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A recent review on waste heat recovery methodologies and applications: Comprehensive review, critical analysis and potential recommendations

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ABSTRACT

Due to global warming and environmental issues in recent times, the world's concern is oriented nowadays toward discovering new renewable energy sources and energy management methods. Particularly, researchers are emphasizing on heat recovery technologies and applications in both residential and industrial sectors. While there are plenty of review papers in the literature on the subject matter, there is always a necessity to update the literature with the new advancements in the field. In this context, the purpose of this paper is to present a recent and complete systematic comprehensive review along with critical analysis and potential recommendations related to waste heat recovery (WHR) methodologies and applications. In methodologies, heat exchangers, Rankine cycle and thermoelectric generators are studied. Moreover, applications of WHR are discussed in automotive, and in both residential and industrial zones. Studies show that the optimization of heat recovery systems lead to significant magnitudes of energy savings. On the other hand, hybrid heat recovery systems prove to be the most trending research subject nowadays. For future work, the negative effect of backpressure should be taken into consideration when recovering energy from exhaust gases of engines and power generators, and more importance should be given to hybrid systems.

1. Introduction

During the last decades, human dependency on energy has increased (Energy Systems in Transition: Challenges and Opportunities, 2021). The use of energy in transportation has doubled in the past thirty years, and it is expected to be doubled again by the year 2050(Güven et al. 2019). Industrial sectors account for about a third of the total energy consumed in a country(Cavazzini et al., 2019). However, multiple reports showed the considerable rate of growth in world's energy demand due to an increase in the population (Mahmoudi et al. 2018).Forecasts show that world's energy demand will experience a 35% growth from 2010 to 2035 (Saghafifar et al., 2019). The development of the industrial domain, the reduction of the fuel resources and the fast population growth are the main reasons in the increase in demand of energy (Ramadan, lemenand, and Khaled 2016). Researches show that energy efficiency remains low and is about 30% in China (Wang et al., 2020). Population ageing has been becoming one of the most severe social issues threatening global sustainable development (Haoran Zhang et al., 2021). Therefore, novel technologies for improving energy efficiency are urgently required to save energy and reduce emissions (Ouyang et al., 2019). However, with soaring oil prices, energy conservation, emissions reduction and sustainable development concept are receiving more attention, making engine waste heat recycling a research hotspot. Engine waste heat recycling, not only can reduce environmental pollution, but also can significantly improve the energy efficiency (Yue and Wang 2019).The consumption of energy in buildings has increased due to enlargement of building sectors, expansion of Heating, Ventilating and Air Conditioning (HVAC) systems and economic development (Mardiana-Idayu and Riffat 2012).

As climate change became a reality, improving facility efficiency is important for reducing CO_2 emissions in the industrial and power generation fields (Na et al., 2019). Currently, fighting against climate change is a serious issue that necessitates global cooperation. The European Council, on its Energy Efficiency Directive, has endorsed an indicative target of 30% energy savings by 2030 for Europe

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Abbreviations

WHR	Waste Heat Recovery
HRS	Heat Recovery System
HVAC	Heating, Ventilating and Air
WHRS	Waste Heat Recovery System Conditioning
HHRS	Hybrid Heat Recovery System
EGR	Exhaust Gad Recirculation
TE-HR	Thermoelectric Heat Recovery
LHC	Longitudinal Heat Conduction
DWHR	Drain Water Heat Recovery
HE	Heat Exchanger
ASHP	Air Source Heat Pump
RC	Rankine Cycle
AS-THP	Air Source-Thermoelectric Heat Pump
ORC	Organic Rankine Cycle
D-ORC	Dual- Organic Rankine Cycle
DHW	Domestic Hot Water
CI-ORC	Compression Ignition Organic Rankine Cycle
GHG	Green House Gas
COP	Coefficient of Performance
M-ORC	Mixture-Organic Rankine Cycle
DCS	Domestic Thermoelectric Cogeneration System
HT-ORC	High Temperature-Organic Rankine Cycle
ER	Energy Recovery
NZEB	Net Zero Energy Building
GT	Gas Turbine
ERV	Energy Recovery Ventilator
ICE	Internal Combustion Engine
HRV	Heat Recovery Ventilator
TEG	Thermoelectric Generator
GSHP	Ground Source Heat Pump
HP-TEG	Heat-Pipe Thermoelectric Generator
PLHP	Pump Driven Loop Heat Pump
ETC	Electric-Turbo Compound
CHP	Combine Heat and Power
TEM	Thermoelectric Module
HTC	Heat Transfer Coefficient
PG	Power Generator
HP	Heat Pump

consumption, including main sectors such as transport, electric generation and industry (Bonilla-Campos et al., 2019). With the continuous rise in world oil prices and increasing environmental awareness, how to improve ship energy efficiency and reduce ship pollution emissions became a common concern of the shipping industry (Feng et al., 2020). The rising concern regarding global warming, engineering industries are challenged with the task of reducing greenhouse gas emissions and improving the efficiency of their sites (Jouhara et al., 2018). Recent studies estimated that about half of involved energy is wasted in transportation, power generation, industrial developments, domestic areas and many other activities (Nithyanandam and Mahajan 2018). About 55–70% of fuel energy in Internal Combustion (IC) engines is wasted through exhaust gas, exhaust gas recirculation (EGR), and heat losses, while the remaining energy is considered as useful power (Brückner et al., 2015; Chintala et al. 2018).

Heat is necessary for many building applications and, therefore, must be generated, stored and used efficiently to take advantage both economically and environmentally (Torras et al., 2016). Heat loss transferred by conduction, convection and radiation from combustion progressions is classified as sources of waste heat. However, it can be categorized also as low, medium and high temperature grades (Jouhara et al., 2018).

So, efforts are exercised on renewable energy and energy management concepts as a must, to decrease fuel consumption and thus improve energy production (Khaled et al., 2015; Pong et al., 2021). Recuperating lost energy and/or improving the way of using energy are techniques executed to assist renewable energy. These techniques are "Energy Management". Domestic and manufacturing sectors depend on thermal energy. Usually, the loss in this type of energy is deserted without benefiting from it. Yet, it can be dumped by either exhaust gases, or cooling air, or cooling water. This is also a technique in Energy Management (Jaber et al., 2018). Waste heat recovery (Valenti et al. 2019) (WHR) represents the amount of waste heat of the exhaust gas absorbed by the inlet air in the heat exchanger. Such systems are used for waste heat to attain the best efficiency of WHR. (Jouhara et al., 2018). However, heat recovery is a particular route in energy management where one tends to mainly capture heat generated from various applications, contrary to solar and wind energies where natural energies are invested (Khaled et al. 2015). In other words, it is capturing lost heat in many applications that carry hot fluids such as, internal combustion engines, heat pumps, chillers, chimneys, shower water and power generators and recovering it in an operative and efficient way (Khaled et al., 2015; Ramadan et al. 2015). Few review works are dedicated to heat recovery from exhaust gas. Usually, researchers emphasize on a specific heat recovery application and sum up with an overview for articles which studied this domain.

Patil et al. (Patil et al. 2018) reviewed thermoelectric materials and heat exchangers best structures and functioning settings for power generation. In addition, Zhou et al., (2017) reviewed the current and future application of Rankine Cycle to passenger vehicles for waste heat recovery including thermal energy sources, selecting criteria and working fluids. However, Shi et al., (2018) reviewed the modified organic rankine cycles (ORCs) for internal combustion engine waste heat recovery (ICE-WHR). Mahmoudi (Mahmoudi et al. 2018) presented a review on theoretical and experimental studies on ORC usage for waste heat recovery and investigation on the effect of cycle configuration, working fluid selection and operating condition on the system performance in recent year. Moreover, system design methods, applications of ORC systems are studied as well (Lion et al. 2020; Zhao et al., 2019).

Mardiana-Idayu (Mardiana-Idayu and Riffat 2012) reviewed energy recovery procedures for structure submissions basing their classification according to the types and flow arrangement. These procedures are developed in cohesive energy-efficient systems such as mechanical and passive ventilation, air conditioning, dehumidification and photovoltaic pane. On the other hand, Chintala reviewed the prospect of WHR from exhaust gas, water jackets and intake charge air of compression ignition (CI) engines. This review also studied CI engines, and how to recover waste heat and produce further power output from these engines with the application of organic rankine cycle (ORC) (Chintala et al. 2018). In addition, Jaber et al., (2016) presented a review on heat recovery from exhaust gas. The authors proposed to classify exhaust gas heat recovery systems into three different categories: exhaust gas temperature, exploited equipment and recovery purposes.

Zhou et al. (Zhu et al. 2020) reviewed waste heat recovery from the marine engine with highly efficient bottoming power cycles by studying Trade-offs between working fluid characteristics, cycle configuration, size, cost and WHR potential. Furthermore, Radenahmad et al., (2020) reviewed biomass derived syngas for SOFC based combined heat and power application.

Some reviewers discussed studies on thermoelectric generators and heat exchangers while others showed studies on ORCs. However, some other researchers summed different studies on engines. Yet, none of them made a comprehensive review combining waste heat recovery methodologies and different applications on it. Therefore, what makes this review paper distinct from other review articles in this domain is its premium combination. In other words, it sheds the light on the effective features in studying heat recovery systems and summarizes the recent results of applications on the most imperative systems in this domain. Thus, researchers can depend on this review as a base to start their experimental researches. Both heat recovery methodologies and applications are studied. In methodologies, heat exchangers, Rankine cycle and thermoelectric generators are studied. While applications of WHR are discussed in vehicles, and in both residential and industrial zones. In addition, hybrid systems, the most trending heat recovery studies, are investigated in this article.

This article is concerned with recent heat recovery methodologies and its application in daily life systems based on 127 published papers. The review is composed of five sections including introduction. Section 2 deals with the methodologies of heat recovery especially heat exchangers, rankine cycle and thermoelectric generators. Then section 3 deals with the applications of engine, residential and industrial systems. Section 4 deals with hybrid systems and finally section 5 draws some discussions, conclusions and recommendations.

The novelty of this review paper resides in:

1. Drawing key conclusions about the working process and the pros and cons of several devices used in waste heat recovery.
2. Classifying studies according to newly defined criteria and providing appropriate interpretation on the subject matter.
3. Providing a comparative review on heat recovery devices according to its pros and cons and the effect of important parameters on the efficiency of the waste heat recovery system.

2. Methodologies

Since WHR is a wide term that accommodates many methods and mostly affected by different parameters and variables, researchers made some classifications and enhancements concerning heat exchangers, rankine cycle and thermoelectric generators that will be discussed in this part. Fig. 1 presents a schematic for the main studied topics in Methodologies.

2.1. Heat exchangers

Heat exchanger is a heat transfer device that exchanges heat between two or more process fluids. Heat exchangers have widespread industrial and domestic applications (Zohuri and McDaniel 2018). Every heat exchanger is affected by certain factors, and correspond to a specific geometric shape, which lead to a distinct efficiency.

Zohuri (Zohuri and McDaniel 2018) classified the types of heat exchangers based on flow path configuration, contact, construction features, and compactness factor. In flow path configuration, four types were determined: parallel flow, counter flow, single-pass cross flow, and multi-pass counter flow heat exchanger. Whereas, based on contact, a heat exchanger of direct contact type is that having two immiscible fluids, while the one with indirect contact type refers to surface heat exchangers. However, tabular (shell and tube), plate, plate-fin, tube-fin and regenerative heat exchangers are the types classified based on construction features. It is noted that as compactness factor increases, heat transfer increases and thus efficiency increases too. Compactness factor for Plate-fin heat exchanger shows the best value (6000 m^2/m^3). Fig. 2 shows cross-section of Plate-fin heat exchanger, which is the best type within this classification.

On the other hand, basing the studies on heat recovery applications for housing sectors according to the categorization of types and flow arrangement, every heat recovery type showed a range for efficiency. That is, the efficiency of Fixed Plate was 50–80%, Heat Pipe 45–55%, Run around 45–65%, and finally rotary wheel HE greater than 80%. Based on the above results, rotary wheel HE proved to be the best system to be used (Mardiana-Idayu and Riffat 2012). Nevertheless, to keep away from cross contamination, plate heat exchanger and heat pipe systems are used to transfer heat from one source with different temperature ranges, while heat pumps appears good for low-temperature waste heat recovery, as it gives the capability to upgrade waste heat to a higher temperature and quality (Khordehgah et al., 2018). Liu et al. (Torras et al., 2016) investigated the effects of longitudinal heat conduction (LHC) on the heat recovery effectiveness of the heat wheel (the best heat exchanger currently) in power-house building. The result of LHC effect was unexpected low temperature efficiency of heat wheel, and reaching high temperature efficiency (85%) was hard due to LHC (P. Liu, Mathisen, and Alonso 2017). Fig. 3 shows a schematic for heat wheel HE, which is the best type according to this study.

