***Paper ID: ET-04***

# Towards the Potential Applications of Waste Heat Energy: A Review

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## Abstract

*The internal combustion engines or other waste heat related machineries, nowadays, become an indispensable technologies for different purposes. A huge amount of waste heat causes environmental hazards that turn in danger of human health, increases GHG, and contamination of ground water and air. Management of this enormous amount of waste heat is very challenging. Lack of feasible technologies, proper development of thermoelectric materials and other challenges are the prime causes of the improper management of waste heat. In this study, the waste heat production and available technologies which are used to recover waste heat have been reviewed extensively. It emerges that, there is no improved technologies are used for proper management of waste heat. A set of research and development activities has been proposed along with the challenges that would emerge during the implementation of these strategies. Successful execution of the outputs of the research and development activities would enhance the quality of waste heat recovery.*

Keywords: Waste heat recovery, GHG reduction, feasible technologies, challenges and solutions.

## 1. Introduction

After combustion process or any thermal or chemical process the remaining heat, which is exhausted to the environment, is generally called waste heat (WH). The carbon dioxide emissions and global energy consumption have been increased after the industrial revolution which makes the global resource and environmental problem more and more serious [1]. 53% of total energy is consumed by the industrial sector because of different technical limitations and 72% of the primary energy sources are wasted in the process of combustion and conversion [2]. The amount of heat, which is wasted by different industrial processes, is about 20-50% of the input heat. Due to waste heat recovery, the efficiency of the energy system can improve about 10-50% [3]. Mechanical equipment, thermal engines and industrial processes are the major waste heat sources [4][5]. The majority percent i.e. about 60% of heat is wasted as low grade heat [6]. Although, the amount of waste heat is very high but it is difficult to utilize the low grade heat [7]. Low grade heat includes solar heat, geothermal heat, biomass heat and industrial waste heat sources [8][9]. Waste heat and low grade heat recovery mitigate the risk of future climate change and reduce energy cost besides improving the efficiency of the energy system [10][11].
Moreover, one is the most important way to reduce the $CO_2$ concentration is to utilize waste heat from different sources [12]. Environmental problems can be overcome through two different approaches. The first is to use different renewable energy sources like solar, wind [13], biomass [14], and geothermal [15]. The second option is to improve the efficiency of the energy system by utilizing waste heat [16][10]. Different literature shows that more than 50% of used energy is wasted all over the world [17][18]. It is required to utilize the waste heat for improving the efficiency of the energy system and to reduce environmental pollution.
There are some benefits of waste heat recovery, which are broadly classified as direct benefits and indirect benefits. Low amount of energy consumption, efficiency improvement of the energy system and lower process cost are considered as direct benefits. On the other hand, reduction in pollution, reduction in equipment sizes, and reduction in auxiliary energy consumption are considered as indirect benefits of waste heat recovery [19]. From the best of the author's knowledge, there is no literature available which describes the waste energy sources, and their effects on the environment. The aim of this study is to describe briefly the waste heat sources, its effect on human health and environment, the available technologies that can be used to recover waste heat, the barrier to use these technologies and finally the research and development programs have been operated to retrieve waste heat successfully.

## 2. Waste energy amount

The system efficiency can be increases by using the available technologies for power generation from waste heat, which can lead to fuel consumption reduction [20]. For example, it can be shown that for a midsize cement plant the waste heat recovery can reduce the $CO_2$ pollution up to 10000 tons/year and enhance the energy efficiency up to 20% [21]. There are some parameters which can affect the feasibility of waste heat recovery, such as temperature, flow rate, and specific heat or enthalpy of the waste heat stream [22]. Fig. 1 shows different waste heat sources. Among them, the diesel engine produces the maximum amount of waste heat. On the other hand, different refinery factories produce a minimum amount of waste heat. CNG engine and flue gas produce around 3% of recoverable waste heat. After that, the fuel cell produces 4% of recoverable waste heat. Boiler and other power generation plant produce the same amount of waste heat, which is 5%. The gas turbine produces 7% and internal combustion engine rather than diesel engine produce 14% waste heat [23].

