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Review

Energy Recovery in Air Conditioning Systems: Comprehensive Review, Classifications, Critical Analysis, and Potential Recommendations

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Citation: Aridi, R.; Faraj, J.; Ali, S.; Gad El-Rab, M.; Lemenand, T.; Khaled, M. Energy Recovery in Air Conditioning Systems: Comprehensive Review, Classifications, Critical Analysis, and Potential Recommendations. *Energies* **2021**, *14*, 5869. https://doi.org/10.3390/en14185869

Academic Editor: Fabrizio Ascione

Received: 28 June 2021
Accepted: 10 September 2021
Published: 16 September 2021

Abstract: Energy has become the backbone of humanities daily activities. Heating, ventilating, and air conditioning systems (HVAC), which consume around 39% of energy in the residential sector, have turned into an essential constituent for providing fresh air, especially after COVD-19, not only in hospitals but also in any simple construction. Thus, decreasing this percentage or recovering part of the energy lost is an essential issue in today's energy management scenarios. In this context, the present manuscript suggests a comprehensive review, classifications, critical analysis, and potential recommendations for energy recovery in air conditioning systems. It classifies energy recovery into two main categories: using lost energy for external uses, such as heating domestic water, or with other devices; and using lost energy for internal uses, such as the hot airflow which can be reused again for increasing efficiency of HVAC. In addition, this paper presents a summary of previous research and undertakes a review of the devices used for recovering energy. Furthermore, this review identifies superior devices in terms of climate and weather conditions. These objectives are accomplished by investigating around 190 published papers to conclude that energy recovery devices show a considerable effect on energy consumption in HVAC, mainly the heat pipe, fixed plate, and rotary wheel devices.

Keywords: energy management; heat recovery; review; HVAC; heat exchanger; classification

1. Introduction

Energy has always been an essential requirement for the existence of all living organisms, as it is essential for growth, movement, maintenance, and creating work. Nowadays, with the rise of technological evolution and the rapid development of applications that need work, the human lifestyle has become more and more energy-dependent, especially in developing urban cities [1]. For instance, India has witnessed a rapid increase in energy consumption of around 16 times during the last six decades [2]. The International Energy Agency (IEA) predicted that by 2050, global energy consumption will increase by 50% [3,4], and buildings will account for the largest source of emissions due to the rapid growth in industries. Likewise, the growing demand for energy is likely to be more intense in growing states due to the growth of new buildings [5].

Based on the first law of thermodynamics, rising energy demand, global warming, energy shortage, and the necessity of providing fresh air, particularly after COVID 19, makes reducing energy loss a significant challenge [6]. The reduction of energy loss leads to developing a new strategy that arranges the use of energy, and, most importantly, ensures that power, which would otherwise have been lost, is made use of and provides benefits [7]. This strategy is called recovering lost energy [8].

Energy management has been comprehensively studied for almost 40 years. Recently, it has emerged as one of the most challenging issues and popular research topics, where its importance is equal to that of finding a new source of energy [9]. This is because the percentage of lost energy sometimes surpasses 60% [10], and, in addition, 72% of all-inclusive primary energy consumption is wasted during energy conversion [11]. Thus, recovering part of this loss is very beneficial. Lately, in residential and commercial buildings, energy consumption has escalated firmly. The main reason for this was due to the HVAC systems in those buildings [12,13]. HVAC accounts for almost 50 to 82% of the energy, of which 40% of the world's overall final energy is spent in buildings [14]. While in non-industrial buildings, HVAC is responsible for around 18–35% of the total energy consumption [15], in commercial buildings HVAC accounts for approximately 30% of energy consumption [16,17]. In some countries, like Sweden, HVAC is frequently used to reduce radon problems, which makes heat recovery a vital requirement to reduce energy consumption [18].

The high-energy consumption of HVAC contributes to Energy Management System (EMS) becoming a fundamental issue for improving efficiency and providing significant energy savings in construction, particularly in relation to hospitals due to their utility for removing contaminated air [19]. Nowadays, EMS has become a primary concern in building projects, with many types of research completed on the BEMS (Building Energy Management System) over the last decade [20]. In addition, statistical results indicate that the effect of savings of BEMS raises from 11.39% to 16.22% yearly. This is due to the effort of continuous research which has led to improving this area [21]. Despite the improvements and high interest in research in BEMS, it has been estimated that 90% of HVAC systems do not operate optimally [21]. This demonstrates the necessity for developing systems to be more effective and, above all, for systems to operate at a lower cost in order to ensure their rapid spread [22].

2. Theoretical Background

During the last decade, HVAC systems have been used, not just for luxury purposes, but in situations where the primary function of HVAC is to provide fresh air circulation, and healthy and easy interior situations for occupants with the least non-renewable energy [23]. These systems have become more and more common, which makes recovering energy in HVAC nowadays a pressing issue.

The HVAC systems studied in this paper follow the Vapor Compression Refrigeration cycle (VCR), as shown in Figure 1. cold low-pressure vapor passes into the compressor and is compressed isentropically into high-pressure vapor, compression increases the temperature (from Tc to Th) and pressure of refrigerant (from Pl to Ph), as shown in Figure 2, the Clapeyron or P-V (Pressure-Volume) diagram and the entropy or T-S (Temperature-Entropy) diagram [24]. The gas then flows to the condenser; gas is condensed at constant pressure (Ph) to liquid and released its heat to the outside air (Qh) [25]. For this reason, if you place your hand directly above the condenser, you will feel hot air upcoming. This heat will be lost energy unless it is captured and used again. The high-pressure liquid is then transported to the expansion valve, which lowers the liquid's pressure (from Ph to Pl) and the liquid's temperature (from Th to Tc) at constant enthalpy via the throttling process. Refrigerant exits from the expansion valve as liquid-vapor mixture transport to the evaporator, where it is completely evaporated by absorbing the latent heat of vaporization (Ql). The change of state from a mixture to a gas within the evaporator requires heat absorption from the cold space. This process occurs at constant low pressure (Pl) to gas at the evaporator exit.

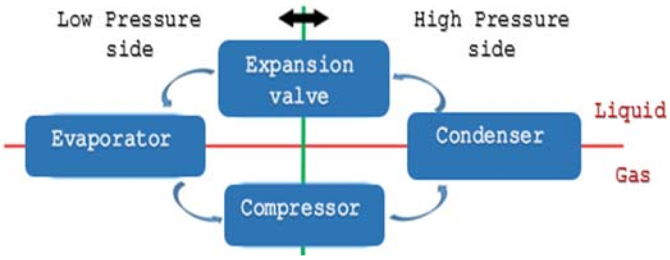


Figure 1. Refrigeration cycle basic working process [26].

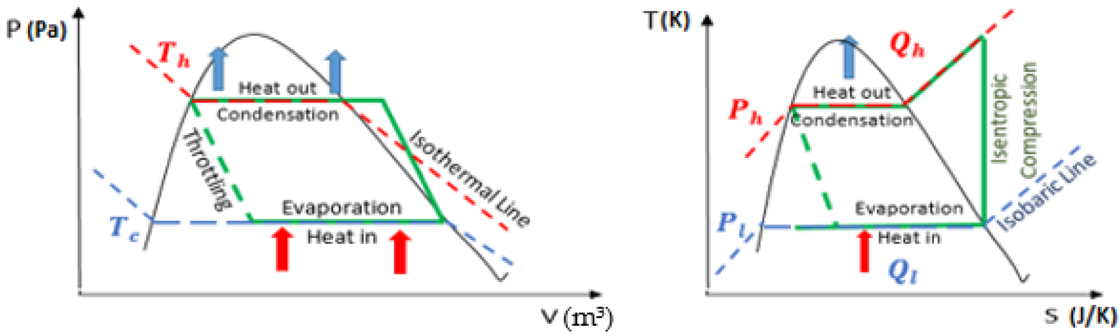


Figure 2. Change of state on P-V [27] and T-S [28] diagrams.

The high usage of HVAC, along with the tendency of today's world to employ energy management where heat recovery is one of its main axes, and the significant heat loss in the condenser have attracted the attention of the scientists to search for well-designed and efficient systems that benefit from heat loss [29]. In other words, capturing lost heat and transforming it into useful energy is called heat recovery.