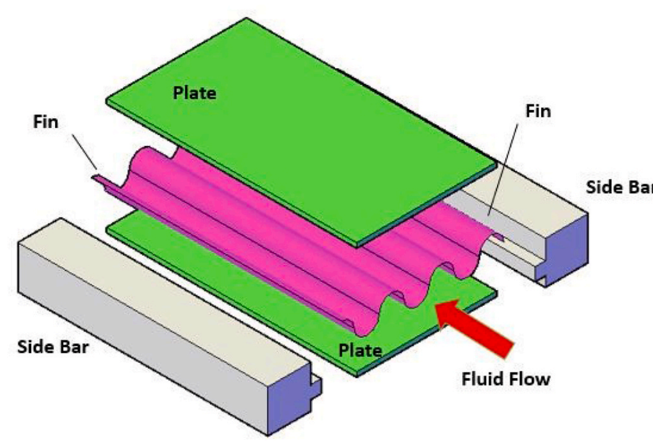

Fig. 2. Cross-section of Plate-fin heat exchanger.

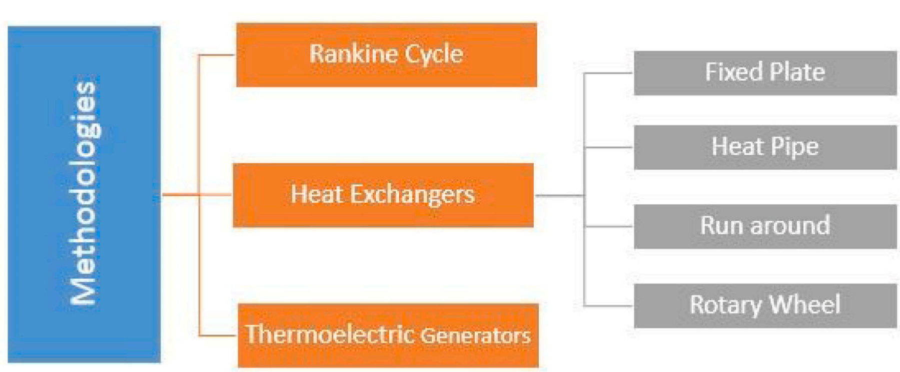

Fig. 1. Main studied topics in Methodologies.

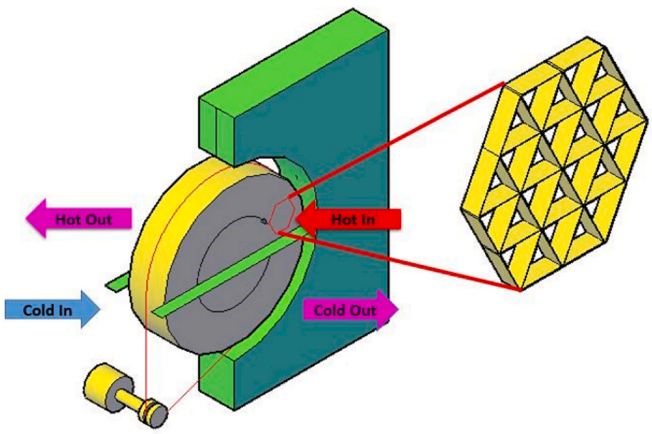

Fig. 3. Schematic of heat wheel HE.

Dealing with heat exchangers used for thermoelectric generators (TEGs), plate type is recommended. This heat exchanger delivers primary heat to the TEG. However, fin structure, formation of the heat exchanger and functioning settings are supplements that improve the heat transfer rate and thermal consistency of the heat exchanger. In addition, the engine exhaust flows into the heat exchanger (HE) and transfers heat, which drop the pressure level of the different structures with a wide range of operating conditions. However, engine operating condition, allowable pressure drop, and temperature limit of the thermoelectric module (TEM) control the selection of internal structure of the HE (Patil et al. 2018). Table 1 shows a summary for some studies about heat exchangers, its main objectives and further obtained results.

Heat exchanger is the most important part in heat recovery systems. Thus, comparing different heat exchangers and applying the best one increases efficiency of the whole system. Studies show that plate-fin and rotary wheel heat exchangers prove to be the best among other types. Therefore, there is no final conclusion toward the best heat exchanger to be used by researchers. Then, researchers should build deep studies on heat exchangers, their types and the enhancements that can be done to improve efficiency of the HE and the whole WHR system.

2.2. Rankine cycle

Rankine cycle (RC) which is a reliable technology to efficiently convert low and medium temperature heat sources into electricity, has been known as a promising solution to recover the waste heat (Mahmoudi et al. 2018).It consists of four main parts: pump, boiler, turbine and condenser. This cycle is a major component of many applications on waste heat recovery. Fig. 4 shows rankine cycle components. However, waste heat recovery technologies are the key technologies to realize the comprehensive and efficient utilization of energy. The ORC system, which can convert heat at low and medium temperatures into mechanical energy or electricity, is investigated and used widely due to its simplicity in the design and operation (Zhao et al., 2019). Organic Rankine cycles (ORC) have emerged as a promising technology for recovering low (<230°C) and medium temperature (230–650°C) waste heat. Compared with other cycles such as trilateral flash cycles or kalina cycle, ORCs have a much simpler cycle architecture (Surendran and Seshadri 2020).

ORC system is considered also as a promising technology for energy recovery from the waste heat rejected by IC engines (Wang et al., 2017). The highest sources for WHR by ORC are Diesel Engines (Regenerative dual loop), internal combustion engines (ICEs) and gas turbines (GTs). Yet, the increment of heat source has a positive feedback on ORC system performance, while that of condensation temperature has a negative one. In addition, the most influential thermo-physical characteristics of working fluids affecting the system performance are critical state, sensible heat and ratio of vaporization latent heat. Thus, this performance is improved when fluids are mixed (Mahmoudi et al. 2018). In other words, for the regaining and conversion of low-grade heat energy, ORC plays a major role for the simple, compact and low cost system components with small sizing and the properties of organic fluids that can exploit low and variable temperature heat sources (Ã, Chien, and Wang 2004; Baccioli et al. 2017; Gang, Jing, and Jie 2010; Jing et al. 2010; Leung 2017; Roy et al. 2010).Therefore, this technology is outstanding due to its low cost and good thermal efficiency (Wang et al., 2020).

A single ORC system is usually unable to recover energy efficiently from both of the aforementioned waste heat sources (E. Wang et al., 2017). Systems with hydrocarbons as the working fluids exhibit good thermal performance. However, the flammability of hydrocarbons limits their applications because of safety concerns (Song and Gu 2015). A dual loop ORC system, cascaded to recover energy from the engine's exhaust gases and coolant separately, is proposed to address this challenge. The results show that to recover energy from the waste heat of a compressed natural gas (CNG) engine, a pair of environmentally friendly refrigerants, R1233zd and R1234yf, are used as working fluids, and the proposed dual loop ORC system could achieve better performance than other ORC systems for similar applications (E. Wang et al., 2017). Besides, Zhou et al., (2017) reviewed the application of rankine cycle to passenger vehicles aiming for waste heat recovery. There are two thermal energy sources in engine: engine coolant and exhaust gas; where the last one proves to have greater recovery potential in terms of exergy. Yet, two main points are discussed as selection criteria: working fluid and expander. However, many studies use other different working fluids. However, organic fluid is suitable for low temperature heat sources. On the other hand, according to the type of expander to be used. Zhou et al. [47] found that scroll type is superior on other types such as turbine, screw and piston. Table 2 shows comparison of working fluids performance in some papers.

Table 1
Summary for some heat exchangers studies.

Ref.	Main Objective(s)	Methodology	Results	Best HE
Zohuri and McDaniel (2018)	**Discussing heat exchangers, their selection guides and further main characteristics**	HE	-As compactness factor increases heat transfer increases and thus efficiency increases too. -Plate-fin heat exchanger shows the best compactness value (6000 m^2/m^3).	Plate-Fin HE
Mardiana-Idayu and Riffat (2012)	**Review on heat recovery technologies for building applications**	HE	- Rotary wheel heat exchanger proved to be the best system to be used	Rotary wheel HE
Khordehgah et al. (2018)	**Studying waste heat recovery technologies and applications**	HE	-Plate heat exchanger and heat pipe systems are used to transfer heat from one source with different temperature ranges. - Heat pumps appears good for low-temperature waste heat recovery	Plate and heat pipe HE
Patil et al. (2018)	**Review on thermoelectric materials and heat exchangers for power generation**	HE	-For thermoelectric generators, plate type is recommended. -Fin structure, formation of the heat exchanger and functioning settings are supplements that improve the Heat transfer rate and thermal consistency of the heat exchanger	Plate HE

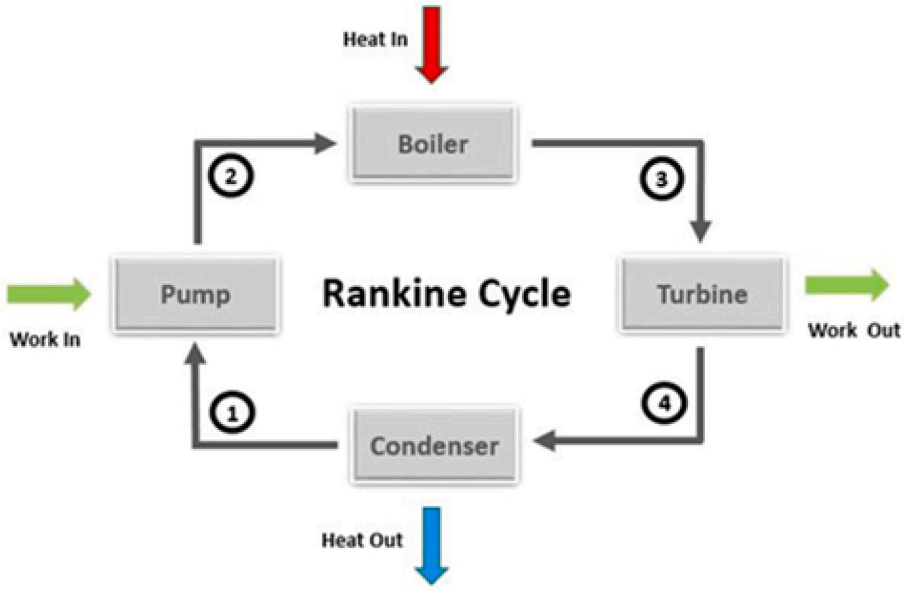

Fig. 4. Rankine cycle components.

Many previous works showed that toluene is a good choice for recovering high-temperature heat, but the ORC performance decreases when the exhaust gas temperature is low (Carcasci and Winchler 2016; Clemente et al., 2013). Furthermore, Sanaye (Sanaye et al., 2020) compared toluene and water in standings of economical and thermal terms, where water serves to be better with respect to power output and payback period, while toluene shows better exergy destruction ratio and lower cost. Fig. 5 shows the distribution of working fluid study among 14 papers. Therefore, no single working fluid is best for all ORC's, as the selection of the proper working fluid requires consideration of operating conditions, environmental concerns and economic factors (Sprouse and Depcik 2013). Table 3 shows a summary for some studies about Rankine Cycle, its main objectives and further obtained results.

As any essential part in heat recovery systems, researchers are doing a huge effort on enhancing ORC. Yet, studies emphasize on choosing the best working fluids, especially that none of the tested fluids proved itself the best one. At the same time, studies always are leading to new organic fluids, in which some give promising results. However, boundary conditions, which are important to any new study, are not well clarified in some studies. Therefore, for upcoming studies it is recommended to specify boundary conditions clearly and study the best working fluid, which suits different heat mediums.

2.3. *Thermoelectric generators*

Thermoelectric generators (TEG)s are defined as direct electrical conversion devices, which reduces the necessity for transforming heat from mechanical to electrical energy, by generating electricity directly from waste heat (Jouhara et al., 2018). Fig. 6 shows a schematic explaining the working principle of TEGs.