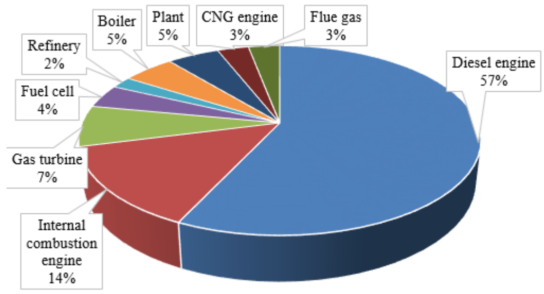


**Fig. 1.** Different waste heat sources for recovery [23].

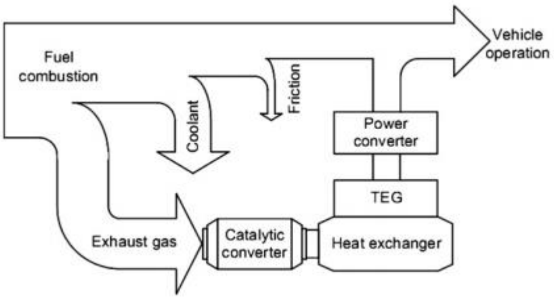


**Fig. 2.** A typical waste heat energy recovery system for automobile engine [24].

Since a large amount of waste heat is produced by diesel engine thus it is required to elaborate on the energy distribution of a diesel engine. Only 32% of total energy is converted into mechanical power. But, generally, the remaining percentage of energy is wasted. It has been shown that the exhaust gas potential energy of diesel engine is around 25-40% [25], since the engines use traditional diesel fuel. The waste heat potential energy is considered as a function of waste heat temperature and mass flow thus the waste heat recovery capacity is increased with increasing the waste heat temperature. The detail waste heat distribution of a diesel engine has been shown in the previous literature [26]. According to the potentiality of waste heat, researchers differentiate different grades of waste heat [19]. Generally, the quality of waste heat is determined depending on the temperature of it. The usefulness of waste heat also depends upon its quality. Generally, the low temperature waste heat is used for space heating or air preheats. On the other hand, the high temperature waste heat is generally used to produce power.

## 3. Coolant and cooling temperature

Generally, there are three categories of waste heat energy sources which are liquid streams, flue gases, and steam and process gases. The categories are also classified as high temperature (>650$^0$C), medium temperature (230$^0$C-650$^0$C), and low temperature (<230$^0$C) waste heat [23]. Different types of heat sources with their temperature ranges and recovery methods were described in previous literature [3]. Generally, the high temperature waste heat produces from the waste gases of the industrial process equipment. The waste heat produces from direct fuel fired processes is usually known as high temperature waste heat [25]. The advantages of high temperature waste heat (WH) are high quality energy, high efficiency power generation and high heat transfer rate per unit area. On the other hand, the disadvantages of high temperature WH are, high temperature creates increased thermal stress on heat exchange materials, and increased chemical activity and corrosion [27]. Most of the waste heat in this temperature range comes from the exhaust of directly fired process units. The advantages of medium temperature WH are: it is more compatible with heat exchanger materials and more practical for power generation. There is no severe disadvantages of medium temperature waste heat.

In the low temperature range, it is usually not practical to extract work from the source, though steam production may not be completely excluded if there is a need for low-pressure steam. Low temperature waste heat may be useful in a supplementary way for preheating purposes [25]. The advantages of low temperature WH are: large quantities of low temperature heat contained in numerous product stream. Conversely, the disadvantages of low temperature waste heat are: few end uses for low temperature heat, low efficiency power generation and for combustion exhausts, low temperature heat recovery is impractical due to acidic condensation and heat exchanger corrosion.

Depending on the temperature of the waste heat sources the selection of materials for heat exchangers and recovery systems are different. With increasing the temperature of the waste heat sources the corrosion and oxidation reactions such as chemical reactions are accelerated dramatically. Due to containing higher corrosive substances in the heat sources, the heat recovery surfaces can quickly become damaged. The oxidation begins for carbon steel when the temperature is above $425^0$C [27]. The same process occurs for stainless steel when the temperature is above $650^0$C thus the composite materials or advanced alloys must be used for high temperature waste heat sources. The temperatures above $871^0$C metallic materials cannot be used [28]. There are some alternative technologies which can be used for high temperature waste heat sources. Such as bleeding dilution air into the exhaust gases to lower the exhaust temperature or using ceramic materials that can better withstand the high temperature. The total quantity of heat remains constant during air bleeding but the quality is reduced due to the temperature drop.

## 4. Environmental harm due to hot exhaust gas

Waste heat (WH) cause immediate and long term effects on the environment. Exhaust gases from different WH sources emit a wide range of solid matter and gases, having effects on human health, causing global warming, acid rain and harming the environment.

### 4.1 Effect on human health

Carbon monoxide, hydrocarbons, particulate matter and other exhaust pollutants harm human health [29]. Mainly, the particulate matter produced by diesel engine is higher compared to the other engines. The particulate matter of diesel engine is airborne particles of soot and metal. These cause skin and eye irritation and allergies, and very fine particles lodge deep in lungs, where they cause respiratory problems. The ozone, which is formed by the reaction of nitrogen dioxide and sunlight, is beneficial for upper atmosphere but harmful at ground level [30]. The harmful effects of ozone on human health are, it causes lung problem, causing chest pains and coughing and making it difficult to breathe. Another harmful exhaust gas is carbon monoxide, which affects infants and people suffering from heart dieses. Sulfur dioxide, benzene and formaldehyde are the other exhaust pollutants which affect human health. The harmful effects on human health by different exhaust gases and fumes was described in previous literature [31].