Recently, new technology has been introduced to cooling systems as an alternative for refrigeration, air conditioning, heat pumping, or power generation applications. This technology is a solid-state physics and known as a caloric energy conversion [30,31]. The caloric effect is divided into four categories: barocaloric, electrocaloric, magnetocaloric, and elastocaloric. Generally, the highest progress has been observed in the magnetocalorics domain, where it has proven to be efficient and ecofriendly [32]. On the other side, considerable efforts have been undertaken in the elastocaloric refrigeration and electrocaloric refrigeration fields [33]. Caloric cooling and air conditioning have been studied intensively, where caloric cooling has shown to be much more environmentally friendly than the vapor compression technology due to significant efficiency [34].

3. Historical Notes

As mentioned in the introduction, most of the community concerns are directed towards reducing energy consumption, whereas Europe has found that the only way to reduce total energy demand is by minimizing the energy demand of buildings [35]. This can be achieved in two ways: either by improving the efficiency of HVAC in buildings or by capturing the lost energy for useful purposes. However, if both ways are correlated, capturing lost heat will result in improving the efficiency. Thus, energy recovery systems were developed to achieve minimum energy consumption [36,37]. In this paper, two types of highly remarkable recovery systems, which used either energy recovery systems or heat recovery systems, were investigated:

1. Energy recovery systems have highly remarkable recovery systems for improving the efficiency of HVAC because they simultaneously recover latent heat, which is

the heat caused by changes in phase, and sensible heat, which is the heat-related to changes in temperature where no change in phase occurs [38]. Enthalpy wheels and fixed plates with permeable materials are the types of energy recovery devices used in these systems [39–41].

2. Heat recovery systems are unable to recover latent heat since they only recover sensible heat, although they have a significant effect on the HVAC system. The heat pipe, thermosiphon, runaround coil, and oscillating heat pipes are the types of heat recovery devices discussed in this paper [42].

3.1. Energy Recovery Systems

Energy recovery systems, also called total energy recovery, transfer both the latent and sensible heat. These systems have the advantage of increasing the efficiency and competency of the enthalpy devices in energy recovery. In winter, it is found that enthalpy devices recover over 25% of energy. Enthalpy or rotary wheels transfer both latent and sensible heat. They are frequently used in HVAC due to their high efficiency, humidity, and frost control; however, their design causes a high-pressure drop in the airstream, and as a result high-powered fans are added in order to deliver proper air ventilation with a low-pressure drop [43]. Fixed plate heat exchangers (FPHE) has been developed for over 40 years and have become the most utilized type of heat recovery system. To date, cross-counter flow, which is a combination of cross and counter flow, is the most commonly used type (around 89%) [44,45]. Over the last 20 years, many tests have been completed on new designs of FPHE (L shape and Z shape) which show major results in terms of energy savings [46,47].

3.2. Heat Recovery Systems

Since 1970, research on heat pipe heat exchangers (HPHE) for HVAC has been done in industries located mainly in Britain, North America, and Australia [48–50]. Since 2010, over 3600 papers have been published concerning all types of HPHE in various applications. It was found that heat pipes are suitable for electronic devices, domestic and industrial applications. In addition, they can be used in surgery rooms in hospitals [51,52]. Lately, researchers have shown strong interest in heat pipe technology for heat recovery due to its excellent features and high efficiency [53–56]. In HVAC applications, HPHEs are highly recommended and they compete efficiently with other heat recovery systems, such as run-around coils and heat recovery wheels [49,57,58].

A run-around coil is a reliable system for recovering heat. London and Kays [59] discovered that this system achieves the best performance when the coupling liquid and air have equal heat capacity rates under constant number of transfer units (NTU) conditions [60]. Run-around coil systems are used in hospitals and other industries [61].

Thermosiphon (THE) is a type of heat pipe that works on gravity [62]. Its natural phenomenon has encouraged researchers, such as Azad and Geoola [63], Lee and Bedrossian [64], and others, to do theoretical calculations on its thermal performance. THE has a positive effect on HVAC systems, as is observed in the investigated papers [65]. However, it is most commonly used in other applications, such as solar heating [66,67].

Pulsating heat pipe (PHP) or oscillating heat pipe (OHP) is one of the newest evolutions in heat pipe (HP) technology. In the 1990s, Akachi [68] proposed and patented PHP, and PHP's working process and schematic are summarized in Table 1. There are over 340 published papers about PHP [69]. It is measured as one of the promising cooling technologies, especially for electronics, due to its high thermal performance, simple design, quick response to high heat load, and low cost [70]. In HVAC, PHP is a candidate for heat recovery as it does not require any moving parts and inline air streams. In addition, it has a lower cost than other devices [71].

Loop heat pipe (LHP) is a system which was first developed in 1972 [72]. LHP can transfer significant heat flow passively over long distances compared to other two-phase passive devices. Gerasimov and Maydanik [73] proved that water is the best working fluid in LHP.

Phase change material (PCM) is a method of thermal storage that uses sensible heat, latent heat, and thermochemical reactions to absorb and release heat [74]. Recently, PCM has acquired high interest among researchers, and a considerable amount of research has demonstrated the potential of PCMs [75]. Researchers have suggested that PCMs may have utility for commercial use [76]. In addition, researchers have studied hybrid systems, in which PCM is combined with other systems, such as Earth to air heat exchangers and solar energy [77,78]. PCMs have been shown to have a significant effect on HVAC consumption, and a large amount of research has been directed towards evaluating PCM for cooling/heating applications [79,80].

Geothermal systems can contribute to significant savings of the energy demands of buildings' HVAC systems, making this type of system a very appealing solution. Geothermal energy is an old method for producing energy and, combined with ventilation systems, it minimizes the load by precooling the supply air by around 25–75% and saving 30–70% of the energy demand and electrical energy consumption for the heating/cooling of buildings' HVAC systems in central and northern Europe [81]. Water to earth heat exchangers and earth-to-air heat exchangers (EAHEs) are two types of geothermal energy. EAHEs combined with other systems show considerable results of reducing energy consumption [82–84]. A statistical study was done on the satisfaction of building owners with ground heat pumps (GHP) and the results show that more than 85% of owners would recommend this system to others [85]. Geothermal systems have a positive effect on HVAC because they reduce the consumption of energy used in the heating/cooling process [85].

Table 1 displays detailed information about the working process, advantages, properties, disadvantages, and main parameters of each device [86,87].

Among the energy recovery devices mentioned in Table 3, it is noticed that:

1. RW and FPHE have the highest efficiency, due to their capacity to transfer both sensible and latent heat, which increases their efficiency among other systems. Thus, RW is highly recommended. However, there are some limitations, such as the need for regular maintenance in addition to contamination, and this is why this system is not used in hospitals unless it is equipped with a filtration system.
2. FPHE is a good choice, especially because it has no moving parts. However, frosting problems, high-pressure drops, and condensation build-up should be taken into consideration.
3. PCM provides a great opportunity for energy storage.
4. Combining PCM with other systems is recommended because PCM offers the opportunity for storing energy, and adding PCM slows the temperature rise and guarantees safe operation of the devices in the long term.

Table 1. Summary of energy and heat recovery systems.