In the literature, there are plenty of studies that summarize heat transfer rate, thermal consistency, and pressure descent in thermoelectric materials and heat exchangers. The main outcomes were as follows: a semiconductor having low electric resistance and high thermal resistance is used to generate power in a TEG; the power of a TEG is greater, as the difference in temperature between the heat source and heat sink is larger. In addition, the physical properties of fluids affect the power produced in a TEG.

Also, maximizing the seebeck coefficient, and increasing the electric conductivity and thermal resistivity of the material can improve the thermoelectric conversion efficiency (Patil et al. 2018). However, the impact of flow commands on performance of TEG mounted on chimney wall is studied. Accordingly, it is shown that increasing the inlet velocity of the hot gases without increasing cooling air velocity or vice versa does not have a great effect on the TEG output power. Likewise, the heat transfer of the cold side of the TEG is more effective on the TEG output power compared to that of the hot side at the same total flow velocity entering the chimney (Eldesoukey and Hassan 2019). Zabeka and Morinib (Zabek and Morini 2019) showed in their study that thermoelectric waste heat recovery technologies need a heat source temperature of 100 °C which shows reasonable generator power densities of up to 80 μW/mm^2 (Zabek and Morini 2019). TEM and HE are the most important factors to be enhanced, in order to improve the structure of a TEG system. However, the role of heat exchanger in this energy transfer unit is to absorb the waste heat contained in the hot fluid and transfer it to the TEMs. Thus, to avoid affecting the normal operation in HE, the pressure drop should be as low as possible, while it is necessary to enhance the heat transfer between the HE and hot fluid as the best operative method to improve the performance of the HE (Du et al., 2015; Luo et al., 2020; G. Zhang et al., 2015). Apart from this, Mahajan et al. (Nithyanandam and Mahajan 2018) presented some enhancement approaches to maximize the energy transferred from the hot exhaust gas to the hot side of the TEM which lead in increasing the productivity of TEG. Hence, from the analysis of an arithmetical model of metal foam-enhanced TEG, results show that metal foams existence magnifies the surface Heat transfer coefficient (HTC) at the walls of the heat tube, thus improving the HT from the bulk of the exhaust gas to the hot side of TEM. As a result, an important development in the thermoelectric efficiency and power density is achieved. However, configuring the generation of electric power with the existence of metal foam resulted with a net power seven times higher than that achieved in a process without metal foam. Table 4 shows a summary for some TEG studies, its main objectives and further obtained results.

Nowadays, thermoelectric generators are used in many heat recovery systems as a key to convert recovered heat into electricity. However, many factors such as thermoelectric numbers, filling factor, length of P–N legs, couple numbers of TEC and overall thermal conductance affect the efficiency of TEG. Thus, enhancing TEGs and optimizing its functioning can lead to the enhancement in the overall recovery system.

Table 2
Comparison of Working fluids performance.

Working fluids used in rankine cycle			
Reference	Working fluids studied	Discussion	Best Choice
Hossain and Bari (2014)	Water, ammonia and HFC-134a	Water-steam shows the big benefit of the cost, environment and good thermodynamic performance, however, it is frozen at low temperature. Alcohols are very suitable for recovering the heat from the high-to-medium temperature sources but they are so flammable.	Water
Chintala et al. (2018)	R245fa	the best working fluid is chosen to be R245fa, based on economy, availability, environment and system performance.	R245fa
(T. Wang et al., 2014)	Water, R141b, R245fa	water and R141b show the best performances in G-EERS and D-EERS, while economically water is the best	water
Pan, Lu, et al. (2020)	Ammonia, Butane, Benzene and R245fa	butane had similar thermodynamic and economic performance to R245fa; how- ever, butane is far more ecofriendly. Ammonia's performance with regard to the COP and CP were inferior to that of benzene, but its SIC performance was the best. Therefore, am- monia	Butane and Ammonia
Abrosimov et al. (2020)	Pentane, toluene and R245fa	The maximum generated power is demonstrated by regenerative ORC with pentane as the working fluid, although its critical temperature is far below the maximum available temperature of the cycle (380 °C). Interestingly, the use of toluene yields the lower performance level, even though it has a much higher critical temperature.	Pentane

3. Applications

WHR has become a necessity in all life domains. That is, heat loss is not found in engines only, but exceeds that to exist in residential systems, and industrial systems. Fig. 7 presents the studied applications in which WHR systems are applied on.

3.1. Engines

In terms of dual-fuel engines, a small portion of the total energy is useful, while 55%–70% of fuel energy is lost and released in the form of heat through exhaust gases, jacket water, and lubrication oil (Liang et al., 2019). Recovering waste heat from engines show a diversity of applications. Nowadays people are becoming aware of the depletion and negative environmental issues of fossil fuels. Currently, CO_2 concentration has reached around 400 ppm in the atmosphere, which resulted in an increase of the global surface temperature by 0.85 °C from 1880 to 2012. In case CO_2 concentration reaches 450 ppm in the atmosphere, the global surface temperature will increase by 2 °C. As a result, 70 reduction in the emissions by 2050 are required to drop the CO_2 concentrations to an acceptable level (Omar et al., 2019).

On the other hand, original equipment manufacturers (OEM)s offered in the last years some concepts in WHR technologies such as engines downsizing, stop/start systems, and full hybrid solutions to encounter the increase in restrictions on CO_2 emissions from light-duty vehicles.

Yet, TEG, ORC and electric-turbo compound (ETC) are implemented as WHR technologies on few heavy-duty applications, but still have not been verified yet as operative and affordable solutions for passenger cars (Arsie et al., 2015).

3.1.1. Internal combustion engines

Currently, the average efficiency of internal combustion engines (ICEs) under driving conditions is 25% (Cao et al. 2018). The rising price of fossil fuels and their environmental impacts have led researchers to make great efforts to reduce fuel consumption in ICEs (Jannatkhah et al. 2020). On the other hand, more than 30–40% of fuel energy wastes from the exhaust and just 12–25% of the fuel energy converts to useful work (Hatami et al. 2014).

However, wasted energy is liberated through heat losses, exhaust gas recirculation (EGR), and exhaust gas. There has been growing interest in reducing fuel consumption and decreasing the CO_2 emissions of ICEs by means of WHR due to the occurrence of peak oil, climate change, increased oil price, environmental damage, and emission legislations. The use of WHR technologies offers the potential for significant fuel-savings because WHR systems capture and reuse the waste heat from ICEs for heating or generating mechanical or electrical work (Aghaali and Ångström 2015). In WHR methodologies, ORC shows to be the best applicable one for converting thermal energy into mechanical or/and electrical energy for different temperature mediums. Some other

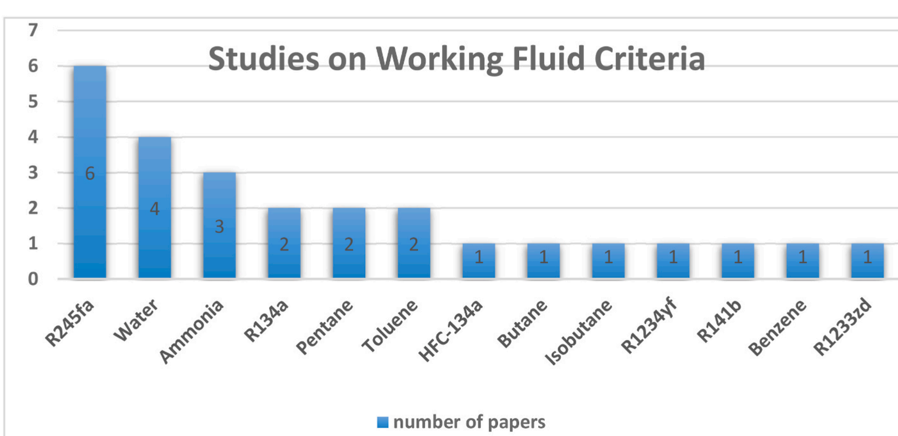

Fig. 5. Distribution of working fluid study among some papers.

Table 3
Summary for some Rankine cycle studies.

Ref.	Main Objective(s)	Applied System	Methodology	Boundary Condition(s)	Key Results
Fernández et al. (2011)	Thermodynamic analysis of high-temperature regenerative organic Rankine cycles using siloxanes as working fluids	High temperature ORC	ORC	Not specified	Simple linear (MM, MDM) siloxanes in saturated regenerative schemes show good efficiencies and ensure thermal stability of the working fluid
Ahmed et al. (2018)	Design Methodology of organic rankine cycle for waste heat recovery in cement plants.	Cement plant	ORC	-Turbine inlet temperature was between 120 °C and 220 °C -pressure varies from 22 to 35 bar	- R134a as a working fluid- -exergy losses in turbine are 20%, -Effectiveness of the ORC 93%.
Chintala et al. (2018)	A review on waste heat recovery from compression ignition engines using organic rankine cycle.	CI engines	ORC	variable temperature and mass flow rate profiles	-Best working fluid: R245fa
Shi et al. (2018)	A review of modified organic rankine cycles (ORCs) for internal combustion engine waste heat recovery (ICE-WHR).	IC engines	ORC	Not specified	-ORCs for ICE-WHR are into 4 parts namely: High Temperature-ORCs, Mixture-ORCs and Dual loop-ORCs.
Surendran and Seshadri (2020)	Performance investigation of two stage organic rankine cycle (ORC) architectures using induction turbine layouts in dual source waste heat recovery.	2.9 MW natural gas IC engine	ORC	-high temperature (primary) exhaust gases (573–773K) and -low temperature (secondary) jacket water (353–393K)	-STORC delivers 8.5% more power output whereas PTORC delivers 0.3% less power output than preheated ORC. -ORC better than trilateral flash cycles and Kalina cycle
Jouhara et al. (2018)	Waste heat recovery technologies and applications.	steel and iron, food, and ceramic industries	ORC	Not specified	WHR selecting criteria (Quality, Type of fluid recovered, temperature range, and quantity). ORC operates in Low-Medium grade, Kalina Cycle operates in Medium-High Grade.
Zhou et al. (2017)	A review and future application of rankine cycle to passenger vehicles for waste heat recovery.	Passenger Vehicles	RC	Not specified	-Thermal energy sources in engine, Engine coolant, and Exhaust Gas (best). - Selection criteria: Working fluid and Expander. -Working Fluids: Water (best) and organic fluid
Abrosimov et al. (2020)	Techno-economic analysis of combined inverted brayton – organic rankine cycle for high-temperature waste heat recovery.	heavy-duty internal combustion engines	ORC	-Temperatures in the range 470–570 °C	- ORC faces efficiency limit with high-temperature waste heat. - Combined inverted Brayton plus ORC is the solution. - Pentane the best working fluid among toluene and R245fa.
Sanaye et al. (2020)	A comprehensive approach for designing, modeling and optimizing of waste heat recovery cycle and power generation system in a cement plant: A thermo-economic and environmental assessment.	grate coolers (Air Quenching Cooler or AQC boiler)	ORC	Not specified	- Water working fluid: 9.14 MW power output, with cost 2.1×10^6 $/year and payback 3.4 years. -Toluene working fluid: 6.56 MW power output, with cost 1.46×10^6 $/year and payback 5.1 years.
(P. Liu et al., 2019)	Preliminary experimental comparison and feasibility analysis of CO_2/R134a mixture in organic rankine cycle for waste heat recovery from diesel engines.	Diesel Engine	ORC	-ambient cooling conditions (25.2–31.5 °C)	- Under the ambient cooling source, it is expected that ORC using CO_2/R134a (0.6/0.4) mixture will improve the thermal efficiency of a diesel engine by 1.9%.
Mashadi et al. (2019)	Low-temperature rankine cycle to increase waste heat recovery from the internal combustion engine cooling system.	Internal combustion engine cooling system	ORC	Not specified	- By the application of the thermodynamic analysis to 19 different working fluids, Ammonia had the highest compatibility with the proposed system.
Pan, Lu, et al. (2020)	Thermodynamic, exergo-economic and multi-objective optimization analysis of new ORC and heat pump system for waste heat recovery in waste-to energy combined heat and power plant.	municipal solid waste	ORC	-evaporator pressure: 2773 kPa, HP evaporator temperature: 301.6 K -ambient temperature: 284.15 K.	-The results indicate that butane and ammonia are the most suitable working fluids.

strategies are used such as kalina cycle, rankine cycle, brayton cycle and TEG (Chintala et al. 2018). However, significant researches on ORCs for ICE-WHR with the application of temperature-entropy method provided valuable information for investigators interested in ORCs in ICE-WHR. Therefore, ORCs for ICE-WHR are divided into 4 parts: high-temperature ORCs (HT-ORCs), mixture ORCs (M-ORCs), ORCs combining with extra loops and dual loop ORCs (D-ORCs). Besides, HT-ORCs and M-ORCs were approved to achieve better thermodynamic performance with a better thermal matching (Shi et al., 2018). Wang et al. studied an exhaust energy recovery system (EERS) based on rankine cycle (RC) in internal combustion engines. The study covers heavy-duty diesel engines (D) and light-duty vehicle gasoline engines (G). After studying different working fluids in different conditions, water and R141b show the best performances in G-EERS and D-EERS, while economically water is the best. Results show that EERS based on RC is more applicable on the heavy-duty diesel engine, while it might be feasible for the light-duty vehicle gasoline engine as the state-of-the art technologies are developed in the future (T. Wang et al., 2014).