### 4.2 Greenhouse gases

Waste heat i.e. the exhaust gases consists of 72% carbon dioxide, 18% methane, 8% nitrous oxide and 1% other gases [32]. The amount of carbon dioxide is higher which largely contributes to form the greenhouse gas (GHG). The contribution of greenhouse gases to increase global warming is higher compared to the anthropogenic heat. In 2005, although anthropogenic waste heat flux was significantly high in certain urban areas globally it accounted for only 1% of the energy flux created by anthropogenic greenhouse gases. Global forcing from waste heat was 0.028 $W/m^2$ in 2005. This statistic is predicted to rise as urban areas become more widespread [33]. Although waste heat has been shown to have an influence on regional climates, climate forcing from waste heat is not normally calculated in state-of-the-art global climate simulations [34]. Simple global-scale estimates with different growth rates of anthropogenic heat that have been actualized recently show noticeable contributions to global warming, in the following centuries. For example, a 2% growth rate of waste heat resulted in a 3 degree increase as a lower limit for the year 2300 [35].

### 4.3 Pollutants and air quality

There are different natural and anthropogenic sources to produce air pollutants. Natural sources of air pollutants may be the volcanic eruptions or wind erosion. Most important source of anthropogenic air pollutant is the emission of internal combustion engine. The primary pollutants transform into different chemical species by different atmospheric reactions. These reactions may create both harmless compounds and different secondary pollutants which may be more harmful than their precursors.

### 4.4 Effects of thermal pollution

In case of thermal pollution, there are generally two different schools of thoughts among the recognized scientist and scholars. Some lean on the side of the negatives of this pollution on marine ecosystems and how it is detrimental to positive environmental practices. However, some lean towards the side that without these industries operating the way they do, then some of the most basic parts of human life would be completely obsolete [36]. The effects of thermal pollution on ecosystems, however, greatly outweigh the benefits that industries have by participating in the act.

## 5. Available technology to retrieve waste heat energy

There is a huge amount of waste heat produced from different sources. Since these waste heat can harm the environment and human health thus it is required to recover and produce energy through different available technologies. Table 1 shows some feasible technologies and their output to retrieve the waste heat from different sources.

**Table 1.** Different practical waste heat sources, feasible technology to retrieve, output and applications.

| Waste heat sources | Feasible technology | Output | Applications |
|---|---|---|---|
| IC Engine Movable (Bus, Trucks) | Thermo-electric generation | Electricity | Fan, Light, Tape recorder inside the vehicle. |
| IC Engine Stationary (Power generation) | Heat exchanger | Thermal | Food drying, Room heating. |
| Brick kiln | Heat exchanger | Thermal | Food drying, room heating. |
| Power plant (Thermal, Nuclear) | Cogeneration | Thermal, Electricity | Food drying, Room heating, home appliances. |
| Heat exchanger (Condenser), Heat pipe | Heat exchanger | Thermal | Food drying, Room heating. |

## 5.1 Engine waste heat recovery

Owing to the considerable amount of energy and availability that is normally dissipated through the coolant and exhaust gas systems of automotive powertrain, there is considerable interest in using waste heat recovery technologies for converting thermal energy into mechanical energy or electrical energy. The following sections outline the most relevant technologies that are used today the state of the art.

There are different types of technologies which can be used to retrieve waste heat such as organic Rankine cycle (ORC), Stirling cycle, steam Rankine cycle, Brayton cycle, Kalina cycle, supercritical $CO_2$ cycle, and Trilateral flash cycle [37]. The above mentioned cycles have different difficulties compared to the ORC. Because of some advantages such as high safety, flexibility, good thermal performance and low maintenance requirements; the organic Rankine cycle (ORC) is a well-known promising solution to recover waste heat [38]. Apart from using refrigerants or volatile organic liquids as the working fluid rather than water, the ORC system is similar to the conventional Rankine cycle [39]. Due to the lower boiling points of organic fluid compared to water, which make it possible to retrieve waste heat from low temperature sources. The thermal efficiency of an ORC not only depends upon the thermodynamic properties of working fluid but also the operating conditions of heat source, sink and cycle [40]. Depending on the application of ORC the choice of working fluid is different. The use of working fluids depending on the ORC configurations, the amount of waste heat recovery and the efficiency of the system are different which are extensively described in the literature. The advantages of retrieving waste heat from different sources by organic Rankine cycle are reduction of electrical loads, economical utilization of the energy and reduction of $CO_2$ emission [41].