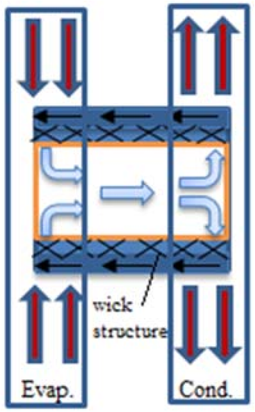
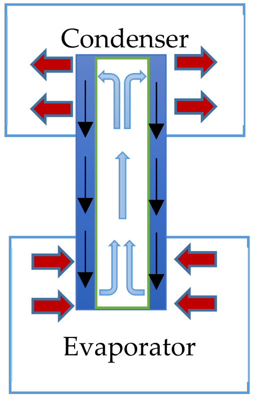
Devices	Working Process	Advantages	Disadvantage	Parameters
Heat Pipe 	In the evaporator section, liquid in the pipe evaporates due to the temperature which is above the boiling point of the liquid; vapor then goes through an adiabatic section in a vapor form; it then reaches condenser section which returns into liquid due to the temperature which is below the dew point of the vapor; the liquid goes back to the evaporator section through the wick structure.	• Sensible (45–65%) • Counter flow • Parallel flow • No cross-contamination • No moving parts [88] • High reliability • Does not require any external power for its operation [89] • No mechanical or electrical input	• Transfers only sensible energy • Difficulty in choosing the best working fluid • Overheating [90]	Performance of HP is affected by the operating conditions and the design of the HP [91]: • Inlet temperature • Inlet flow rate • Wick structure • Working fluid • Dimensions of pipe geometry • Inclination
Thermosiphon 	The process in thermosiphon is the same as in the heat pipe, but with no wick structure. Liquid returns back to the evaporator section due to gravity; for this reason, thermosiphon is called gravity pipe or wickless heat pipe [92].	• Sensible (40–60%) • Counter-flow • Parallel-flow • No mechanical or electrical input Easy to maintain	• Transfers only sensible energy • Water can be a working fluid, but its high pour point makes it unsuitable for applications with low-temperature [93]	Efficiency is affected by the design of the thermosiphon: • Working fluid • Dimensions of pipe geometry • Inclination [94]

Table 1. *Cont.*

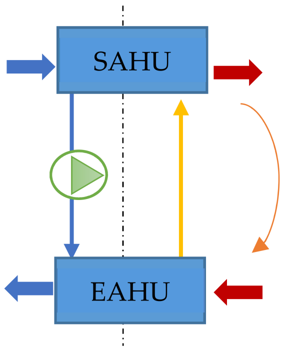
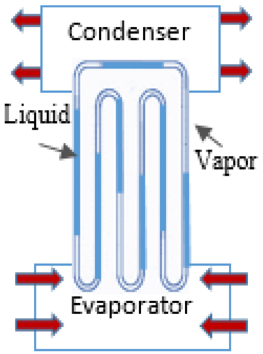
Devices	Working Process	Advantages	Disadvantage	Parameters
Runaround  out in	This system consists of two or more multi-row finned tube coils linked to each other by a pump that runs the cycle. Outside air enters the supply air-handling unit (SAHU), in heating mode; pipework transfers the heat from the exhaust air-handling unit (EAHU) through the circulating fluid to the SAHU. Return air enters the EAHU and transmits its heat to the pipework then circulating fluid. Hence, heat is transmitted from the EA stream over the pipework coil to the flowing fluid, and then from the fluid over the pipework coil to the SA stream [95].	• Sensible (55–65%) • Counter flow • Parallel flow • No cross-contamination • Low-pressure drop • No moving parts [96] • Highly recommended in laboratories due to its ability to eliminate cross-contamination [97] • Supply and exhaust duct does not have to located side by side	• Requires pump to move the fluid • Low efficiency • Freezing problems [96] • Sensible heat • Lower efficiency compared to other devices • Requires electrical power for running the pump [60]	Factors that affect runaround coil [98]: • Airflow • Glycol concentration • The flow rate of the brine • If permeable material is added, then the runaround coil becomes a total energy recovery device and is called runaround membrane energy exchanger [41] (RAMEE)
OHP [70] 	PHP is evacuated, and then slightly filled by working fluid. At the evaporator end, the tube is exposed to a high temperature, which leads to evaporating the working fluid, which increases the vapor pressure, and expansion of the bubbles in this zone. The growing bubbles push the liquid to the condenser, which is at a low temperature. The low temperature causes condensation and a further increase in pressure difference. However, because the tubes are linked, liquid and vapor bubble motion at the evaporator section push the liquid at the condenser back to the evaporator section.	• Sensible (52%) in case R134a • Counter-flow • Parallel-flow • Low-pressure drop [99] • Passive, does not require input power [100] • Low cost [70] • R134a PHP has better thermal performance for specifically low heat application devices. • Quick response to the high heat load	• Low efficiency • Effect of inclination angle depends on the properties of working fluid used in CLPHP [101] • A low-pressure fluid temperature near the freezing point borders the PHP process [70]	Operating limitations for PHP such as [102]: • Number of turns • Filling ratio • Aspect ratio • Working fluid • Inclination angle • Length of adiabatic section • The internal diameter of the tube. • Operating temperature [103]

Table 1. *Cont.*

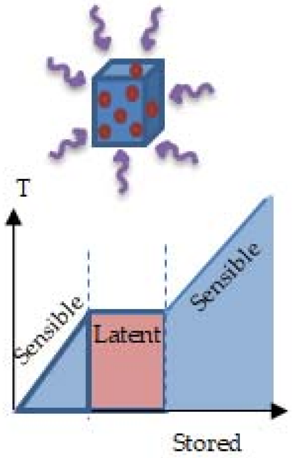
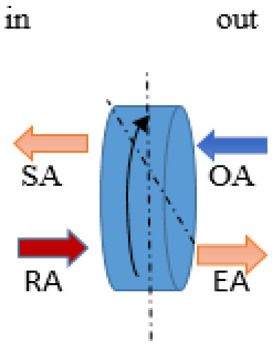
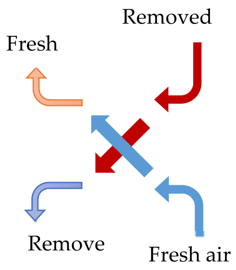
Devices	Working Process	Advantages	Disadvantage	Parameters
PCM 	PCM is a material with high thermal energy storage (TES) density and high power capacity for charging and discharging. This material melts and solidifies at a specific temperature. When the material phase is changed from liquid to solid and vice versa, heat is captured or released. This makes PCM latent heat storage [75].	TES by [104]: (i) Sensible heat; (ii) Latent heat; (iii) Thermochemical reaction • No moving parts • Long life cycle • No pressure loss • Passive • No cross-contamination	• Difficulty in choosing material • Requires high thermal conductivity [90,105] to guarantee high-energy storage density and high power capacity for charging and discharging	Requirements of PCM [106]: • Thermo-physical • Kinetic • Chemical • Another (economical, • environmental) • The challenge is to augment the latent heat storage capacity [107]
Rotary Enthalpy Wheel [108] 	Rotary Wheel (RW) exchanges heat and humidity from one air stream to another. The wheel rotates at a constant speed, the channel is subjected to two counter-flow arrangement streams. Outside Air (OA) enters the wheel, heat is transferred from the lower section to the Supply Air (SA), Return Air (RA) enters the lower section and transmits the heat to the wheel and leaves as Exhaust Air (EA) with lower temperature. In cooling mode, the coming air is pre-cooled and dehumidified. Moisture is given to the wheel, containing a hygroscopic substance or coated with desiccant to absorb humidity.	• Sensible (50–80%) [109] • Total (55–85%) • Transfers latent + sensible energy • Counter flow • Parallel flow • THumidity control • High efficiency • Frost control means no freezing problems [96,110] • Low-pressure drop [108] • No working fluid is required	• Cross-contamination [111] • Regular maintenance • Moving parts [96] • Airstreams must be adjacent to each other relatively • Requires filtration to keep the air stream clean [43] • The calculation is critical [112,113]	Enthalpy wheel depends upon [108]: • Wheel length • Channel base • Height • Thickness • Revolution speed • Geometrical parameters: wheel size • Desiccant material • Boundary conditions: face velocity [114]

Table 1. *Cont.*

Devices	Working Process	Advantages	Disadvantage	Parameters
Fixed Plate 	Fixed Plate Heat Exchanger (FPHE) contains a box with a set of parallel metal or plastic plates which allows the removed air to pass over the incoming air, transmitting the energy and warming it up. The two air streams are parted by the plates and do not mix. Liquid desiccant dehumidification system (LDDS) can be added to the FPHE to recover latent and sensible energy.	• Sensible (50–80%) • Total (55–85%) • Counter flow • Parallel flow • Crossflow • No moving parts [96] • Humidity control	• Freezing problems in very cold climates • Condensation build-up [115] • High-pressure loss	Parameters that affect Fixed plate [116]: • Type of flow • Number of channels • Working fluid

4. Research Objectives

This review investigated over 184 published papers, which were published between 1992 and 2020. The investigated papers are classified into the categories shown in Figure 3, where RW, fixed plate, and HPHE share the highest percentage among the devices. Thirty-five per cent of the papers were review papers, which means that heat recovery devices are highly studied and a remarkable portion of the research sector is dedicated to researching them.