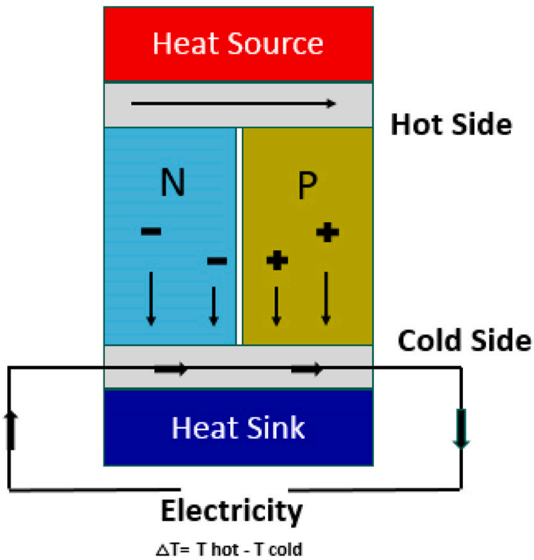

Fig. 6. Schematic explaining the working principle of TEGs.

3.1.1.1. Compression ignition engines. Compression ignition engines (CI) are heat engines, which use the properties of a gas converting energy from heat mode to mechanical mode. Mechanical force is generated by exploiting the gas pressure, which increases in turn when adding heat to a restricted volume containing a mass of air such as cylinder of an engine. Yet, spark ignition engines like most diesel engines have four strokes (Breeze 2018).

Most studies emphasized on ORC systems. Armas et al. (Fernández-Yáñez et al., 2018) employed TEG to Diesel engines which gave a 0.6% of fuel savings at common driving conditions. On the other hand, the aim was to generate extra power output and recover waste heat from IC engines by studying the utilization of ORC (Chintala et al. 2018). So, engines with power less than 20 kW showed low thermal efficiency due to low mass flow rate, while high capacity multi-cylinder engines had a high thermal efficiency due to high mass flow rate. Also, the best working fluid is chosen to be R245fa, based on economy, availability, environment and system performance. Later, Chintala et al. (Chintala et al. 2018) studied the potential of WHR from water jackets, intake charge air and exhaust gas of CI engines in order to increase its low thermal efficiency (10–25%). Consequently, dual ORC proved to be the solution for these engines. Yet, some investigations were made on CI-ORC engine such as, type of evaporator, backpressure, condenser, and organic working fluid. So, studies showed that this combined system suits engines with power above 20 kW, which have exhaust gases with great mass flow rate and temperature, summing up with 60–90% thermal efficiency. Also, compared with other working fluids, R245fa was nominated again to be the favorable one based on better performance, availability, economic and environmental aspects.

Hoang (2018) studied the recent work of ORC system in the application of WHR from heat sources on diesel engine. Standalone ORC system showed 10–25% thermal efficiency compared with 60–90% for

Table 4
Summary for some TEG studies.

Ref.	Main Objective(s)	Applied System	Methodology	Boundary Conditions	Key Results
Arsie et al. (2015)	Modeling analysis of waste heat recovery via thermo-electric generator and electric turbo-compound for CO_2 reduction in automotive SI engines.	compact car, powered by a turbocharged SI engine	TEG	Not specified	-TEG and ETC applied on a compact car lead to: CO_2 reduction ranging from 5.6% to 6.6% for the analyzed scenarios.
Cai et al. (2018)	Thermoelectric heat recovery units applied in the energy harvest built ventilation, parametric investigation and performance optimization.	thermoelectric heat recovery unit	TEG	Not specified	-Parameters influencing the performance of thermoelectric-heat recovery system: Thermoelectric numbers, filling factor, length of P–N legs, couple numbers of thermoelectric coolers and overall thermal conductance.
Fernández-Yáñez et al. (2018)	A thermoelectric generator in exhaust systems of spark-ignition and compression-ignition engines. A comparison with an electric turbo-generator.	spark-ignition and in a compression-ignition engines	TEG	Not specified	-TEG serve better in recovering energy in low power modes, -Electric-turbo generators are more preferable in high power modes.
Jaber et al. (2019)	Domestic thermoelectric cogeneration drying system Thermal modeling and case study-annotated.	Chimneys	TEG	Temperature of hot air up to 363 K -air flow rate of 0.0076 kg/s.	-Diesel: Power: 240 W/Energy recovered: 20% -Coal: Power: 240 W/Energy recovered: 42% -Wood: Power: 94 W/Energy recovered:84%
Patil et al. (2018)	Thermoelectric materials and heat exchangers for power generation – A review.	No system applied-review	TEG	Not specified	-Power of TEG is dependent on the temperature difference between heat source and heat sink, and physical properties of fluids -Plate type HE to be used for TEG.
Rodrigues et al. (2018)	Recovery of thermal energy released in the composting process and their conversion into electricity utilizing thermoelectric generators.	Composting process	TEG	-load resistance of 500 Ω at a temperature gradient of 20 °C.	-Electrical output from TEG varies with different temperature gradients.
Cao et al. (2018)	Performance enhancement of heat pipes assisted thermoelectric generator for automobile exhaust heat recovery.	Automobile	TEG	exhaust temperature of 300 °C and mass flow rate of 80 kg/h	-Power output and pressure drop are 13.08 W and 1657 Pa, respectively. -Optimized thermoelectric power generation efficiency of the HP-TEG as 2.58%.
(Y. Choi, Negash, and Kim 2019)	Waste heat recovery of diesel engine using porous medium-assisted thermoelectric generator equipped with customized thermoelectric modules.	Diesel Engine	TEG	Not specified	- The conversion efficiency and power output of the present TEG can be maximized via application of porous media with porosities of 0.461 and 0.32, respectively. -The use of a porous medium with a porosity of<0.32 in the present TEG configuration should be avoided, as the backpressure would exceed the allowable limit of ~3 kPa for a passenger vehicle."

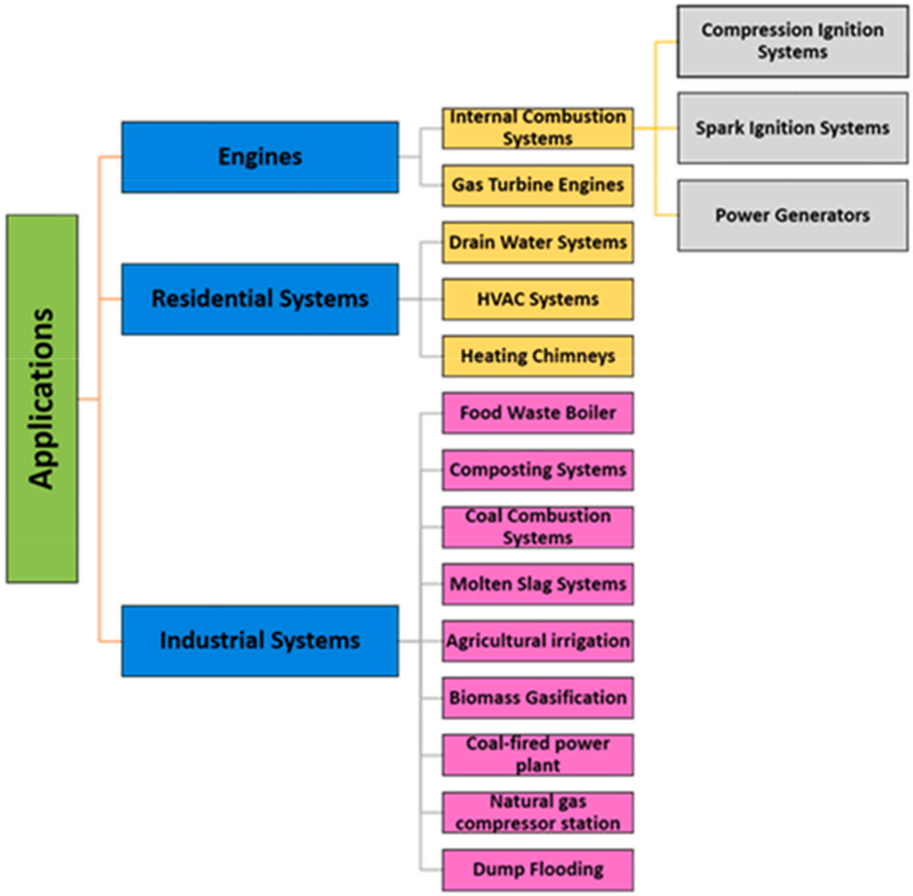

Fig. 7. Classification of WHR applications.

dual ORC system, noting that temperature and mass flow rate of waste heat source were proved to be the most significant factors in ORC design and calculation. Hoang summed up with a result that Diesel engines with power output greater than 20 kW are applicable for ORC system integration due to the high mass flow rate of exhaust gas, while those with less than 20 kW power output are not appropriate. However, a decent ORC system must satisfy certain criteria such as compactness, low weight and small size, high efficiency, suitable thermal management, low cost, low environment pollution, high safety, and reliability. An experimental assessment of ORC unit bottomed heavy duty ICE is performed. ICE has ran in the range of brake power between 50 and 110 kW, with a thermal power available in the exhaust gases from 50 to 88 kW. While thermodynamic efficiency is about 10% in all tested working points, the final DC electric power is about 2–2.5 kW, showing an overall plant efficiency of about 2–3% (Cipollone et al. 2017).

3.1.1.2. Spark ignition engines. A Spark ignition engine (SI) is a heat engine that develops the properties of a gas to convert energy from heat to mechanical mode gas (Breeze 2018). In this type of engine, fuel and air are mixed before initiating combustion with fuel introduced in either the intake manifold or now commonly in cylinder with direct injection technologies. In either case the fuel vaporizes and mixes with the charge gases to an ignitable mixture (Naber and Johnson 2014). When employing TEG to Gasoline engine, 1.1% of fuel is saved. Yet, these generators (TEGs) serve better in recovering energy in low power modes, while electric-turbo generators are more preferable in high power modes. In addition, by-passing reduces high pressure drop power losses caused by TEG, and increases the net power production of energy recovery in diesel engines (Fernández-Yáñez et al., 2018).

Furthermore, relying on engine speed and load and auxiliaries demand, proper organization and structure of the WHR systems can lead to a substantial enhancement of fuel economy and CO_2 reduction (Arsie et al., 2015). Nevertheless, constructing a new type of heat pipe assisted thermoelectric generator (HP-TEG) for automobile exhaust waste heat recovery, and after applying a prototype, the experimental results indicated that the power output of HP-TEG favored high exhaust temperature, cold water flow rate and mass flow rate. Also, the maximum open circuit voltage of 36 thermoelectric modules (TEMs) is measured as 81.09 V. Moreover, the corresponding power output and pressure drop are 13.08 W and 1657 Pa, respectively, with an optimized thermoelectric power generation efficiency of the HP-TEG as 2.58% (Cao et al. 2018).

3.1.1.3. Power generators. It can be inferred how it is essential to implement and develop new efficient emission reduction technologies in order to reduce emitted pollutants, as well as new technologies that could improve the ship and engine fuel efficiency. Among these last mentioned, waste heat recovery systems, already developed and applied in industrial stationary power generation applications, will have a predominant role in the very next future of the shipping industry (Lion et al. 2020). Efficient waste heat recovery during the energy production and conversion has attracted much attention because it is one of the most important approaches utilized to improve energy conversion efficiency and diminish negative environmental and economic impacts (Liu et al., 2020). However, using environmentally friendly alternative energy sources for power generation is a promising way to achieve clean production of electricity (Han et al. 2020).