## 5.2 Recuperative thermal management systems

In case of internal combustion engine almost 65% of the energy produced in the combustion chamber being dissipated to the environment [42]. Harvesting this wasted energy by recuperative thermal management system increases the fuel temperature, which helps to reduce the vehicle's fuel consumption. Thermal management systems mainly focus on balancing the needs of multiple subsystems and components which may require heat for operation, heat rejection, or operation within specified temperatures [43]. This is the reason why the thermal management system can offer the ability to recover some of the exhaust heat by aiding rapid warm-up of the engine as well as powertrain fluids.

## 5.3 Thermoelectric energy conversion technology

In future, thermoelectric generators (TEG) will become one of the most important and outstanding devices for automotive waste heat recovery. Now-a-days the TEG technology achieves great attention of many scientists and engineers for clean energy production. The potential of thermoelectric technology for implementing fuel economy vehicles and the thermoelectric (TE) materials available in the market were studied [44]. For hybrid vehicles, the effects of thermoelectric waste heat recovery were studied [45]. The possibilities of thermoelectric generation were investigated [46] in which they found that the 1.3 kW output of the thermoelectric device could potentially replace the alternator of a small passenger vehicle. For vehicles, the potentials in fuel saving of thermoelectric devices were reviewed [47]. The summary of their review was the fuel economy efficiency could be achieved up to 4.7% for internal combustion engine. Based on the above discussion it would be notified that the thermoelectric generation will be a promising new technology to recover waste heat from internal combustion engines. Engine performance, design flexibility, reliability, and efficiency could be improved significantly by converting the waste heat into electricity.

For an automobile engine, the exhaust gas system and radiator are the two main waste heat sources [48]. Generally, the TEG is mostly installed in the exhaust gas system due to the simplicity of operation of the engine. Moreover, the TEG system with heat exchanger is mostly installed in the exhaust manifold which is suitable for high temperature region [49]. Fig. 2 shows a practical waste heat recovery system which consists of a battery pack, a power conditioning system, a TEG system, a heat exchanger and an exhaust gas system. The produced waste heat of an internal combustion engine is exhausted through the exhaust manifold which is captured by the heat exchanger mounted on the catalytic converter of the exhaust gas system. After transferring the waste heat to the TEG system electricity is produced. The power converter perform the power conditioning system to achieve maximum power transfer.

### 5.4 Turbocharger

A large amount of waste heat is generated from a naturally aspirated internal combustion engine. During combustion process, a large quantity of heat is wasted through the exhaust manifold and finally to the environment. By using a turbocharger this wasted exhausted energy can be recovered. In its simplest definition, a turbocharger is a supercharger that is driven by exhaust energy. Now-a-days most of the diesel engine is equipped with turbochargers. The mass flow rate of air into the engine cylinder can be increased by using a turbocharger which significantly reduces particulates of diesel engines that are released into the atmosphere. The turbocharged diesel engine can improve the fuel economy of passenger vehicle up to 30-50% but for gasoline engine, it would be 5-20% [50]. Turbocharging was largely adopted in diesel engines and recent motivation for more fuel efficient, economic and high performance engines [51].

### 5.5 Cogeneration

Cogeneration means combined heat and power (CHP) generation. The same power station is used to generate electricity and useful heat at the same time. Thermodynamically cogeneration is the more efficient use of fuel. During electricity generation, all thermal power plants emit heat, which is discarded as waste heat into the natural environment through flue gas, cooling tower or by other means. Actually, CHP plants recover this thermal energy for heating, either very close to the plant or especially in Scandinavian and European countries where hot water is used for district heating with temperatures ranging from approximately 80℃ to $130^0$C [52]. This is also called combined heat and power district heating (CHPDH). The temperature of by product heat is 100℃-$180^0$C which is moderate to use in absorption refrigerators for cooling.

## 6. Challenges

Implementing of different new techniques to attain a desirable condition of waste heat management is a challenging task. The barriers of different techniques are different. Particularly the challenges of TEG and turbocharger are briefly discussed here. Apart from, there are different factors such as cost of the technologies, temperature restrictions, chemical composition of the exhaust gas, application specific constraints, and inaccessibility or transportability hindrance to recover waste heat excellently.

### 6.1 Challenges of TEG

Low thermal efficiency of TEG is the primary challenge to use the technology to recover waste heat. The efficiency of thermoelectric materials depends on the figure of merit (Z) of the material. The figure of merit of thermoelectric material is a constant proportional to the efficiency of a thermoelectric couple made with the material. Due to the availability in the market and high applicability in low and high exhaust gas temperature range the BiTe (bismuth telluride)-based bulk thermoelectric material is mostly used in waste heat recovery power generation [51]. The extended piping to the exhaust manifold and the bigger size of the radiator are another challenges of TEG for waste heat recovery.

