00018	0.04
Depletion of abiotic resources fossil fuel - elements ultimate reserves	kgSb eq	279×10^{-8}	8.38×10^{-8}	2.3×10^{-8}	0.465×10^{-8}	2.83×10^{-8}
0.16 €/kgSb eq	€	446×10^{-9}	13.4×10^{-9}	3.6×10^{-9}	0.744×10^{-9}	4.53×10^{-9}
Terrestrial Ecotoxicity	kg _{1,4} DB-eq	5.7×10^{-4}	25.8×10^{-4}	4.7×10^{-4}	11.4×10^{-4}	7.1×10^{-4}
0.06 €/kg _{1,4} DB-eq	€	25×10^{-5}	91×10^{-5}	14×10^{-5}	6.65×10^{-5}	32×10^{-5}
Photochemical Oxidation	kg _{ethylene} eq	6.44×10^{-6}	1.55×10^{-6}	3.2×10^{-6}	0.234×10^{-6}	10.1×10^{-6}
2 €/kg _{ethylene} eq	€	12.9×10^{-6}	3.1×10^{-6}	6.4×10^{-6}	0.468×10^{-6}	20.2×10^{-6}
Eutrophication	kgPO ₄ eq	6.4×10^{-5}	1.21×10^{-5}	21×10^{-5}	0.13×10^{-5}	15×10^{-5}
9 €/kgPO ₄ eq	€	5.76×10^{-4}	1.09×10^{-4}	1.9×10^{-4}	0.2×10^{-4}	13.5×10^{-4}
Acidification potential	kgSO ₂ eq	10×10^{-5}	2.27×10^{-5}	8.1×10^{-5}	0.38×10^{-5}	24×10^{-5}
4 €/kgSO ₂ eq	€	4×10^{-5}	9.07×10^{-5}	32×10^{-5}	1.5×10^{-5}	96×10^{-5}
Marine aquatic ecotoxicity	kg _{1,4} DB-eq	48.67	10.48	3.565	0.74	81.54
10^{-4} €/kg _{1,4} DB-eq	€	4.87×10^{-3}	1.05×10^{-3}	0.4×10^{-3}	0.07×10^{-3}	8.15×10^{-3}
Freshwater aquatic ecotoxicity	kg _{1,4} DB-eq	0.015	0.0069	0.00137	0.00049	0.02798
0.03 €/kg _{1,4} DB-eq	€	4.5×10^{-4}	2.07×10^{-4}	0.4×10^{-4}	0.147×10^{-4}	8.39×10^{-4}
Total	€	0.0104	0.0045	0.00187	0.00036	0.0180

solar, wind, and biomass have higher environmental impacts with ECIs of 0.0104, 0.0045, and 0.00187 €, respectively. These impacts vary by country or region based on the materials used and the processes involved in electricity generation.

To ascertain the precise environmental savings achieved by the DWHR system, we must calculate the Environmental Price (EP) per unit of energy saved. Table 4 presents the EP saved by the heat recovery system, determined from the environmental study conducted in openLCA. The ECI of 1 kWh is multiplied by the amount needed to provide specific energy corresponding to the temperature difference.

The highest environmental savings achieved by the DWHR system were for pumped storage (1.356 €), as it has the highest ECI, followed by solar, wind, biomass, and hydropower, with EPs of 0.783, 0.339, 0.141,

and 0.027 €, respectively, for a temperature difference of 7.5 °C. This ranking is consistent with the ECI associated with each source. Although these savings may appear small, they accumulate over time, as the saved costs are calculated daily.

4. Conclusions

This research paper presents a comprehensive numerical-analytical study of a novel heat recovery design proposed in a previously published article [17]. The design incorporates a Concentric Tube Heat Exchanger (CTHE) equipped with 10 rows of Vortex Generators (VGs) distributed along the tube length. Utilizing Ansys Fluent, various heat transfer parameters such as heat transfer rate, overall heat transfer, and

Table 4
Environmental savings by the heat recovery systems for the four electrical sources of heating and one energy storage system.

Temperature difference (°C)	Q		EP (€)				
	(MJ)	(kWh)	Solar	Wind	Biomass	Hydropower	Pumped storage
3.5	126.6	35.154	0,366	0,158	0,066	0,013	0,633
4.5	162.7	45.198	0,470	0,203	0,085	0,016	0,814
5.5	198.9	55.242	0,575	0,249	0,103	0,020	0,994
6.5	235.0	65.286	0,679	0,294	0,122	0,024	1,175
7.5	271.2	75.33	0,783	0,339	0,141	0,027	1,356

thermal heat transfer factor were computed to assess the system's efficiency in recovering heat from wastewater. The study also examined the initial and monthly costs associated with the design to evaluate its feasibility. Furthermore, economic and environmental analyses were conducted, considering the utilization of five different types of renewable energy sources, namely solar, wind, biomass, hydropower, and pumped storage, for heating the system. The objective was to determine the environmental impact and potential economic savings associated with each energy source when integrated with this particular design. Previous research indicates that integrating this design with fossil fuels reduces both environmental and economic impacts. Therefore, the main question addressed in this study is whether integrating this design with renewable energy sources is a worthwhile endeavor, considering its potential benefits in terms of environmental sustainability and cost-effectiveness.

According to the results in the numerical study, the design provides a temperature increase of 3.5 to 7.5 °C in cold conditions and 2.2 to 4.6 °C in summer, affecting various aspects of the economy, and environment. The conclusions for each section are as follows:

1. Economic

- While the initial investment in renewable systems is high, the price per kWh is acceptable over a system's lifetime, given the free energy source.
- The economic savings for solar, wind, biomass, hydropower, and pumped storage are up to 3.62 €, 2.49 €, 5.05 €, 3.62 €, and 6.70 € per day, respectively.

2. Environmental

- The environmental impact of the five distinct renewable energy types was examined, revealing that hydropower has the lowest impact, while pumped storage has the highest.
- The HRS offers environmental savings costs for solar, wind, biomass, hydropower, and pumped storage of up to 0.783 €, 0.339 €, 0.141 €, 0.027 €, and 1.356 € per day, respectively.
- Although renewable energy sources have relatively low environmental impacts, it is essential to incorporate thermal recovery systems, as long-term savings are worthwhile.

As a conclusion, this design is worth to be integrated with renewable energy sources as well. It does not just save energy but it has lower environmental and economic costs. The environmental savings are expressed per day so over a year the prices saved will be 286, 124, 52, 10, and 495 € for solar, wind, biomass, hydropower, and pumped storage respectively. Conversely, yearly economic savings are 1322, 909, 1844, 1322, and 2446 € for solar, wind, biomass, hydropower, and pumped storage respectively. This makes this system essential for saving energy, the economy, and the environment.

CRediT authorship contribution statement

Rima Aridi: Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft. **Samer Ali:** Conceptualization, Formal analysis, Investigation, Supervision, Project administration, Writing – review & editing. **Thierry Lemenand:** Conceptualization, Formal analysis, Investigation, Supervision, Project administration, Writing – review & editing. **Jalal Faraj:** Conceptualization, Formal analysis, Investigation, Supervision, Project administration, Writing – review & editing. **Mahmoud Khaled:** Conceptualization, Formal analysis, Investigation, Supervision, Project administration, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors are unable or have chosen not to specify which data has been used.

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