One of ICEs is power generator. Electric energy is produced by an electro-mechanical combination. Internal combustion outcomes energy in thermal and mechanical mode, where the thermal energy is released through engine cooling system, fan radiation losses and exhaust gas. Conversely, mechanical energy is distributed as electrical energy and generator losses. Heat recovery systems are applied to recover thermal energy from exhaust gases and heat water by using heat exchangers (Khaled et al., 2018). In this study, the methodology of heat recovery is obtained by capturing heat from the exhaust gas of a 500 kVA power generator. Two flow patterns are considered, one having exhaust gas in inner tube and water in annulus (Pattern I), and the other one having water in inner tube and exhaust gas in annulus (Pattern II). Results show that mass flow rate affect the heating of water, which can reach 100°C. In addition, pattern II exposed greater heat rates than that in pattern I, and thus chosen to be the solution, taking into consideration that the inner diameter is located in a close area of the persistent outer diameter. Finally, the captured average heat rate was found to be 26 kW (Khaled et al. 2015). The results of a study similar to the previous mentioned one (pattern I & II), show the same results choosing pattern II as the best choice to be applied. Moreover, as heating load of boiler increases, the percentage of recovered heat from exhaust gases decreases. At last, this percentage decrease by 10% with a 0.5 kg/s water flow rate, as the boiler heating load speeds up from 100 to 1500 (Haddad et al., 2018).

In power generators, hot gases resulting from combustion of fuel can be recovered in the form of heatusing a HE between exhaust gases and water. Studies show that the temperature of water reach 50.5 ^{0}C depending on the mass flow rate and the water inlet temperature. In addition, as shown in Table 5, for 15 kVA power generator, as water mass flow rate increases by 10 times, the recovered average heat rate increases also by 1.8 times (Khaled et al., 2018).

With constant water flow rate and inlet temperature, the variation in the power of generator causes a variation in both water outlet temperature and recovered average heat rate. On the other hand, a study is made up on a hybrid heat recovery System (HHRS) that develops exhaust gases of a generator to heat water and produce electric energy through TEG. The influence of varying the load of the generator on the water temperature and power generation is discussed, and a thermal modeling of the system was carried out. Results were extracted from both 10 kW and 38 kW load generators (Jaber et al. 2019).

3.1.2. Gas Turbine Engine

As ICE, gas turbine (GT) is designed in different sizes and applicable in many submissions. It is used for helicopters, also for civil aviation. However, micro-GT is used as convenient energy supply for military functions. In addition, it is developed for hybrid electric vehicles. Unlike in ICE, pressure increase is limited during combustion in GT, which is related for being an open thermodynamic system with in and outflow. However, GTs consist of three basic elements: a turbine, a compressor and a combustion chamber. Studying the ORC combination with a gas turbine, using R134a as a working fluid, to transform the gas turbine waste heat into electric power yielded to some considerable results. It was found that R134a, with operating temperature 120 °C and 220 °C, increases the effectiveness of the ORC heat exchanger up to 93%. Also, exergy losses in turbine are found to be 20% which is less than those in steam turbine. Yet, the low boiling point of this fluid caused dryness of it, which in turn increased the turbine efficiency (Ahmed et al., 2018). Two TEG systems, each with a different thermoelectric material, were used in Matlab/Simulink-based model to evaluate the benefits (fuel savings) of using thermoelectric electric generators in hybrid electric vehicles (the heat engine can be ICE also) over a prescribed drive-cycle.

Table 5
Change of recovered average heat rate with change of water flow rate.

Heat recovery from the exhaust gas of power generators		
Power of Generator (kVA)	Water flow rate (Kg/s)	Recovered average heat rate (kW)
15	0.05	4.3
	0.5	7.7

Studies on Skutterudite-based system showed a mean thermal efficiency of 6.99% and a fuel economy of 38.33L/100 km, with a resultant fuel saving of 7.58%. However, that of SiGe-based TEG exhibited a mean thermal efficiency of about 5% and a fuel economy of 38.6L/100 km, with a resultant fuel saving of 6.82%. Moreover, CO_2 emissions had a reduction of 7.58% and 6.82%, in Skutterudite and SiGe systems respectively. Finally, studies showed that fuel savings were achieved with minimal adverse effects of back pressure and weight (Muralidhar et al. 2018). Table 6 shows a summary for some WHR-Engine studies, its main objectives and further obtained results.

Table 6 shows many research articles some with experimental setups concerning engines and generators. Each experiment has its own system, with researchers comparing systems to sum up with the best system, or enhancing an existing system to increase the efficiency of the system. Usually, review articles do not specify boundary conditions. However, research articles use mostly temperature, mass flow rate and pressure as primary boundary conditions. Moreover, the temperature of the heat medium, the working fluid used, and the pattern of flow affect results in some systems. In general, most obtained results are for parameters such as produced power output, investment cost, payback period, heat rate and efficiency of the system. Such research articles are recommended, because they give valuable results, taking into consideration all variables without need for assumptions. Having many experiments in this way can be a strong basement for every researcher in WHR domain.

3.2. Residential buildings

Industrial applications and internal combustion engines are sources of huge heat loss, which need waste heat recovery. In fact, energy consumption in residential buildings has exceeded the other major sectors, namely, industrial and transportation. Key reasons attributing to this increasing figure include: (1) growth in population; (2) greater demand for building services; (3) the need for better comfort levels; and (4) longer duration of occupants spent time inside buildings (Chua et al., 2013).

Further studies worked on Heat Recovery in housing sectors (Ramadan, lemenand, and Khaled 2016). A basic requirement for WHRS is that the temperature of waste heat must be high enough to serve as a useful heat source. Heating chimneys provides this high temperature through its exhaust gases [6]. Conversely, one of the promising sources of heat loss useful for recovery is hot drain water [9]. One application, which would greatly benefit from waste heat recovery, is water heating [6]. Yet, heating water is considered as a great partition in the overall amount of energy consumption in buildings [9].

3.2.1. Drain water systems

In warm climates, the diffusion of heat recovery chillers able to couple air-conditioning and domestic hot water (DHW) production is strongly increasing during the last period and many studies is addressed to the evaluation of the seasonal performance indexes of these systems (Naldi et al. 2015). A wastewater heat recovery system can recollect heat from the drainage and serve as the first stage of heat recovery [22]. Drain water heat recovery (DWHR) is designed to recover the residual energy from the hot or warm drain water, and using them to preheat the inlet cold water. Such systems show an efficient and low-cost way of recovering thermal energy for its reutilization in typical building processes, as space heating and sanitary hot water generation [27]. Ramadan et al. (Ramadan, lemenand, and Khaled 2016) studied a drain water heat recovery system applied as a solution in order to decrease domestic energy consumption. Results showed that effectiveness increase with the increase of boiler outlet temperature and/or water flow rate. Table 7 shows the studied cases with the resulted effectiveness.

However, in a large residential building, shower WHR from bathrooms prepared with direct water heaters are studied. For a 50 mm diameter drainage pipe and 1.5 m long counter-flow HE, about 4–15% savings from shower water heat yearly. Yet, in both hot and humid

Table 6
Summary for some WHR-Engine Results.

Paper	Main Objective	Application	Boundary Conditions	Results
(C. Wu et al., 2020)	Proposal and assessment of a combined cooling and power system based on the regenerative supercritical carbon dioxide Brayton cycle integrated with an absorption refrigeration cycle for engine waste heat recovery.	Internal Combustion Engine	-hot gases exiting from the cyclones temperature (340 °C) and mass flow rate (58.97 kg/s) -hot air exiting from grate cooler temperature (320 °C) and mass flow rate (40.2 kg/s) of	- Generate 248.19–253.90 kW of net power output, accounting for 8.48–8.67% of the rated power output of the engine. (−10 to 10 °C). -Produce (70.57–168.86) kW of cooling capacity by consuming (0.445–0.532) kW of pump work.
Song et al. (2020)	Parametric optimization of a combined supercritical CO_2 (S– CO_2) cycle and organic rankine cycle (ORC) system for internal combustion engine (ICE) waste-heat recovery.	Internal Combustion Engine	-The optimal ORC evaporation temperature can be raised significantly (to > 70 °C) by including a pre-cooler in the combined system. - (S–CO2 cycle system: T,in = 320 °C and P,in = 20 MPa, and ORC system Tevap = 72 °C)	-Maximum net power output of 215 kW at a minimum specific investment cost (SIC) of 4670 $/kW which are 58% and 4% higher than those of the standalone S– CO_2 cycle system, respectively.
Zhu et al. (2020)	A review of waste heat recovery from the marine engine with highly efficient bottoming power cycles.	Marine Engine	-The minimum steam pressure of exhaust boiler is 7 bar with the evaporation temperature of 165 °C	-Trade-offs between working fluid characteristics, cycle configuration, size, cost and WHR potential lead to fuel savings ranging from 4% to 15%. -The payback time of installing a bottoming WHR system lies typically in the range from 3 to 8 years, depending on the fuel price, ship type, heat and power demands and component costs.
Ji et al. (2019)	Investigation on performance and implementation of tesla turbine in engine waste heat recovery.	Automobile Engine	Not specified	-The total power and overall thermal efficiency of the WHR system can be improved by selecting appropriate viscosity of the working fluid and number of nozzles. -It is necessary to improve power output and thermal efficiency for an automobile engine at a lower expense of volume and cost.
Liang et al. (2019)	Theoretical analysis of a regenerative supercritical carbon dioxide brayton cycle/ organic rankine cycle dual loop for waste heat recovery of a diesel/natural gas dual-fuel engine.	Dual-fuel engine	fixed speed of dual loop: 1500 rpm	-The results revealed that the maximum net power output of this system is up to 40.88 kW, thus improving the dual-fuel engine power output by 6.78%.
(P. Liu et al., 2019)	Preliminary experimental comparison and feasibility analysis of CO_2/R134a mixture in organic rankine cycle for waste heat recovery from diesel engines.	Engine	-Temperature of the exhaust gas reaches 180 °C. -The set operating conditions of the diesel engine are 600 Nm and 1100 rpm.	Under the ambient cooling source, it is expected that ORC using CO_2/R134a (0.6/0.4) mixture will improve the thermal efficiency of a diesel engine by 1.9%.
Mashadi et al. (2019)	Low-temperature rankine cycle to increase waste heat recovery from the internal combustion engine cooling system.	Internal Combustion Engine	Not specified	-This system can recover more than 57% of the available energy in the cooling fluid.
Mohammadkhani et al. (2019)	A zero-dimensional model for simulation of a diesel engine and exergoeconomic analysis of waste heat recovery from its exhaust and coolant employing a high-temperature kalina cycle.	Diesel Engine	-The exhaust condition of Temperature: 815 K and mass flow rate: 1.56 kg/s is preferable for the design	-Results showed that the proposed cycle could produce 21.74 kW power from the waste heat recovery process, which is significant for a 98.9 kW engine. -The produced power unit cost, as well as the system total cost, is reduced with increasing the turbine inlet temperature and pressure.
Güven et al. (2019)	Optimization and application of Stirling engine for waste heat recovery from B61a heavy-duty truck engine.	Diesel Engine	-The exhaust is in the range of 530–600 K.	-WHR system with Beta-type Stirling engine is more effective than Alpha and Gamma types due to its higher power density. -The WHR system presented provides more than 1.3% of ICE power output and about 1% reduction in fuel consumption.
Pan, Bian, et al. (2020)	Thermodynamic analysis of a combined supercritical CO_2 and ejector expansion refrigeration cycle for engine waste heat recovery.	Engine	-Exhaust temperature 557.5 °C -Exhaust mass flow rate: kg/h 741	-The results show that the refrigerating capacity and coefficient of performance (COP) comb of the system with R32/CO_2 (0.9/0.1) are up to 225.5 kW and 2.05, respectively. -The equivalent power loss due to the additional weight is estimated to be 5.21 kW.
Haddad et al. (2018)	An in-house code for simulating heat recovery from boilers to heat water.	PG	-Water flow rates of 0.3 and 0.5 kg/ s. -boiler heating load is varied from 900 to 1500 kW.	-Flow-pattern II Better then Flow-pattern I -Water is heated to a temperature of 100 °C depending on the mass flow rate. -Flow pattern II has superior heat rates than flow-pattern I.
Khaled et al. (2018)	An iterative algorithm for simulating heat recovery from exhaust gas – Application on generators.	PG	Exhaust temperature and mass flow rate vary among Four different power generators studied (15 kVA, 30 kVA, 60 kVA and 180 kVA).	-Recovered average heat rate increases with increase of water mass flow rate. -Temperature of water and recovered average heat rate increase with increase of load generator.