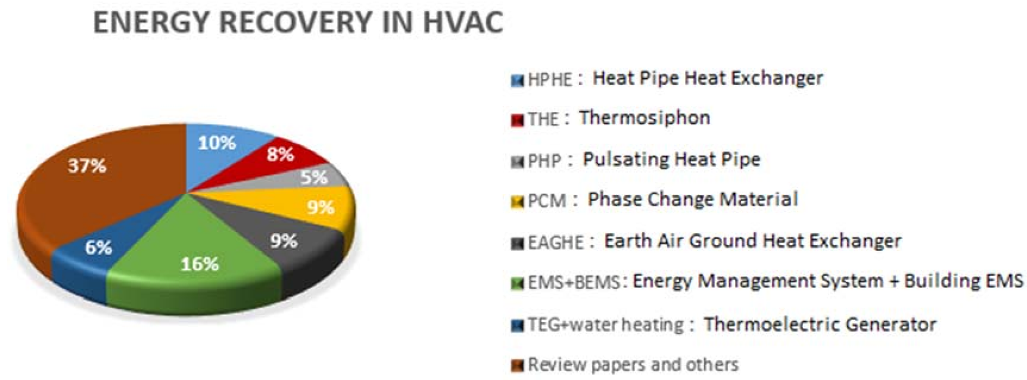


Figure 3. Investigated papers according to the topic.

Figure 4 shows the number of papers, organized according to years in which they were published, that were investigated from 1992 to 2018. Each column in the chart represents the number of studied papers published every three consecutive years. The results demonstrate that energy recovery in HVAC is increasing year after year, and, in particular, there has been a great increase since 2012, with ten times more articles published than in the fifteen years before. This fact is a sufficient motivation to study more about this topic.

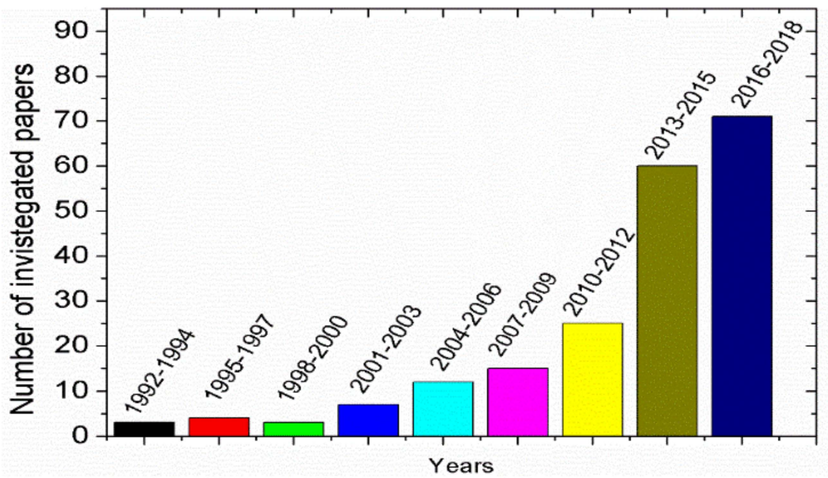


Figure 4. Investigated papers according to years.

Among the main review papers, it is noticed that all the review papers have studied the effectiveness of waste heat recovery (WHR) methods in diverse fields. Jouhara et al. [117] reviewed WHR methods in industrial processes from diverse approaches in order to obtain the optimum efficiency for a system. Miró et al. [118] executed a review on WHR in industries for thermal energy storage (TES) where TES technologies were applied in order to capture industrial waste heat (IWH). Nazari et al. [119] presented a review on PHPs through solar to cryogenic applications. Hoang [120] discussed the WHR from diesel engines built on the organic Rankine cycle. Huang et al. [121] carried out a review of WHR for district heating.

Some review papers studied heat recovery, energy-saving, and management in HVAC, such as Abdel-Salam et al. [122], who reviewed the estimated energy, economic benefits, and environmental effect for liquid-to-air membrane energy exchangers in HVAC. Romdhane S. et al. [123] conducted a review on using PCMs in passive buildings. However, Shehadi M. [124] presented a review on humidity control in buildings. She et al. [125] completed a comprehensive review of energy-efficient and -economic technologies for air conditioning with VCR. Chua [126] reviewed technologies and approaches for attaining a better and more energy-efficient air conditioning system (AC).

From the above-mentioned review papers, it is noticed that all of them recommended the WHR in all fields and they agreed on the necessity of studying WHR in later research. However, none of them completed a comparative review of the literature on heat recovery (HR) devices according to their pros and cons and the effect of climate on the efficiency of the WHR system.

Accordingly, this review aims to present the main methods for energy management in HVAC, in order to identify the most effective device. This is not only about HR, but is about choosing the optimum HR. This will be done by defining the devices and discussing their effects from already-published papers. From this, we will draw out a conclusion. Throughout the research, it is noticed that the climate is an important factor that most of the research papers did not take into consideration, and thus a section related to the climate effect is added. The novelty of this research is:

1. Providing a table about the working process and the pros and cons of each device;
2. Classifying the papers using a new methodology which is:
    a. saved energy is used for external systems
    b. saved energy is used in the HVAC system equipped with the energy recovery device;
3. Bringing conclusions on the reviewed papers and finding the best device based on the conclusion of each section.

5. Energy Recovery Systems

The chart, seen in Figure 5, divided energy management in HVAC into the following categories:

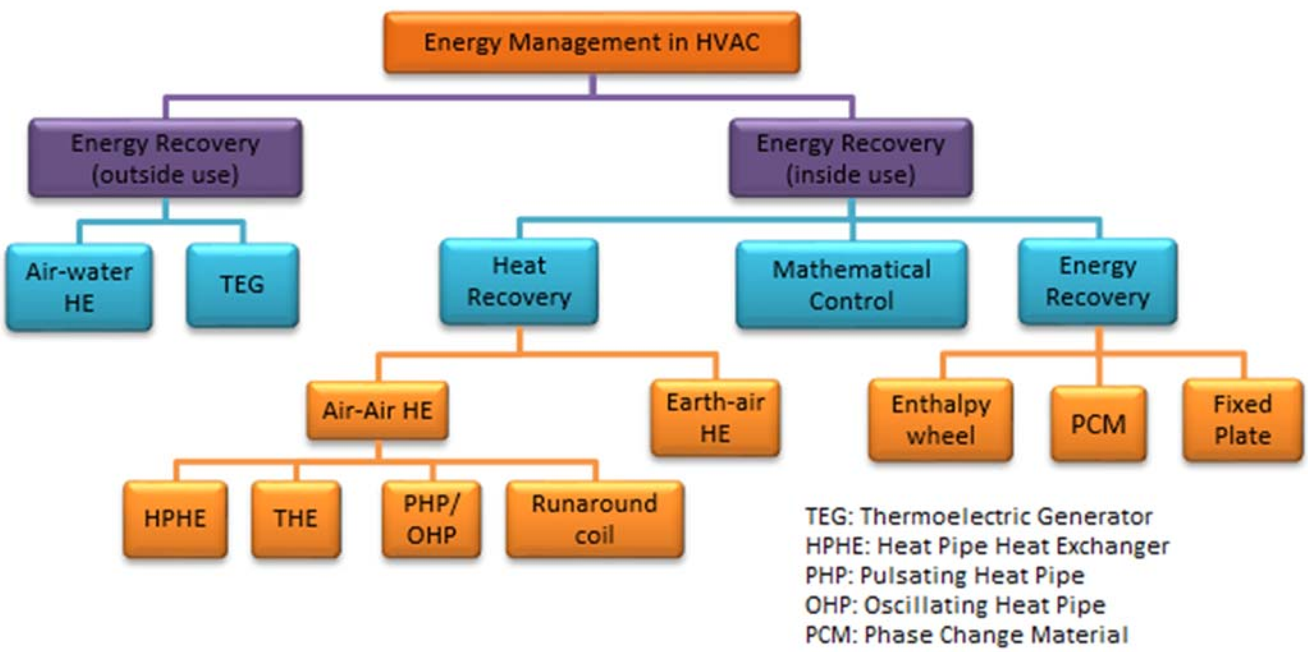


Figure 5. Energy management classified into categories.