### 6.2 Challenges of turbocharger

Generally, the turbochargers are mostly used in heavy-duty applications. There are mainly two reasons behind the lower acceptance of the turbocharger in the automotive industry [53]. Turbochargers suffer turbo lag which is known as hesitation or transient response during low speed acceleration and there are major concerns with heated bearings. The performance of the engine and drivability are poorly affected by turbo lag.

### 6.3 Costs

Costs of heat recovery equipment, design services and auxiliary systems lead to long payback periods in certain applications. Apart from, there are several industry subsectors which produce high quality waste heat i.e. metal casting are renowned for small profit margins and intense internal competition for limited capital resources [54]. For certain applications, more costly materials are required. The overall cost of materials for per unit waste heat recovery is increased as larger surface areas are required for more efficient, lower temperature heat recovery systems. Economies of scale equipment costs favor large scale heat recovery systems and create challenges for small scale operations. Operation and maintenance costs corrosion, scaling, and fouling of heat exchange materials lead to higher maintenance costs and lost productivity.

## 6.4 Temperature restrictions

Many industrial facilities do not have an onsite use for low temperature heat. Meanwhile, technologies that create end use options (e.g., low temperature power generation) are currently less developed and more costly. Materials that retain mechanical and chemical properties at high temperatures are costly. Therefore, waste heat is often quickly diluted with outside air to reduce temperatures. This reduces the quality of energy available for recovery [55]. Liquid and solid components can condense as hot streams cool in recovery equipment. This leads to corrosive and fouling conditions. The additional cost of materials that can withstand corrosive environments often prevents low temperature recovery. The heat flow in some industrial processes can vary dramatically and create mechanical and chemical stress in equipment. Small temperature differences between the heat source and heat sink lead to reduced heat transfer rates and require larger surface areas.

## 6.5 Chemical Composition

Waste heat stream chemical compatibility with recovery equipment materials will be limited both at high and low temperatures. Deposition of substances on the recovery equipment surface will reduce heat transfer rates and efficiency. Streams with high chemical activity require more advanced recovery equipment materials to withstand corrosive environments. Costs streams with high chemical activity that damage equipment surfaces will lead to increased maintenance costs. Waste heat recovery from exhaust streams may complicate or alter the performance of environmental control and abatement equipment [56]. Chemically active exhaust streams may require additional efforts to prevent cross contamination between streams.

## 6.6 Application specific constraints

Equipment designs are process specific and must be adapted to the needs of a given process. For example, feed preheat systems vary significantly between glass furnaces, blast furnaces, and cement kilns. Heat recovery can complicate and compromise process/quality control systems.

## 6.7 Inaccessibility and transportability

Many facilities have limited physical space in which to access waste heat streams e.g. limited floor or overhead space. Many gaseous waste heat streams are discharged at near atmospheric pressure which limits the ability to transport them to and through equipment without additional energy input. It is difficult to access and recover heat from unconventional sources such as hot solid product streams e.g. ingots and hot equipment surfaces e.g. sidewalls of primary aluminum cells [57].

# 7. Research and development

There is one of the most important challenges in the materials used of thermoelectric generator. The research and development of thermoelectric materials have been studied [58]. He stated that future thermoelectric materials show the promise of reaching significantly higher values of the thermoelectric figure of merit (Z), and thus higher efficiencies and power densities can be obtained. Different thermoelectric materials such as SnTe (tin telluride), SiGe (silicon–germanium), ZnBe (zinc–beryllium), CeFeSb (skutterudite), BiTe (bismuth telluride) and new nano-crystalline or nano-wire thermoelectric materials are currently in development stage to improve the conversion efficiency of TEGs [59]. The extended piping of the exhaust gas and the large size of radiator of TEG can be mitigated by using a nano-fluid in a radiator system. By using nanofluid, the size and weight of an automotive car radiator could be reduced without affecting its heat transfer performance [27]. For turbocharger, turbo lag is an important barrier to recover waste heat which has been studied [60]. He investigated the mechanism of a turbocharger response delay and stated that the interruption of boost pressure response is due to a combination of issues. The physical properties of the turbocharger systems such as weights of the compressor and turbine are the main cause of turbo lag. By using new materials in the compressor and turbine blades weight can be reduced and transient response can be improved. Apart from, by reducing the intake and exhaust system volume, the transient response of the turbocharger can be improved.

# 8. Conclusion

An enormous amount of waste heat is being produced all over the world. Proper management of these waste is indispensable to save the environment from the hazardous effect of waste heat. However, lack of facilities, proper material development for TEG, and other challenges hinder in proper management of waste heat. Moreover, traditional technologies are not effective and adequate in the waste heat recovery system. Several potential waste heat management research and development techniques have been stated with the challenges that would be encountered during the implementation of these strategies. Successful implementation of the research and development outputs would mitigate the waste heat management related problems and be the promising source of energy.