climates, WHR studies in these sectors seem to be interesting and challenging (Wong et al. 2010). Oliva et al. (Torras et al., 2016) studied the process of recovery of the waste heat from domestic warm drain water, and transferring it to the cold water entering the house. A DWHR unit is built in this work, and the maximum heat recovered is reached at the lowest flow rates (3 l/min) for in-tank temperature. Nevertheless, the DWHR storage had the capacity to recover from 34% to 60% of the energy available in the drain water for the investigated flow rates. In addition, 50% reduction in stored energy is observed after 24 h, which reveals its limitations for long-term storage applicability. For industrial waste heat recovery, heat pumps are becoming more and more attractive due to increasing energy prices and concerns about energy conservation and significant reductions in greenhouse gas emissions (M. Wang et al., 2020). A great study of an air source heat pump (ASHP) for DHW preparation under cold climatic surroundings by TRNSYS simulation compared two different strategies of installation: Individual (apartment-scale) and collective (building-scale, centralized) installations. Therefore, results of ASHP application on apartment scale showed higher global performance caused by the system simplicity and minimal heat loss. Whereas, building scale showed high electricity due to DHW recirculation as well as heat loss, yet this installation is still predicted. Moreover, ASHP are not competitive from primary energy saving point of view than fossil sources, but still better in green house gas (GHG) emission saving (6/7). Finally, lowering DHW water supply by 1 or 2 °C showed positive effects to the energy factor too (Xiaofeng Guo and Goumba 2018). Shen et al., (2019) suggested an innovative wastewater source heat pump system including a wastewater tower. The system is experimented in a prototype built to study its operation performance. The long testing (41 days) showed that hot water temperature is greater than that of wastewater (40 and 16 °C). While the average COP of unit and system were 3.35 and 2.15 respectively. Finally, the power input of the circulating fan, wastewater and hot water pumps was about 1/3 the total power input, while that of the compressor was about 2/3 of the total power input.

3.2.2. Heating chimneys

Single and hybrid heat recovery systems are used to produce hot water and generate electricity. This is due to the great volume of thermal energy being lost through exhaust gases (Ramadan and Lemenand, 2017). Khaled et al. (Jaber et al., 2018) investigated domestic thermoelectric cogeneration system (DCS) which permits generating electricity and heating water via TEG benefiting from the lost heat of exhaust gases. Experiments showed that DCS with TEGs located on the inner wall of the pipe has a payback period of 1 year and 8 months when water is heated 60 times per month. Conversely, since the amount of CO_2 gas reduced is not affected by the location of TEGs the placement structure of TEGs at the inner wall of the pipe is the best cost-effective energy recovery structure. However, hybrid solar chimneys are proposed by Al-kayiem et al. (Al-Kayiem et al., 2019) as an alternative for conventional solar chimneys which are deficient at night. This new work achieved 7% more enhancement than the conventional one. In addition, promising enhancements were observed: 12% in mass flow rate, 51% in system performance indicator, and 64% in the collector efficiency.

Similarly, to make use of energy of chimney exhaust gases, exhaust gases through pipes inserted in a water tank are heating the water supply. Therefore, the suggested WHR showed the ability to increase the temperature of water from 10 to 78 °C during 1 h of chimney operation. Also, convection and radiation exchanges at the bottom surface of the tank recorded a considerable value reaching 70% from the total heat transfer rate of the water (Khaled et al., 2015). Furthermore, a study prepared by Khaled et al. (Ramadan et al., 2017) aimed at producing DHW and electric power using TEG_s when recovering exhaust gases. As an outcome, as exhaust gas temperature ($T_{exhaust}$) increases, the power of TEG increases (P_{TEG}). Likewise, P_{TEG} increases 5 times when $T_{exhaust}$ is doubled. Besides, for $T_{exhaust} = 300$ °C, the produced power is $P_{total} = 67$ W. Finally, HHRS is affected by quality of $T_{exhaust}$ and quantity of flow rate. Jaber et al. (Jaber et al., 2019) studied producing electric power, heating air domestic water by exploiting thermal energy released from combustion through exhaust gases. Combustion was made using diesel, coal and wood. The parameters studied were: exhaust gases temperature, mass flow rate, percentage of heat loss from furnace walls of initial thermal energy, reduction in exhaust gas due to energy loss through pipe, Heat loss from the furnace walls, the percentage of system recovery from energy dissipated to the environment and the power output. Fig. 8 shows a comparison of the studied cases with the corresponding results.

A HHRS, which aims to recover the thermal energy captured by exhaust to produce electric power and DHW via TEG is studied, and light shadowed on the parameters that affect the performance of this system, before and after utilization. These studies showed that both quality and quantity of thermal energy lost affect the heat recovery procedure. That is, as exhaust gases temperature increased the TEG's layer temperature and heat rate increased, thus increasing the power generated by TEG. However, when the HHRS was utilized, the gases temperature was doubled, thus increasing the power generated by 5 times (Ramadan et al., 2017).

Table 7
Comparison of studied cases with the resulted effectiveness of a DWHRS.

Aim	Decrease domestic energy consumption		
Parameters	Water flow rate	Boiler outlet temperature	Effectiveness
Case 1	0.058 kg/s	80° C	23%
Case 2	0.097 kg/s	60° C	22%
Case 3	0.146 kg/s	60° C	16%

3.2.3. HVAC systems

Heating, ventilating and air conditioning (HVAC) systems changed to be a critical requirement in human's life (Ramadan et al. 2015). As any other mechanical system, HVAC system have large amounts of lost energy in its application. Yet, when the exhaust air wastes large amounts of energy, heat recovery is used to recover a fraction of it, thus saving energy and being economical at the same time (Lazzarin and Gasparella 2002). However, applying energy recovery methods on HVAC system yielded to energy saving with great results such as having better climate, fresh air and enhancing energy efficiency (Ramadan et al. 2015). Heating in HVAC systems is categorized into All-water, water-air, and all-air heating systems. However, all-air systems are the most popular heating systems. It includes an air handler unit, which is responsible for adding or removing energy to airstreams before entering the conditioned space. It allows heating, cooling, humidifying, dehumidifying, cleaning and distributing airstreams to the conditioned zones (Khaled and Ramadan 2016).

Eades (2018) introduced a methodology applicable in humid and hot climates, which resulted in valuable outcomes. It's about using the

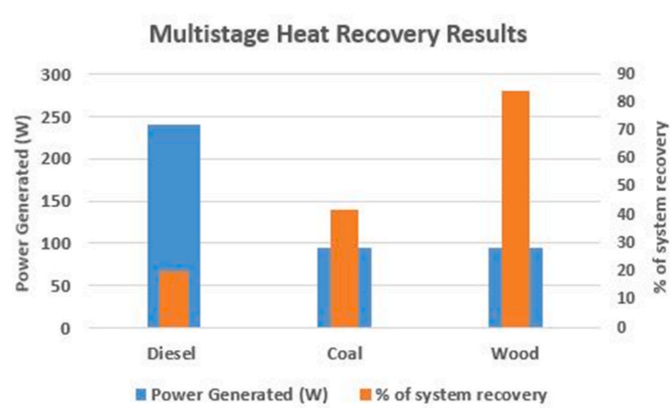

Fig. 8. Comparison of diesel, coal and wood Cases.

derivative of the condensate produced from 100% external air in cooling and dehumidification in order to reduce energy and water consumption. Yet, 13.5% energy and 45% water savings in Miami and Florida sum it up. M. Skye et al. (W. Wu, Skye, and Domanski 2018) studied the available HVAC technologies with energy, comfort and economic performance for a residential net zero energy building (NZEB), where an authenticated tested model is taken as a reference to evaluate the different kinds of HVAC options: Ventilation, dehumidification, and heat pump. Each of these options are discussed and compared and promising results are found. It was found that ASHP with dedicated dehumidification and ERV proved to be more reasonable economically, while the ground source heat pump (GSHP) with the ERV and dedicated dehumidification showed maximum energy savings but unfortunately, are the most expensive.

A study emphasized on heating fresh air by hot-exhaust air of all-air HVAC systems. A 5.3 kW air conditioner is used, and economized power reached 110 W at a 0.1 kg/s air mass flow rate at duct, and 0.005 kg/s air mass flow rate at condenser. However, extrapolation showed that when all of the supply air in a room of 4 kW heating load is exhausted, the economized power will exceed 1 kW. However, the increase of duct hot and condenser cold flow rates cause and increase in both the efficiency and performance of the HRS purposed (Khaled and Ramadan 2016). Khaled et al. (Ramadan et al. 2015) aimed to apply heat recovery concepts to HVAC applications working on refrigeration cycles, where it uses the waste energy of condenser hot air to heat/preheat domestic water. Experiments showed that as cooling load of HVAC system increases, the water outlet temperature increases too, where mass flow rate was 0.01 kg/s and T_W ranged between 304 K and 347 K. In addition, T_W decreases significantly when air flow rate through condenser increased. Energy saving potentials of a HRV coupled with an air-to-air heat pump is applied to save a residential apartment suite for three ASHRAE climate zones using detailed building and HVAC system models. Operating HRV always showed reduction in annual heating energy consumption. Also, residential buildings located in colder weather showed more consumption in heating energy but also higher heating energy saving potential when HRV is employed. This would offer shorter payback times for apartments in colder climates (Li et al. 2019).

However, a new energy recovery system that combines heat recovery and energy generation using thermoelectric generators TEG was proposed, and promising results were settled. The model took into consideration different types of boundary conditions that are constant flux, constant temperature, and convection. In addition, energy recovery can be captured from two different sources: condenser hot air and cold exhaust air. Nevertheless, for space cooling load 100 kW and 40 × 40 cm^2 flat plate, the electric power generated was about 90 W (Ramadan et al., 2017). The operating parameters influencing the performance of TE-HR system are found to be: Thermoelectric numbers, filling factor, length of P–N legs, couple numbers of thermoelectric coolers and overall thermal conductance (Cai et al., 2018). Al-Zubaydi & Hong (Al-Zubaydi and Hong 2018) made their experimental study on an all-air HE which is applied for HR ventilation in its cooling mode. In this study, two polymers heat exchangers of different plate geometries, one with a flat plate and the other with a dimpled surface plate, are tested. Comparing the dimpled and flat plate HEs thermal performance, the cooling capacity of the flat plate HE functioning as a ventilation HRS in cooling mode was 40–50% less than that of the dimpled HE. In addition, the same HE was better in terms of sensible efficiency at lower air velocities and higher air initial temperatures. Thus, dimpled HE proved to have the highest COP with 32.6°C operating air temperature.

Table 8
Summary of results of using WHR of an HVAC system on a dryer.

WHR of condenser hot air of an HVAC system on a dryer			
Case			Drying time (hour)
1	**Number of AC_s**	1	11.8
		4	1.1
2	**Air Temperature (°C)**	30	2.3
		45	0.9
Results			\$ 228.8 saved and 1249.5 Kg CO_2 reduced annually

Ramadan et al., (2019) aimed to supply a dryer by recovering waste heat of condenser in HVAC system. So, an in-house code is developed in order to simulate the heat recovery, and experimental setup was installed to validate the code. It is shown that drying time needed increases with number of people. However, drying time decreases with the increase of number of AC_s and increases as air temperature increase. Results are summarized in Table 8.

Variable heat exchange efficiency of an ERV system is analyzed. Analysis showed it's changing while producers base their work on constant heat exchange efficiency. This change is due to indoor and outdoor unstable conditions. Yet, results of comparison Table 9 showed that the variable heat exchange effectiveness should be included in Energy Recovery Ventilator (ERV) studied to be applied in building energy performance simulations (Youn hee Choi et al., 2018). Table 10 shows a summary for some WHR-Residential Systems, its main objectives and further obtained results.

In residential systems, every study has specific chosen variables to base the comparative tests on. Some researchers build comparisons on changing location of TEGs, while others vary heat exchangers types. Each experiment has different conditions and objectives. Therefore, it is hard to unify variables in all researches.