1. Outside use, which means that the lost heat that is captured is used for external benefits. In other words, the saved energy is used for external systems, like generating electricity, in our case.
2. TEG was mainly used for heating water by air-water HE [127]. Using the lost energy for outside use is not only necessary for the heat recovery concept, but also enhances the efficiency of the HVAC system [128].
3. Inside use, which means air saved energy is used in the HVAC system that is equipped with the energy recovery device in order to improve the efficiency and heat/cool the supply. This section is divided into:
   i. Heat Recovery: energy transferred in this case is just sensible heat; this energy can be transferred by different types of heat devices that will be discussed in detail in the upcoming sections.
   ii. Mathematical Control which is related to the controlling and predicting system, such as a smart system, with which a positive impact on saving energy has been revealed.
   iii. Energy Recovery or total energy recovery, which is described as total because it transfers both the latent and sensible heat; this advantage increases the efficiency and competency of the enthalpy devices in energy recovery.

5.1. Energy Recovery for Outside Use

In the following section, the saved energy is used for external systems, such as heating domestic water, or using the captured lost heat to generate electricity. This process shows remarkable results, as it is considered a free source of energy.

5.1.1. Air-Water HE

The concept of heating domestic water from the recovered lost heat is achieved by capturing the rejected heat from the condenser by using a heat exchanger, where the cold water is heated by the warm flow that is produced from the condenser. Table 2 summarizes the methodology and results of the main investigated papers that were related to energy recovery using an air-water heat exchanger.

Table 2. Summary of the investigated papers related to heating water for domestic use from the lost heat.

Authors	Methodology	Result
Ramadan et al., 2015 [29]	Counter-flow concentric tube heat exchanger at the condenser is used. Hot air upcoming from the condenser warmth up the water inside the tube.	The outlet temperature of the water rises from 304 K to 347 K when the cooling load rises from 3.52 to 63.31 kW.
Stalin et al., 2012 [129]	One inlet and one outlet tank are used for water flow, a pump is used for circulating water from tank to the water-cooled condenser, and this procedure lasts until the desired temperature is reached.	2.71 h are spent to raise the temperature of 350 L of water from 20 °C to 50 °C with a payback period of 6 months.
Lokapure et al., 2012 [130]	A refrigerant to water HE is placed between the compressor and the condenser. Water is propagated through one side of HE, and hot refrigerant gas from the compressor is transmitted over the other side. Heat is then transmitted from the hot refrigerant to the water.	Inlet water of 33 °C becomes 43 °C outlet water, the heat in the water is increased by 30.3%.The COP of the system is raised by 13.66% after using the HE with the air conditioner.

From Table 2, it can be observed that the results obtained in the air-water HE system were considerable, and it is worthwhile heating domestic water from the lost heat. This system is efficient due to:

1. The high heat capacity of water which allows it to conduct heat at a rate which is about 25 times faster than air. Therefore, water is considered to be more efficient than air.

2. The increase of the outlet temperature of the water as the load increases. This indicates that applying air to the water heat exchanger in buildings that have a high use of HVAC is very efficient.

5.1.2. Thermoelectric Generator TEG

This system is also called a Seebeck generator. It is a solid-state device, which transforms the difference of temperature on its opposite sides into electricity following the phenomenon of the Seebeck effect. TEG is a considerable technology that recovers the lost heat in various applications [131]. Table 3 represents the methodology and results of the main investigated papers that were related to energy recovery using a Thermoelectric Generator TEG.

Table 3. Summary of the investigated papers related to generating electricity from the lost heat.

Authors	Methodology	Result
Ramadan et al., 2017 [10]	Placing a flat plate TEG of 40 × 40 cm^2 horizontally where the air of the condenser is considered the heat source and the exhaust airflow is used as a cooler.	At a load of 100 kW, TEG was able to generate 90 W of electrical power
Kumar et al., 2015 [132]	TEG in a vertical direction facing the condenser from a side and the outside air from another side.	30% of waste heat is recovered by the condenser side.
Damanhuri et al., 2018 [133]	Six Peltier were arranged between Cu plates. 3 cases were monitor depended on the temperature difference of the cooling coil and condenser temperature.	A difference temperature of 9–10 °C and the load of 1.5 hp generated 1.61 V.
Trinidad et al., 2015 [134]	Experimental studies on a TEG array design were held to study the energy consumption of this device. The hot air and cold air entered a square channel with a wall separating them. The hot air entered the bottom section and the cold air entered the top section. The hot side had 1850W maximum capacity while the electrical loads ranged from 390 to 760 Ω.	Results show that the application of the electrical load has a high effect on the gradient temperature between the outlet and inlet of the hot air. On the other hand, the numerical analysis indicates that this system behaves differently compared to that of a conventional counter flow heat exchanger.

As a conclusion drawn from Table 3, it is observed that:

1. TEG has low efficiency due to its design.
2. However, in some cases, it produces significant results due to higher gradient temperature.
3. When the temperature difference increases, the value of generating electricity increases.
4. TEG shows a positive effect in HVAC but some improvements should be made in order to increase its efficiency.

5.2. Energy Recovery for Inside Use

In this section, employing saved energy for internal use through previous published paper is discussed.

5.2.1. Heat Recovery

Air-Air HE

A method of capturing heat loss from hot air enclosures, the air-air HE is a type of system designed for exchanging heat. This, however, occurs in a passive way, whereby the design enhances the heat transfer. Table 4 shows the methodology and results of the papers that studied air-air energy recovery devices (HPHE, THE and PHP/OHP, Run around coil) [135].

Table 4. Summary of investigated papers related to air-air energy recovery devices.

	Authors	Methodology	Results
HPHE	Yau et al., 2015 [136]	HPHE with 2, 4, 6, and 8 numbers of rows were tested. The coil face velocity was 2 m/s and the return air temperature was at 24 °C. The results of the HPHE were recorded for one week.	The results showed that a total amount of 2885 kWh can be saved yearly; this amount can be raised to 7023 kWh per year if eight-rows HPHX was used. The volumetric flow rate is increased, and a higher amount of energy recovery is expected as the face velocity is increased, but this results in a higher-pressure drop in the coil, which decreases the effectiveness.
	Firouzfar et al., 2011 [137]	HPHE is placed in two streams of fresh air (32–40 °C) and return air (26 °C) in AC. Ratios of mass flow rates 1, 1.5, and 2.3 were tested to observe heat transfer and change in the temperature of fresh air.	The heat transfer and effectiveness rate of both the condenser and evaporator sections were raised to 48%.
	Sanaye et al., 2014 [138]	A HPHE, made from copper with water as working fluid and wick structure of 10 sheets of the 100-mesh bronze screen, is placed horizontally to recover heat from the exhaust air, in heating mode, and transfers it to the cold inlet fresh air; whereas, in cooling mode, it pre-cools the hot inlet fresh air.	The optimal point is with the effectiveness of 0.774 and a total cost of $1474, with a return period of about 2.5 years.
	Ahmadzadehtalatapeh, 2013 [139]	TRNSYS software was used to study the hourly influence of HPHE on HVAC. Eight-row HPHE was added with an average of 22.4 °C indoor temperature and 54.5% indoor air relative humidity (RH).	The results revealed that by reheating and pre-cooling, a total amount of 236.9 MWh energy could be saved yearly. This amount results in saving $24,572 annually.
THE	Firouzfar et al., 2011 [137]	3-row THE was investigated which consists of 48 wickless heat pipes organized in 6-row.	The cooling capability for the system was improved by 20 to 32.7%. In an evaporator and condenser, the equal value of air face velocities should be avoided.
	Guoyuan Ma et al., 2013 [140]	THE is used in an AC system for outlet air heat recovery in a shopping mall in Beijing.	The results show that the seasonal temp effectiveness (STE) is 66.08% in winter and 55.43% in summer.
	Jouhara et al., 2018 [92]	Wraparound loop heat pipes (WLHP), are thermosiphons which are used commercially. It depends on gravity to return the condensed liquid. HP filled with R134a and water were investigated at two different air velocities: 2.56 m/s and 2.6 m/s.	The results show that the effectiveness declines with the rise of air velocity. The effectiveness of the HP filled with water varied from 20.14% to 19.61%, whereas it varied from 13.76% to 13.25% when it is filled with R134a. This means water HP was 46 to 48%, which is greater than R134a.
	Vanyasreet al., 2017 [141]	Thermosiphon of an outer diameter of 16 mm, and 570 mm long is used with a working fluid de-ionized water. Different flow rates are set in the test 10 mL/s, 15 mL/s, and 20 mL/s for various heat inputs of 155 W, 200 W, 250 W, and 300 W and different inclinations 30°, 45°, and 90°.	A comparison was done on the results obtained, and it was concluded that in thermosiphon, 45° is more efficient than other inclinations when de-ionized water is used as a working fluid.