## 9. References


[1] V. Minea, "Power generation with ORC machines using low-grade waste heat or renewable energy," *Appl. Therm. Eng.*, vol. 69, no. 1–2, pp. 143–154, 2014.

[2] C. Forman, I. K. Muritala, R. Pardemann, and B. Meyer, "Estimating the global waste heat potential," *Renew. Sustain. Energy Rev.*, vol. 57, pp. 1568–1579, 2016.

[3] I. Johnson, W. T. Choate, and A. Davidson, "Waste heat recovery. Technology and opportunities in US industry," BCS, Inc., Laurel, MD (United States), 2008.

[4] Jj. Bonilla, Jm. Blanco, L. López, and Jm. Sala, "Technological recovery potential of waste heat in the industry of the Basque Country," *Appl. Therm. Eng.*, vol. 17, no. 3, pp. 283–288, 1997.

[5] S. R. Latour, B. L. Blaney, and J. G. Menningmann, *Waste heat recovery potential in selected industries*. US Environmental Protection Agency, Industrial Environmental Research Laboratory, 1982.

[6] T. X. Li, R. Z. Wang, T. Yan, and T. F. Ishugah, "Integrated energy storage and energy upgrade, combined cooling and heating supply, and waste heat recovery with solid–gas thermochemical sorption heat transformer," *Int. J. Heat Mass Transf.*, vol. 76, pp. 237–246, 2014.

[7] S. I. Garcia, R. F. Garcia, J. C. Carril, and D. I. Garcia, "A review of thermodynamic cycles used in low temperature recovery systems over the last two years," *Renew. Sustain. Energy Rev.*, vol. 81, pp. 760–767, 2018.

[8] R. A. Victor, J.-K. Kim, and R. Smith, "Composition optimisation of working fluids for organic Rankine cycles and Kalina cycles," *Energy*, vol. 55, pp. 114–126, 2013.

[9] J. Sarkar, "Review and future trends of supercritical $CO_2$ Rankine cycle for low-grade heat conversion," *Renew. Sustain. Energy Rev.*, vol. 48, pp. 434–451, 2015.

[10] B. F. Tchanche, G. Lambrinos, A. Frangoudakis, and G. Papadakis, "Low-grade heat conversion into power using organic Rankine cycles–A review of various applications," *Renew. Sustain. Energy Rev.*, vol. 15, no. 8, pp. 3963–3979, 2011.

[11] M. Imran, M. Usman, B.-S. Park, H.-J. Kim, and D.-H. Lee, "Multi-objective optimization of evaporator of organic Rankine cycle (ORC) for low temperature geothermal heat source," *Appl. Therm. Eng.*, vol. 80, pp. 1–9, 2015.

[12] A. Omar, M. Sagha, K. Mohammadi, A. Alashkar, and M. Gadalla, "A review of unconventional bottoming cycles for waste heat recovery : Part II – Applications," vol. 180, no. June 2018, pp. 559–583, 2019.

[13] R. Rayegan and Y. X. Tao, "A procedure to select working fluids for Solar Organic Rankine Cycles (ORCs)," *Renew. Energy*, vol. 36, no. 2, pp. 659–670, 2011.

[14] U. Drescher and D. Brüggemann, "Fluid selection for the Organic Rankine Cycle (ORC) in biomass power and heat plants," *Appl. Therm. Eng.*, vol. 27, no. 1, pp. 223–228, 2007.

[15] F. Heberle and D. Brüggemann, "Exergy based fluid selection for a geothermal Organic Rankine Cycle for combined heat and power generation," *Appl. Therm. Eng.*, vol. 30, no. 11–12, pp. 1326–1332, 2010.

[16] K. Hemmes, L. M. Kamp, A. B. H. Vernay, and G. De Werk, "A multi-source multi-product internal reforming fuel cell energy system as a stepping stone in the transition towards a more sustainable energy and transport sector," *Int. J. Hydrogen Energy*, vol. 36, no. 16, pp. 10221–10227, 2011.

[17] C. E. Cong, S. Velautham, and A. M. Darus, "Sustainable power: solar thermal driven organic Rankine cycle," in *Proceedings of the International Conferences on Recent Advances in Mechanical and Materials Engineering, Paper*, 2005, no. 91, pp. 424–429.

[18] N. Armaroli and V. Balzani, "The future of energy supply: challenges and opportunities," *Angew. Chemie Int. Ed.*, vol. 46, no. 1- 2, pp. 52–66, 2007.

[19] S. Waste, H. Recovery, and H. Losses, "8 . Waste heat recovery," pp. 173–189.

[20] L. Zhang and T. Akiyama, "How to recuperate industrial waste heat beyond time and space," *Int. J. Exergy*, vol. 6, no. 2, pp. 214–227, 2009.