3.3. Industrial systems

In industrial domains, studies aim to enhance production efficiency, decrease destructive emissions and reduce fuel consumption. The use of WHRS in this domain is benefiting from the industrial waste heat, which is useless and wasted to the atmosphere (Jouhara et al., 2018).

This part reviews application of HR on food waste, coal combustion, composting systems and Molten slag systems. In Singapore, after many researches and practices on waste to energy,Tong et al., (2018) concluded that if food waste, animal manure and waste wood are diverted away from incineration and fed into anaerobic digester (AD) and combined heat and power boiler (CHP), more electricity could be harvested, and less pollution can be resulted. Macháčková et al., (2018) analyzed the water condensing heat exchanger used for recovery of residual heat from flue gases generated during coal combustion. Two numerical and two experimental models were performed. Compared with each other, experimented models show very good conformity. This study showed that differences between the calculated and measured flue gases and water outlet temperatures do not exceed 4 °C. Also, temperature of flue gases at high temperature outlet is higher when excluding condensation than when taking it into consideration. Whereas, temperature of water outlet without condensation is greater than that with condensation. A study on an innovative type of thermoelectric heat recovery system to gain wasted heat energy from composting processes

Table 9
Constant Vs Variable heat exchange efficiency.

ERV system heat exchange efficiency				
Cases	Sensible exchange efficiency %	Enthalpy exchange efficiency %	Heating load %	Heating Demand %
Constant heat exchange efficiency	Fluctuates from 30 to 65	Fluctuates from 25 to 70	–	–
Variable heat exchange efficiency	81	73%	88%	69%

yielded to some promising conclusions. For example, it is shown that the electrical output from TEG varies with different temperature gradients. Also, results showed a maximum voltage generation of about 11.3 V, a maximum current of 18.5 mA and a maximum power density of 175 mW/m^2 at a temperature gradient of 20 °C (Rodrigues et al., 2018).

On the other hand, the exhausted molten slag having a very high temperature (1500°C) presented a prospective resource of energy. Traditionally, HR technology develop glassy products by cooling down slag using cold water. Yet, it is not effective because of consuming large amount of cold water compared to the recovered heat from slag. Therefore, to reach better results, some chemical and physical methods are projected. In chemical methods, coal gasification and methane reforming reaction are planned, while physical ones can be processed as mechanical crushing and air blast. Unfortunately, none of these processes can lead to the sustainable requirement (Hui Zhang et al., 2013). Table 11 shows a summary for some WHR-Industrial systems, its main objectives and further obtained results.

4. Hybrid systems

Scientists are exploring the ways for reusing the high amount of thermal energy being lost through exhaust gases (Ramadan et al., 2017). HRS are classified according to the apparatus used, aim of HR, and quality of energy lost (Jaber et al., 2016). These systems can result in producing electric power, using energy in any form (heating, cooling, or storing), or by combining more than one purpose (Jaber et al., 2018). This combination of purposes is the latest trend in HR, which is called hybrid heat recovery Systems (HHRS). Fig. 9 shows the applications on which hybrid recovery systems are applied.

Ramadan et al. [31] studied a HHRS, which exploits exhaust gases of a load generator to heat water and generate electricity via TEG. Tests showed that power production and water temperature increase with the increase of load. Table 12 and Fig. 10 show comparison of results for 10 kW and 38 kW power generators (Jaber et al. 2019).

Khaled et al. (Jaber et al., 2018) investigated domestic thermoelectric cogeneration system (DCS) which permits using the heat lost from exhaust gases to generate electricity and heat water through TEG. Experiments showed that DCS with TEGs located on the inner wall of the pipe has a payback period of 1 year and 8 months when water is heated 60 times per month. Conversely, reduction of CO_2 gas, which is 10 tons annually, is not affected by the location of TEGs, while the placement of TEGs at the inner wall of the pipe is the best and economic configuration.

Furthermore, a study prepared by Khaled et al. (Ramadan et al., 2017) aimed producing DHW and producing electric power via TEGs by recovering exhaust gases. As an outcome, as exhaust gas temperature increases, the power of TEG increases too. Likewise, P_{TEG} increases 5 times when $T_{exhaust}$ is doubled. Besides, for $T_{exhaust}$ = 300 °C, the produced power is P_{total} = 67 W. Finally, HHRS is affected by quality of $T_{exhaust}$ and quantity of flow rate.

Jaber et al. Jaber et al., 2019 aimed to heat air and water, and produce electricity by developing a new HRS which exploits thermal energy from exhaust gases caused by combustion. Combustion was made of diesel, coal and wood. Results showed that wood is the best choice to be used with a production of 94 W and a high percentage of energy dissipating to the environment (84%).

A heat pump system is applied in public shower services to recover exhaust heat. This system contains separate drainage and solar energy collections, in addition to a heat pump system. The solar system initially heats shower's tap water while the drainage system collects the used shower water. At the end, exhaust heat from collected water is recycled to heat the shower's tap water by the electric heat pump (L. Liu, Fu, and Jiang 2010).

The advantages of this heat pump system compared to gas-fired (oil-fired, coal-fired, electric) boilers are lower energy consumption, less pollution, and lower operating costs. Therefore, the system is superior in energy conservation and has a promising application prospect.

The table below summarizes the main applications on WHR, on which the main objectives, the methodology and the key results of each application study are clarified. Table 13 shows summary for WHR-hybrid applications, its main objectives, and further obtained results.

Table 10
Summary for WHR-Residential systems.

Paper	Main Objectives	Application	Variables	Results
Jaber et al. (2018)	Domestic thermoelectric cogeneration system, optimization analysis, energy consumption and CO_2 emissions reduction.	DCS	Place of TEGs in the pipe	1.66-year payback period. 10 tons CO_2 reduction annually. Placing TEG_s at inner wall of the pipe is the best choice.
Khaled et al. (2015)	Heating supply water.	DWHR	The quantity of burned firewood (heat input)	Increasing water temperature from 10 to 78°C during 1-h chimney operation. 70% of heat transfer rate is through bottom surface of tank.
Eades (2018)	Energy and water recovery using air-handling unit condensate from laboratory HVAC systems.	HVAC	Location of Air Handling Units	13.5% energy and 45% water savings in humid and hot climates in Miami and Florida.
Bellocchi et al. (2018)	Reversible heat pump HVAC system with regenerative heat exchanger for electric vehicles Analysis of its impact on driving range.	HVAC	-Location of ERV -Type of HE	- Driving range about 2–6% less than conventional models - Effectiveness of heat pump systems achieves 17–52% energy savings
Radenahmad et al. (2020)	A review on biomass derived syngas for SOFC based combined heat and power application.	SOFC	-Type of gasifiers	- Combined heat and power (CHP) for houses is highly efficient (>90%). - Micro CHP for space heating in Europe and Japan is already been popular using natural gas as fuel. - Biomass derived syngas μ-CHP is more interesting. - By the development of Solid oxide fuel cell (SOFC) material, the entire energy integration system seems to offer greater energy efficiency for sustainable and renewable energy route.

Table 11
Summary for WHR-industrial applications.

Ref	Objective	Application	Comparative parameters	Result
Amirfakhraei et al. (2020)	Performance improvement of adsorption desalination system by applying mass and heat recovery processes	Adsorption desalination system	2-bed advanced Vs 2-bed conventional ADS system	- The specific daily water production (SDWP) of the advanced 2-bed ADS is 66% more than the conventional 2-bed ADS
Hongsheng Zhang, Zhao, and Li (2019)	Waste heat recovery and water-saving modification for a water-cooled gas steam combined cycle cogeneration system with absorption heat pump	Steam turbine	-New air-cooled gas-steam combined cycle cogeneration system vs conventional water-cooled gas-steam	- Net generating power is approximately increased by 11,082 kW. - Equivalent coal consumption is reduced by 2.71 g/kWh. - The net overall thermal efficiency is improved by 0.91% with 334,245 kW heating load at 100% load of the gas turbine in the modified system. - The overall exergy loss is decreased by 6448 kW and exergy efficiency is improved by 0.98%.
Xu et al. (2020)	Double-section absorption heat pump for the deep recovery of low-grade waste heat	Absorption Heat Pump	Not specified	- Temperature decrease of 29.1 °C for waste hot water. - Heat water up to 52.5 °C for domestic heating application with capacity of 8666.4 kW and high coefficient of performance of 1.77.
Riaz, Lee, and Chou (2019)	Thermal modelling and optimization of low-grade waste heat driven ejector refrigeration system incorporating a direct ejector model	Refrigeration system (using ejectors)	Not specified-Analytical study is compared with experimental one.	- Refrigerant R245fa is used as a working fluid. - The designed ERS produces 1.8 MW of cooling with estimated annual savings of S$0.42 million while operating at 0.3 COP
Sarpong et al. (2020)	Waste heat recovery of power plant with large scale serial absorption heat pumps	Absorption Heat Pump	Conventional absorption heat pump and original heating supply system	- COP of 1.77 - Heating capacity of 63.57 MW - Waste heat inlet/outlet temperature of 34.63/28.33 °C and return water inlet/outlet temperature of 45.94/81.34 °C
Butrymowicz et al. (2020)	Experimental validation of new approach for waste heat recovery from combustion engine for cooling and heating demands from combustion engine for maritime applications	Refrigeration system for marine applications	Not Specified	- The refrigeration system produces up to 30 kW of cold by consuming 75 kW of heat gathered from flue gases
Tong et al. (2018)	Diversion of food waste from incineration and fed into AD & CHP.	Food Waste	-Waste to Energy practices	- More electricity harvested, and less pollution resulted
Macháčková et al. (2018)	Recovery of residual heat from flue gases generated during coal combustion.	Coal Combustion	-Tests with calculating heat transfer with and without condensation	- Temperature of flue gases at high outlet temperature is higher for (without condensation than with condensation). Whereas, temperature of water outlet without condensation is greater than that with condensation
Rodrigues et al. (2018)	Waste heat recovery from composting systems.	Composting Systems	-Temperature gradients	- 11.3 generated voltage, with 20°C Temperature Gradient
Crespo et al. (2020)	Estimating regional potential for micro-hydropower energy recovery in irrigation networks on a large geographical scale.	Agricultural irrigation	-Irrigated surface area of pressurized systems. -Irrigation requirements (directly related to the crops and the agro climatic parameters). -Mean slope of the area were the input variables.	- 21.05 GWh was identified as the energy potential, which could have been recovered using micro-hydropower during the 2018 irrigation season. - The energy consumption reduction of the irrigation process in this region by approximately 12.8%. - Reduction in energy consumption in the agriculture sector of this magnitude could have significant impacts on food production and climate change.
Bonilla-Campos et al. (2019)	Energy efficiency assessment: Process modelling and waste heat recovery analysis.	Aluminium Die-Casting plant	Not specified	- The assessment shows a potential to reduce the natural gas consumption in the aging heat treatment process up to 55%, with approximately a 3-years payback period and savings of 300 MWh/year. - The burners of the aging treatment process present energy reductions from 50% to 80% depending on the burner position. - The new waste heat recovery system provides up to 63% of the new energy required by the aging furnace.
Jin et al. (2019)	Techno-economic analysis on a new conceptual design of waste heat recovery for boiler exhaust flue gas of coal-fired power plants.	Coal-fired power plant	-Low Pressure Economizer and Low Pressor Economizer with Organic fluid cycle	- Production of 5361.98 kW additional net power output and electricity revenue of $1220.04 k, which are approximately 409.19 kW and $127.2 k greater than low pressure economizer (LPE) respectively. - The proposed system could save 5699.36t standard coal and $854.9 k coal cost per year, which are nearly 595.5 t and $89.32 k larger than LPE. - The maximum of recovery heat utilization efficiency of proposed system reaches 17.35% and the maximum efficiency improvement compared to LPE touches 3.48%.