Table 4. *Cont.*

	Authors	Methodology	Results
PHP/OHP	Mahajan et al., 2017 [142]	OHP consists of multiple finned OHP, organized in a staggered way (to increase the heat transfer). Typical HVAC is studied at 60.96 × 45.72 cm^2. The ducted air streams have a constant volumetric flow rate of 1.18 m^3/s opposite to each other. The outdoor temperature is assumed to vary between −8 °C and 48.9 °C.	The results show that the OHP system is energy and cost-effective since a reduction of total average consumption was observed, around 16% yearly. OHP can save, annually, more than $2500 in cities that have continental (warm to hot summer and severe cold winter) climatic conditions
	Supirattanakul et al., 2011 [143]	Copper tubes closed-loop (CLOHP) was used with a diameter of 2.03 mm. Indoor design temperature varies between 20 and 27 °C with 50% RH. R134a, R22, and R502 refrigerants were used as working fluids.	When R134a was used as the working fluid, heat flux increased to 5.19 kW/m^2 at a temperature of 27 °C. The CLOHP/CV resulted in an increase in the surface area and the heat capacity of the base fluid.
	Govinda Mahajan et al., 2015 [144]	OHP-HE was studied with a 70% fill ratio of n-pentane. The performance of OHP was compared with the empty tube, i.e., at vacuum pressure having the same overall dimension.	The results indicate that OHP can recover up to 240 W of heat from the waste exhaust air stream, with a low-pressure drop of almost 62 Pa in the cold air stream. The heat transfer rate with 70% n-pentane is two times that of the evacuated OHP.
	Pachghare, 2016 [101]	Closed loop pulsating heat pipe (CLPHP) consists of 10 turns of copper tubes of ID = 2.0 mm and OD = 3.6 mm. The evaporator, condenser, and adiabatic sections have a length of 50 mm. Different working fluids are used as methanol, R-134a, and water.	With R134a working fluid, PHP indicates, at all orientations, better thermal performance than water and methanol. When using water as a working fluid, PHP shows a negligible inclination angle effect, whereas, with methanol, a significant effect is detected since the better thermal performance was observed in a vertical position than the horizontal one.
	Chawane et al., 2013 [70]	PHP performance is compared by using three different working fluids: ammonia, water, and acetone.	Water-filled devices showed higher performance as compared to R-123 and ethanol in a vertical orientation. Ammonia shows desirable characteristics for heat transfer, as it has a high freezing point.
	Patil et al., 2016 [71]	OHP experiment was done in three different conditions: window, indoor, and outdoor. The working fluid used has a boiling point around 25 °C to deliver a suitable temperature.	The power consumption obtained is around 109 W (less than one ceiling fan). Outlet air temperature and humidity cannot be controlled, due to the inability to control the mass flow rate of the refrigerant.
	Barua et al., 2011 [145]	Mathematical models of falls in temperature in the condenser section were established concerning time for different diameters D and lengths L of the pipes of the evaporator sections.	Temperatures decline exponentially. For a fixed D, the temperature drop depends on the length of the evaporator. For a fixed L, the temperature reduces faster for the smaller diameter of the pipe.

Table 4. *Cont.*

	Authors	Methodology	Results
Runaround coil	J. Wallin et al., 2012 [61]	A summary on increasing the performance of transferring energy through run-around coil ventilation HRS. Studies have also investigated the methods to improve heat pump units by decreasing the energy used; this was done by conducting a modified design of a three-stage heat pump to the system the heat recovery rate per year which was obtained in Stockholm.	The Annual HR rate was improved from 47% to 66%. The system shows considerable and affordable results, for the three-stage heat pump design, the payback period was 5.7 years, for the variable heat pump capacity design 6.2 years.
	R. Zaengerle, 2012 [95]	Integrated system of energy recovery with cooling and heating devices of runaround coil studied in cold climates.	This system is very valuable to recover energy in cold climates, and, thus, decreasing the power of the fan.

Table 4 revealed that:

1. Air-to-air HE decreases considerably the energy consumption, but there are some limitations according to its characteristics and specific configuration.
2. Many factors affect efficiency such as working fluid, size, and climate.
3. It is highly recommended to combine other systems, such as PCM, in order to overcome its overheating problem.
4. It is noticed that OHP in continental climates can save higher energy.
5. The efficiency of THE in winter is higher than in summer. It is recommended to perform a comparative study for each of THE and HPHE in different climates.
6. Papers on integrating run-around coil with HVAC were not available as much as other heat recovery devices. However, it is concluded that this technology is noticed to be effective in cold climates

Earth-Air HE

EAHE is considered an encouraging technology, which can efficiently decrease the load of cooling/heating of a building by warming up the air in the wintertime and the same in summer. Table 5 shows the methodology and results of the papers that studied energy recovery from EAHE.

Table 5. Summary of the investigated papers related to energy recovery from earth to air HE.

Authors	Methodology	Results
Reddy et al., 2015 [146]	Air conditioning system with a ground source heat exchanger (ACSWGSHE) is developed. HE, of helical shape, is placed in a hole of 0.2 m diameter and 15 m deep. The test was done under three different conditions: (i) open hole, (ii) hole filled with water at ambient temperature, and (iii) hole filled with sand. The tube was made of copper and the refrigerant was R22.	When the borehole was filled with water, the COP rose from 2.11 to 3.72. In addition, the power consumption of the AC decreased by 29%. When the bore was filled with sand, COP decreased significantly due to low heat transfer from the condenser to the ground. The cost of the ACSWGSHE system is high. However, after a specific time, savings and energy conservation are significant.
Woodson et al., 2012 [147]	EAHX at 1.5 m depth was designed with varied temperature varies from 25 °C to 43 °C, a 25 m length.	The designed system cooled the inside air from the outside air by more than 7.5 °C when the temperature was 30.4 °C.
Tiwari et al., 2014 [148]	In a room with a height of 2.6 m, and length of 4.5 m., two designs were used: (i) Design I: 5 air changes, 0.1 m pipe diameter, pipe length is 21m. A fan of 0.3 m diameter and 66 rpm requires 90W power to operate. (ii) Design II: 5 air changes and 0.05 m pipe diameter, pipe length is 15 m. A fan of 0.3 m diameter and 66 rpm requires 90 W power to operate.	Design I provides net thermal energy of 0.29 kW in summer and 0.36 kW in winter. Design II provides net thermal energy of 0.26 kW in summer and 0.34 kW in winter. The environmental cost for Design I and Design II is $10.1 and $13.9 respectively.

Table 5. *Cont.*

Authors	Methodology	Results
Congedo et al., 2016 [149]	Under the summer and winter conditions of the Mediterranean climate, a horizontal air-ground heat exchanger (HAGHE) system is studied with a 5 m pipe.	The best performance was at a pipe depth of 5 m with a ground conductivity of 3 W/(mK). A gain of about 23 kWh in winter and 37 kWh in summer.
Fazlikhani et al., 2017 [150]	This study compared the efficiency of the earth to air heat exchanger (EAHE) systems in hot-arid (Yazd) and cold (Hamadan) climates.	In Hamadan, the system works for 225 days and saves 50.1–63.6% energy. In Yazd, it works for 294 days which results in reducing consumption by 24.5–47.9%.