[21] T. Börrnert and T. Bürki, "ABB's flexible ORC power plant," 2010.

[22] C. J. Roos, *Biomass drying and dewatering for clean heat & power*. Northwest CHP Application Center Olympia (WA), 2008.

[23] A. Mahmoudi, M. Fazli, and M. R. Morad, "A recent review of waste heat recovery by Organic Rankine Cycle," *Appl. Therm. Eng.*, no. July, 2018.

[24] J. S. Jadhao, D. G. Thombare, P. G. Student, and D. Sangali, "Review on Exhaust Gas Heat Recovery for I . C . Engine," vol. 2, no. 12, pp. 93–100, 2013.

[25] A. T. Hoang, "Waste heat recovery from diesel engines based on Organic Rankine Cycle," *Appl. Energy*, vol. 231, no. September, pp. 138–166, 2018.

[26] A. T. Hoang, "A Design and Fabrication of Heat Exchanger for Recovering Exhaust Gas Energy from Small Diesel Engine Fueled with Preheated Bio-oils," *Int. J. Appl. Eng. Res.*, vol. 13, no. 7, pp. 5538–5545, 2018.

[27] D. V. Singh and E. Pedersen, "A review of waste heat recovery technologies for maritime applications," *Energy Convers. Manag.*, vol. 111, pp. 315–328, 2016.

[28] F. Baldi and C. Gabrielii, "A feasibility analysis of waste heat recovery systems for marine applications," *Energy*, vol. 80, pp. 654–665, 2015.

[29] J. I. E. LU, "Environmental Effects of Vehicle Exhausts, Global and Local Effects: A Comparison between Gasoline and Diesel." 2011.

[30] J. Sun, J. A. Caton, and T. J. Jacobs, "Oxides of nitrogen emissions from biodiesel-fuelled diesel engines," *Prog. Energy Combust. Sci.*, vol. 36, no. 6, pp. 677–695, 2010.

[31] U. Corsmeier, M. Kohler, B. Vogel, H. Vogel, and F. Fiedler, "BAB II: a project to evaluate the accuracy of real-world traffic emissions for a motorway," *Atmos. Environ.*, vol. 39, no. 31, pp. 5627–5641, 2005.