(continued on next page)

Table 11 (*continued*)

Ref	Objective	Application	Comparative parameters	Result
Kostowski et al. (2019)	Methods of waste heat recovery – A compressor station case study.	Natural gas compressor station	Method of waste recovery (direct, via ORC module …)	- Direct heat recovery is recommended for a pilot plant, and the recovered quantity of waste heat may reach 900 MWh/year from a single engine if operated continuously. - Electricity generation may reach 530 MWh year (gas expander system) or about 300 MWh/year (ORC system).
Liu et al., (2020)	A novel natural gas hydrate recovery approach by delivering geothermal energy through dump flooding.	Dump Flooding	Not specified	- Higher hydrothermal reservoir temperatures and pressures are favorable for hydrate recovery. - Energy efficiency drops as the pore volumes, temperature and pressure of hydrothermal reservoirs increase. - The pressure loss caused by friction is negligible compared with that caused by gravity and therefore has nearly no influence on performance.
Lu et al. (2019)	Thermodynamic and economic analysis of a gas-fired absorption heat pump for district heating with cascade recovery of flue gas waste heat.	Gas-fired boiler	Single absorption system (with and without WHR), proposed system	- The proposed system has energy saving potential of 11.7% and 39.6%, and payback time of 2.9 and 2.5 years compared to the single-effect absorption heat pump and the gas fired boiler, respectively. - The proposed system is suitable to provide 50 kW close range district heating for a typical urban residential building, especially in cold regions.
Men et al. (2019)	Novel flue gas waste heat recovery system equipped with enthalpy wheel.	Gas-fired boiler	Rotation speed of the enthalpy wheel. -Backwater temperature	- The average boiler efficiency reaches 106% and the average total recovery efficiency reaches 88%. - The dew point temperature of the flue gas discharged from the boiler increases to around 60 °C, higher than that of conventional flue gas (around 55 °C). - More latent heat is recovered in the condensing heat exchanger by virtue of the proposed system.
Sarpong et al. (2020)	Evaluation of energy recovery potential in wastewater treatment based on co-digestion and combined heat and power schemes.	Wastewater treatment Plant	-Different combined heat and power (CHP) schemes	- Increasing the removal of chemical oxygen demand (COD) by 10% in primary treatment resulted in an estimated reduction in total energy requirement by 8.5% and increased recoverable energy by 8.8%. - This result illustrates that influent wastewater COD strength and the plant capacity may have significant impact on the energy recovery potential.
Soltani et al. (2020)	A comparative study between ORC and Kalina based waste heat recovery cycles applied to a green compressed air energy storage (CAES) system.	Compressed air energy storage system	-Rankine cycle and kalina cycle. -Working fluids.	The results indicate that the energy and exergy round trip efficiencies can be improved by 1.69–2.67% and 1.70–2.69%, compared to the stand-alone compressed air energy storage. • The supercritical organic Rankine cycle with R290 as the working fluid is the best alternative, which recovers the highest amount of wasted heat and improves the production capacity by 2.47%.

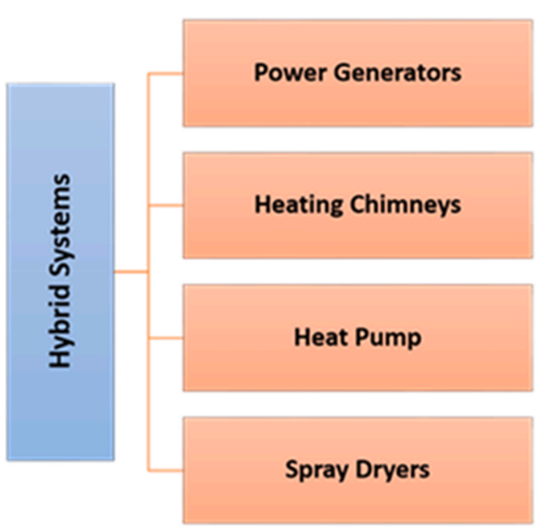

Fig. 9. Applications of hybrid heat recovery systems.

Table 12
Results of testing on 10 & 38 kW load generators.

Load of Generator (kW)	Number of TEG_s	Hot water Temperature (°C)	Recovered average heat rate (kW)
10	100	47	0.141
38		97	1.412

Until now, studies on hybrid heat recovery Systems are still rare. Recently, researches started working on these systems in order to save energy, and get the best efficiency from the initial system. Hybrid system mostly depend on TEGs to produce electricity, and heating water or gas from the exhaust loss gases of the system. Such systems will be very soon, the first worldwide trend in energy domain, because of the encouraging results, and the great profit from applying those systems.

5. Conclusion and recommendations

5.1. Conclusion

A recent review on the recent heat recovery methodologies and its

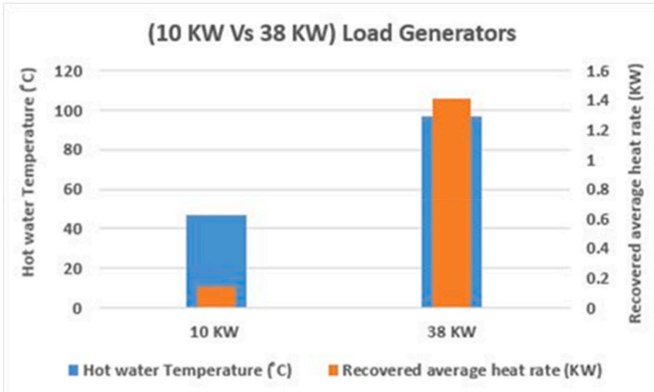

Fig. 10. Results of testing on 10 & 38 kW load generators.

application in daily life systems is carried out. Based on the literature study, all sections are summarized and discussed below:

➢ **Methodologies:**
- **Heat Exchangers:** Plate-fin H.E proves to be the best H.E due to its high compactness factor. Whereas, thermal wheel H.E with highest thermal efficiency (greater than 80%) is the best H.E based on type and flow of arrangement.
- **Rankine Cycle:**
  - For high temperature mediums, water proves to be the best working fluid due to high power output and high thermal efficiency, while its high freezing point and requirement of superheating cannot be overlooked.
  - Organic fluids are widely used and R245fa proves to give the best results based on their performance, but fails in economical fields. On the other hand, Ammonia serves as a good working fluid according to some studies.
- **Thermoelectric Generators:** The efficiency of TEG is maximized by increasing the electric conductivity and the thermal resistivity of the material and the seebeck coefficient. In addition, the temperature difference and physical properties of fluids affect the power of a TEG.

➢ **Applications:**

o **Engine Systems:**
- **Internal Combustion Engine Systems**: wasted energy mainly released through, gas recirculation (EGR), exhaust gas and heat losses. ORC and TEG represent promising candidates for the transformation of thermal energy into electrical and/or mechanical energy, at different temperature mediums.
  - **Compression Ignition Systems:** ORC is suitable for recovering high-temperature heat, but it decreases when the exhaust gas temperature is low. However, no single working fluid is best for all ORC's, as the selection of the proper working fluid requires consideration of operating conditions, environmental concerns and economic factors.
  - **Spark Ignition Systems:** TEG serve in low power modes, while ETC serve in high power modes. Decent management and formation of WHRS lead to a valuable enhancement of CO_2 reduction and fuel economy.
  - **Power Generators:** HRS applied to recover thermal energy from exhaust gases and heat water by using heat exchangers having water in inner tube and exhaust gas exposed in annulus, taking into consideration locating the inner diameter in a close vicinity of the constant outer diameter. Recovered average heat rate increases with the increase of water flow rate.
- **Gas Turbine Engine:** ORC combination with gas turbine using R134a as a working fluid to transform the gas turbine waste heat into electric power thus saving fuel and reducing CO_2.

o **Residential Systems:**
- **Drain water system:** DWHR is designed to recover the residual energy from the hot or warm drain water, and using them to preheat the inlet cold water. Maximum heat recovered is reached at the lowest flow rates. ASHP on apartment scale shows higher global performance caused by the system simplicity and minimal heat loss. Whereas, building scale shows high electricity due to DHW recirculation as well as heat loss.
- **Heat recovery from Hot Exhaust Gases:** TEGs location inside the pipes is the best economic energy recovery setup, while this does not affect the amount of CO_2 reduction. However, HRS is dependent on the quantity and quality of thermal energy lost. Power generated increases with the exhaust gases temperature increase.
- **HVAC Systems:** Both the performance and the efficiency of HRS anticipated rise with both the duct hot and condenser cold flow

Table 13
Summary for WHR-hybrid applications.

Ref	Objective	Application	Results
Jaber et al. (2019)	Effect of generator load on hybrid heat recovery system.	PG	- As load increases, the water temperature and power produced increases. - 38 kW load generator and 100 TEGs, - Hot water temperature is 97 °C and electric power is 1412 W.
Xiaofeng Guo and Goumba (2018)	Air source heat pump for domestic hot water supply: Performance comparison between individual and building scale installations.	ASHP	- The hybrid heat recovery system generated about 240 W for both diesel and coal cases, while it only produces 94 W for wood case. - The water at the tank is heated up to 351 K for diesel and coal cases, however when wood is used as fed fuel the water temperature increased to 331 K at steady state. - The overall system recovered 20%, 42% and 84% of the energy dissipated to the environment for diesel, coal and wood cases respectively.
Ramadan et al. (2017)	Heating supply water and producing electricity.	HHRS	When exhaust temperature is doubled, Power of TEG increases 5 times. - when exhaust temperature is: 300° C, Total power is:67 W HHRS is affected by quality of $T_{exhaust}$ and quantity of flow rate.
Patel and Bade (2020)	Energy targeting and process integration of spray dryer with heat recovery systems.	Spray Dryers	- Among direct and indirect heat recovery configurations, a hybrid heat recovery system with 80% recirculation is having the highest thermal energy saving potential (74%) compared to the base case.
Xiaochao Guo et al. (2019)	Experimental study on the performance of a novel in–house heat pump water heater with freezing latent heat evaporator and assisted by domestic drain water.	HP	- Reducing the negative effect of ambient wind blow on the airflow structure inside the solar collector. - The Hybrid solar chimney demonstrates enhancements of 12.0% in the mass flowrate, 51.0% in system P.I., and 64.0% in the collector efficiency.

rates. Energy recovery captured from two different sources: condenser hot air and cold exhaust air. On the other side, the operating parameters influencing the performance of TE-HRS are TEC numbers, filling factor, length of P–N legs, couple numbers of thermoelectric coolers and overall thermal conductance. Moreover, input power increases with that of unit number while the cooling load reduces with this increase. Finally, the heat transfer capacity, temperature effectiveness, and coefficient of performance of the triple loop PLHP system increase in summer conditions, and more significantly in winter conditions.

o **Industrial Systems:** Food waste boiler, coal combustion, composting systems, agricultural irrigation, biomass gasification, coal-fired power plant, dump flooding, and natural gas compressor station are examples of used WHR technology in industrial systems.

➢ **Hybrid Systems:** HHRS is a combination of more than one purpose, which could be generating electricity, heating, cooling and storing energy for a later use. Thermal energy lost variation affects this process. Heat rate and thus power generated increase with exhaust gases temperature increase. However, when compared with coal and diesel, wood proves to be the best material to be used in combustion. In spray dryers, HHRS with 80% recirculation is having the highest thermal energy saving potential (74%) compared to direct and indirect heat recovery systems. However, a novel in–house heat pump water heater with freezing latent heat evaporator and assisted by domestic drain water The hybrid solar chimney demonstrates enhancements with great values.

Recently, studies on rankine cycle are trending, because it is a major technology in WHR applications. Researchers work on increasing the efficiency of the cycle by studying many working fluids in order to attain the best efficiency. Organic fluids are widely used and R245fa proves to give the best results based on their performance, but fails in economical fields. On the other hand, Ammonia serves as a good working fluid according to some studies. Yet, these working fluids serve for low temperature mediums only. While water, with having many advantages competes in high temperature mediums. However, TEGs are used widely for producing electricity from heat recovery. Therefore, enhancing TEGs may lead to promising results. WHR systems cannot be limited by a specific number or types of applications. That is because heat recovery and energy saving are recommended topics for all new researches in energy domain. Applying such systems is considered as a step forward into making world green. Therefore, researchers are trying to benefit from every loss of energy, and thus increasing efficiency of the working system. Industries, residential buildings and engines, with their different branches and types are always great candidates to apply WHR systems.

5.2. Recommendations

Below is a summary of some useful recommendations obtained based on the literature review performed above:

1. Further studies on working fluids may yield to an inclusive efficient working fluid for different heat mediums.
2. Energy results are important, but it is much better to add cost results and make comparisons with it.
3. In any new experimental study, using TEG is a pronounced benefit to the expected results. Enhancing it will strengthen the recovery system and lead to great results.
4. For better efficiency, it is recommended to optimize heat recovery systems because of its enormous enhancement concerning efficiency and effectiveness.
5. For new studies, using HHRSs, which are the most trending approach for researchers currently, is recommended.

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.

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