It is observed that:

1. EAHE is effective in severely cold/hot weather, when the temperature is high, which results in a higher temperature gradient which means higher heat transfer.
2. It is noticed that the EAHE is most efficient in hot dry climates weather.
3. EAHE depends on some parameters to achieve optimum energy saving, such as the ground, soil properties, depth, climate, working fluid, geometry, and material of the pipes used. As such, location and climate should be taken into consideration.

5.2.2. Mathematical Control

Controlling and smart systems are great inventions that helped in many fields. These systems do not just facilitate the process, but also save energy, as will be shown in the methodology and results of the papers that studied the effect of mathematical control on HVAC systems in Table 6.

Table 6. Summary of the investigated papers related to mathematical control effect on HVAC systems.

Authors	Methodology	Results
Elhelw 2016 [151]	A comparison between modified bin method and cooling load temperature difference/solar cooling load factor/cooling load factor (CLTD/SCL/CLF) method.	The overall energy efficiency ratio was increased by 45.57%. The energy efficiency ratio (EER) of the modified bin method was between 14.29 and 10.58, which was higher than the EER acquired from using CLTD/SCL/CLF method 10.89. Overall EER saved 33.42%.
Sayadi et al., 2016 [152]	Model predictive control (MPC) is used to foresee the situations of the system.	A reduction of about 43% and 31% in energy used when using MPC.
Wang et al., 2017 [153]	Detection of occupancy using Wi-Fi coverage, smart devices, and sensors.	The model showed over 80% accuracy. The designed model reduced the energy consumption of HVAC significantly.
Zlatanovic, 2011 [154]	Simple and cheap method is used for the energy-saving estimation model (ESEM).	The results show that ESEM has a positive effect on HVAC, and 55% of electrical energy savings can be accomplished.
Godina et al., 2018 [155]	Model predictive control (MPC), proportional integral derivative (PID), and ON/OFF control methods in an AC.	Up to 14.2% can be saved by applying the specific model.

Mathematical control is related to controlling and predicting systems, such as the smart system. These systems have been revealed as having a positive impact on saving energy, as shown in Table 6, where it is noted that the model predictive control (MPC), building automation systems (BAS), estimation models, and automatic smart systems have acquired high attention in HVAC for their ease of use. However, these systems require a high cost and level of accuracy in their construction [156–161]. From Table 6, it is noticed that the model accuracy is acceptable. In addition, the model showed a significant positive effect on saving energy. Further research that involves a smart system in HR devices is recommended.

5.2.3. Total Energy Recovery

Enthalpy Wheel

An enthalpy wheel heat exchanger is one of the energy recovery devices that transfers sensible and latent heat. This criterion increases the efficiency of RW and helps in decreasing the moisture in the air. Table 7 shows the methodology and results of the papers that are related to the enthalpy wheel heat exchanger in HVAC.

Table 7. Summary of the investigated papers related to the enthalpy wheel effect on HVAC systems.

Authors	Methodology	Results
Wang et al., 2012 [162]	Two simple design cases of energy recovery with and without air side economizer were studied and compared to a baseline case which is without energy recovery and an airside economizer case.	An airside economizer combined with energy recovery reduced 17% of HVAC energy consumption annually, which is the highest energy benefit. In the Miami climate in summer, the design increased the COP by up to 26%.
Ali et al., 2016 [163]	A comparison between two cases: (i) without heat recovery wheel, (ii) with heat recovery wheel.	After using the heat recovery wheel, the energy is reduced by 15% from 11.6 tons to 9.9 tons of cooling capacity.
Hussaini et al., 2017 [164]	A comparison of heat load calculations with and without a heat recovery wheel for energy-efficient using Eco-Fresh enthalpy wheel software.	When using HRW for sensible heat, a total reduction in the ton of refrigeration decreased to 46.02%, which means about half of the energy can be saved.
Bellia et al., 2000 [165]	An application is done for retail stores, in four Italian cities. An application is done in a theatre in Rome.	The maximum and profitable savings to the corresponding traditional system have been found to be around 22%. Savings are between 23% and 43%. For both cases, the needed electric power is reduced by about 55%.
Herath et al., 2020 [166]	Installing enthalpy wheels (EW) to central air conditioning systems. Energy saving is calculated for various operating conditions. The payback period for involving RW in AC is calculated.	EW can recover around 20% to 40% of total energy consumption compared to a configuration with no EW in operations. Energy recovery increased when the temperature of fresh air and the moisture content increased. The payback period for an EW is obtained to be in the range of 1 to 5 years.

The results of Table 7 show that:

1. EW HE is effective in HVAC applications, due to its high efficiency and ability to transfer latent and sensible energy, which can be saved.
2. In addition, it was noticed that energy recovery increases when the temperature of fresh air and moisture content increases; consequently, the chance of recovering heat using EW rises.
3. It is also noticed that the efficiency of RW in hot and humid climates increases.
4. As such, it is recommended to study the effect of RW in a humid and cold climate. It is logical that the results will be positive where humidity has a positive effect on RW, as it recovers latent heat.

PCM

PCM is a material that releases and absorbs while phases change. This process provides heating and cooling by melting and solidification. PCM offers a storage ability, which makes it useful in many applications. Table 8 shows the methodology and results of the papers that are related to the PCM effect on the HVAC system.

Table 8. Summary of the investigated papers related to PCM effect on HVAC systems.

Authors	Methodology	Results
Chaiyat et al., 2014 [167]	PCM of paraffin waxes material, which melts at around 20 °C was used in the Thai climate for better cooling efficiency of an AC.	9.10% of the electricity cost was saved when PCM was used. The payback period was 4.15 years.
Tranto et al., 2013 [78]	A hybrid conditioning system that joins EAHEs and PCMs that considers surfaces to be sources of cooling or heating. The hybrid system was studied, for 24 h, with airflow rates of 0.02, 0.04, and 0.05 m^3/s	PCM alone can reduce temperature swing by 33%. The hybrid system reduced temperature swings by 40, 47, and 46%, respectively under the given flow rate.
Madyira, 2017 [168]	15 plates were 10 mm separated and assembled in a Plexiglas box, air mass flow rates of 0.027, 0.061, and 0.075 kg/s were provided by an axial fan.	For 0.027 kg/s, PCM discharged about 78% of its latent energy storage. During the day, around 95% of latent storage capacity was recharged

The studies in Table 8 indicate that:

1. PCM possesses a significant effect in terms of energy-saving and storage.
2. The PCM+EAHE system is encouraging, especially due to its enhancement in swing temperature reduction.
3. PCM has a high cost and some limitations, such as its low thermal conductivity [169,170].
4. As such, it is recommended that PCM is used to aid the storage system in order to store the excess heat and discharge it gradually, such as PCM combined with HP, THE, or EAHE where PCM offers the storage which helps in extending the lifetime of the system.

Fixed Plate

The fixed plate uses metallic plates to transfer the heat between fluids. Its novelty is that it can expose the fluid to a greater surface area, as fluids blowout over different plates. This helps in increasing the heat transfer rate for the compacted size. FPHE can transfer latent energy as well as sensible energy, especially when combined with a liquid desiccant dehumidification system (LDDS) [39]. Table 9 shows the methodology and results of the papers that are related to the fixed plate membrane energy recovery effect on the HVAC system.

Table 9. Summary of the investigated papers related to the fixed plate effect on HVAC systems.

Authors	Methodology	Results
Zafirah et al., 2016 [171]	Tests were performed in a range of airflow rates from 1 to 3 m/s and with an intake relative humidity of 70%, 80%, and 90%.	As airflow and RH rise, efficiency is reduced. The efficiency of the system varied between 40 and 74%, and the highest recovered energy was 1456 W.
Nasif et al., 2015 [172]	Quasi-counter-flow HE designs including L-shaped, Z-shaped, Z-shaped opposite flow heat exchanger (HE) were studied.	The results showed that L-shaped HE saved up to 75 GJ energy compared to Z-shaped and Z-shaped opposite HE. L-shaped HE recovered 90 GJ more energy compared to other HE configurations.
Shen et al., 2017 [39]	Fixed plate heat exchanger is united with the hybrid mass and heat transfer model in the regenerator.	16 to 19% of the total energy consumption was recovered from the outlet air which leads to an energy-saving of about 14 to18%.
Nasif et al., 2010 [173]	Performance of Z type flow enthalpy membrane coupled in AC is investigated annually to measure the effectiveness of different climates.	The results showed that in a tropical (humid) climate, this system saved up to 8% of energy annual consumption. But, in a moderate climate, it spent 4% less energy than a conventional AC.
Nasif, 2018 [174]	Investigating the effectiveness of applying for fixed plate energy recovery heat exchangers for HVAC in buildings.	The results showed that this system recovered energy in a humid climate higher than that in moderate and dry climate conditions.