[32] G. Magela and D. A. Cançado, “The Importance of Genetic Diversity to Manage Abiotic Stress,” no. May, 2014.
[33] M. W. Bevan, R. B. Flavell, and M.-D. Chilton, “A chimaeric antibiotic resistance gene as a selectable marker for plant cell transformation,” *Nature*, vol. 304, no. 5922, p. 184, 1983.
[34] G. M. A. Cançado, F. T. S. Nogueira, S. R. Camargo, R. D. Drummond, R. A. Jorge, and M. Menossi, “Gene expression profiling in maize roots under aluminum stress,” *Biol. Plant.*, vol. 52, no. 3, pp. 475–485, 2008.
[35] A. B. Garcia, J. D. A. Engler, S. Iyer, T. Gerats, M. Van Montagu, and A. B. Caplan, “Effects of osmoprotectants upon NaCl stress in rice,” *Plant Physiol.*, vol. 115, no. 1, pp. 159–169, 1997.
[36] K. D. Hirschi, V. D. Korenkov, N. L. Wilganowski, and G. J. Wagner, “Expression of Arabidopsis CAX2 in tobacco. Altered metal accumulation and increased manganese tolerance,” *Plant Physiol.*, vol. 124, no. 1, pp. 125–134, 2000.
[37] A. Franco and M. Vaccaro, “On the use of heat pipe principle for the exploitation of medium–low temperature geothermal resources,” *Appl. Therm. Eng.*, vol. 59, no. 1–2, pp. 189–199, 2013.
[38] D. Wei, X. Lu, Z. Lu, and J. Gu, “Performance analysis and optimization of organic Rankine cycle (ORC) for waste heat recovery,” *Energy Convers. Manag.*, vol. 48, no. 4, pp. 1113–1119, 2007.
[39] F. Vélez, J. J. Segovia, M. C. Martín, G. Antolín, F. Chejne, and A. Quijano, “A technical, economical and market review of organic Rankine cycles for the conversion of low-grade heat for power generation,” *Renew. Sustain. Energy Rev.*, vol. 16, no. 6, pp. 4175–4189, 2012.
[40] B. F. Tchanche, G. Papadakis, G. Lambrinos, and A. Frangoudakis, “Fluid selection for a low-temperature solar organic Rankine cycle,” *Appl. Therm. Eng.*, vol. 29, no. 11–12, pp. 2468–2476, 2009.
[41] J. R. Armstead and S. A. Miers, “ICEF2010-,” pp. 1–10, 2016.
[42] F. Yang *et al.*, “Performance analysis of waste heat recovery with a dual loop organic Rankine cycle (ORC) system for diesel engine under various operating conditions,” *Energy Convers. Manag.*, vol. 80, pp. 243–255, 2014.
[43] T. Wang, Y. Zhang, Z. Peng, and G. Shu, “A review of researches on thermal exhaust heat recovery with Rankine cycle,” *Renew. Sustain. energy Rev.*, vol. 15, no. 6, pp. 2862–2871, 2011.
[44] R. Law, A. Harvey, and D. Reay, “Opportunities for low-grade heat recovery in the UK food processing industry,” *Appl. Therm. Eng.*, vol. 53, no. 2, pp. 188–196, 2013.
[45] B. Ye, J. Liu, X. Xu, G. Chen, and J. Zheng, “A new open absorption heat pump for latent heat recovery from moist gas,” *Energy Convers. Manag.*, vol. 94, pp. 438–446, 2015.
[46] A. M. Hamed, W. R. A. El Rahman, and S. H. El-Emam, “Experimental study of the transient adsorption/desorption characteristics of silica gel particles in fluidized bed,” *Energy*, vol. 35, no. 6, pp. 2468–2483, 2010.
[47] F. Jeremias, D. Fröhlich, C. Janiak, and S. K. Henninger, “Advancement of sorption-based heat transformation by a metal coating of highly-stable, hydrophilic aluminium fumarate MOF,” *RSC Adv.*, vol. 4, no. 46, pp. 24073–24082, 2014.
[48] S. Kwankoameng, “Promvonge, Investigation on a Free piston stirling Engine and Pneumatic Output,” in *TSME International conference on Mechanical Engineering*, 2010, pp. 20–22.
[49] X.-J. Hou and D.-L. Gao, “Analysis of exhaust gas waste heat recovery and pollution processing for Z12V190 diesel engine,” *Res. J. Appl. Sci. Eng. Technol.*, vol. 4, no. 11, pp. 1604–1611, 2012.
[50] J. G. Haidar and J. I. Ghojel, “Waste heat recovery from the exhaust of low-power diesel engine using thermoelectric generators,” in *Thermoelectrics, 2001. Proceedings ICT 2001. XX International Conference on*, 2001, pp. 413–418.
[51] M. Talbi and B. Agnew, “Energy recovery from diesel engine exhaust gases for performance enhancement and air conditioning,” *Appl. Therm. Eng.*, vol. 22, no. 6, pp. 693–702, 2002.
[52] D. Wu and R. Wang, “Combined cooling, heating and power: a review,” *Prog. energy Combust. Sci.*, vol. 32, no. 5–6, pp. 459–495, 2006.
[53] V. Pandiyarajan, M. C. Pandian, E. Malan, R. Velraj, and R. V Seeniraj, “Experimental investigation on heat recovery from diesel engine exhaust using finned shell and tube heat exchanger and thermal storage system,” *Appl. Energy*, vol. 88, no. 1, pp. 77–87, 2011.
[54] J. Stubbles, “Energy use in the US steel industry: a historical perspective and future opportunities,” Energetics, Inc., Columbia, MD (US), 2000.
[55] N. Margolis and L. Sousa, “Energy and environmental profile of the US iron and steel industry,” in *1997 ACEEE summer study on energy efficiency in industry: Proceedings, refereed papers, and summary monographs*, 1997.
[56] M. Hatazawa, H. Sugita, T. Ogawa, and Y. Seo, “Performance of a Thermoacoustic Sound Wave Generator driven with Waste Heat of Automobile Gasoline Engine.,” *Nippon Kikai Gakkai Ronbunshu B Hen(Transactions Japan Soc. Mech. Eng. Part B)(Japan)*, vol. 16, no. 1, pp. 292–299, 2004.
[57] H. Teng, G. Regner, and C. Cowland, “Waste heat recovery of heavy-duty diesel engines by organic Rankine cycle part I: hybrid energy system of diesel and Rankine engines,” SAE Technical Paper, 2007.
[58] X. Hu, J. Jiang, B. Egardt, and D. Cao, “Advanced Power-Source Integration in Hybrid Electric Vehicles: Multicriteria Optimization Approach.,” *IEEE Trans. Ind. Electron.*, vol. 62, no. 12, pp. 7847–7858, 2015.
[59] J. Fu, J. Liu, R. Feng, Y. Yang, L. Wang, and Y. Wang, “Energy and exergy analysis on gasoline engine based on mapping characteristics experiment,” *Appl. Energy*, vol. 102, pp. 622–630, 2013.
[60] T. Park, H. Teng, G. L. Hunter, B. van der Velde, and J. Klaver, “A rankine cycle system for recovering waste heat from hd diesel engines-experimental results,” SAE Technical Paper, 2011.