Table 9 exhibits the following conclusions:

1. FPHE is a promising method to save energy in HVAC applications.
2. It is noticed that the intake air conditions affect the performance of the system, such as increasing the airflow rate and RH, because fixed plate HE transfers latent and sensible energy.
3. The shape of the fixed plate has a significant effect on the amount of recovered energy, whereby results show that the L shape fixed plate shows higher recovered energy.
4. In addition, it is noticed that the amount of recovered energy is higher in humid climates than in dry and moderate climate environments.

6. Effect of Weather Conditions

Based on the above-investigated papers, it is observed that climate has a considerable effect on the performance of each device [175,176]. As such, in this section, energy recovery devices will be classified according to their best climate conditions based on previous research.

All of the papers agreed that the cost savings and efficiency of the systems are higher in winter than in summer [177]. Thus, heating is more efficient than cooling for the same system [178–180]. In addition, Wu et al. [181] indicated that when relative humidity exceeds 70% in hot and humid climates, latent heat becomes a significant constraint. Therefore, energy recovery devices are suitable for such climates due to their ability to transfer both latent and sensible heat systems [139,178]. As such, rotary wheel and fixed plates can be used in cold humid climates, but there is a freezing problem at very low temperatures. In addition, for the fixed plate, the condensation builds up problems, limiting its implementation in severely cold weather. In winter, it is found that enthalpy devices recover over 25% more energy than sensible heat devices. Whereas, in summer, the energy recovery device recovers about three times as much energy as the sensible heat devices [182].

Ground heat pump (GHP) systems have been widely implemented in cold climates. Results show that GHP in cold climate regions is slightly improved, where energy savings are around 7.2% and energy cost savings are on average 6.1% [85]. A horizontal air-ground heat exchanger (HAGHE) system, which is a type of geothermal energy, reduces the consumption of energy in all seasons. These systems show high effectiveness in various climates (hot and humid, cold climate, tropical climate, Mediterranean climate, moderate climate, etc.) [183]. However, they perform optimally in a hot-arid climate, where a reduction of 66% in the gradient temperature between the highest and lowest daily temperatures occurred over the year [149]. Whereas, in the cold climate, the reduction was lower [150]. Thus, EAHE performs in a hot-dry climate better than in a cold climate. These results demonstrate that GHP and EAHE are applicable in hot dry-climate regions.

An experiment was completed in India which showed that heat pipes (HP) saved maximum energy in warm and humid, or hot and dry climates [2]. The results also revealed that wraparound heat pipes, HPs wrapped around a cooling coil, are applicable for hot and humid climates [92]. Thermosiphon is also recommended to be used in a subtropical climate (hot and humid summers, cold winters) [184]. As such, HP is mainly reliable in a hot climate. However, there is a lack of research about HP in cold climates. As such, it is recommended that an experimental study that compares the use of HP in a cold dry climate and cold humid climate is undertaken.

OHPs are most efficient and cost-effective in continental climatic conditions (hot summers and cold winters). G. Mahajan et al. [142] estimated that when OHP was involved in heat recovery ventilator (HRV) systems, more than $2500 were saved yearly in cities with continental climatic conditions. OHP-HRV offers a total average reduction of 16% in energy consumption annually, so it shows a high potential for dropping energy consumption, as well as reducing the operating costs. In addition, it was shown that OHP is suitable for a sub-humid tropical climate, where the WHR of the heating mode exceeds 80% of the total annual WHR. Thus, OHP is reliable in a hot humid climate. It is recommended that OHP efficiency in a hot dry climate is studied and compared to a hot humid climate.

PCM revealed good results for both heating and cooling [76]. Yet, its optimal performance depends on the chosen material. For example, in a cold climate, the material's melting point should be around 26 °C, while in hot climates, a 20 °C melting point leads to better energy savings [185]. Research revealed that PCM is reliable in a tropical climate, like Chennai [186,187]. Thus, PCM is most efficient in a non-arid climate.

Figure 6 proposes a classification of the devices according to their best climatic condition, where each device achieves its optimal effectiveness. For example, RW showed high effectiveness in all climates, but its efficiency in humid climates is better than in arid climates, and thus it is placed in humid climate. This is similar for EAHE, which shows significant results in a hot dry climate, as mentioned in this section. The same procedure goes for the other devices that offer their optimum performance according to the climate.

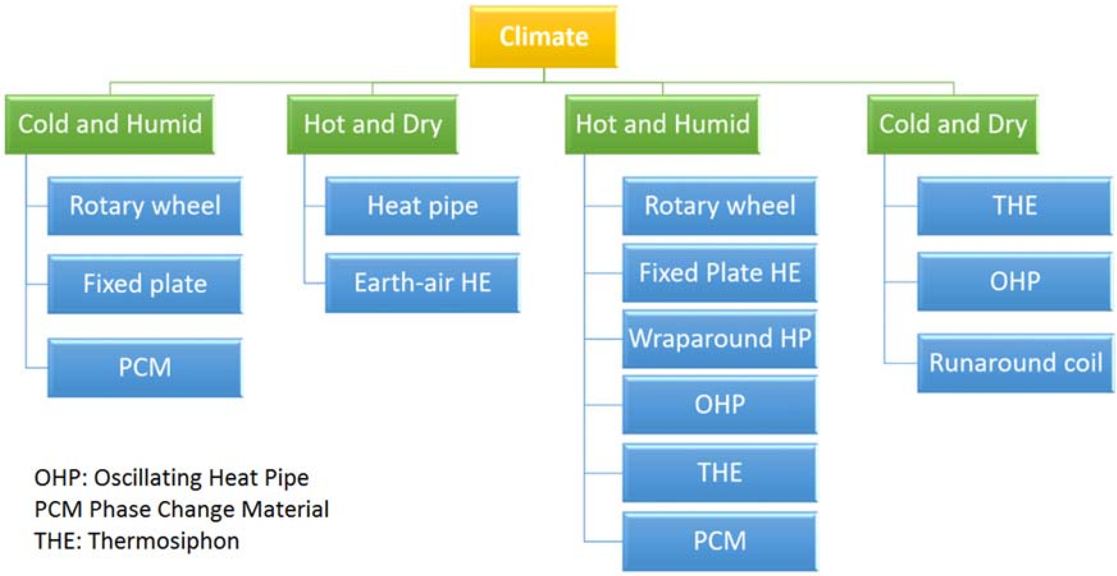


Figure 6. Heat recovery devices according to the climate.

7. Economic Study

Studying the effect of employing heat recovery systems in HVAC from an economical perspective is critical for ensuring that the addition of such a system is worth the investment.

Li lingxue [188] conducted an economic study on the employment of air-water cooled air conditioning systems. The results show that this system saves around 89,822 kWh, with nearly 90,000 yuan for a year (if the average price is 1 yuan per Kwh). Thus, the investment of the system can be recovered in the first year. Moreover, Yau Y. et al. [136] studied the effect of HPHE. In their study, it was obtained that a total amount of 2885 kWh can be saved yearly, and this amount can be raised to 7023 kWh per year if eight-row HPHX was used. In another study, Mahajin G et al. [142] showed that the OHP system is energy- and cost-effective since a reduction of total average consumption was observed, around 16% yearly. In addition, OHP can save, annually, more than $2500 in cities that have continental (warm to hot summer and severe, cold winter) climatic conditions

A study involving HPHE in the HVAC system was undertaken, in which the HPHE was used to recover heat from the exhaust air, while in the heating mode, and transfer it to the cold inlet fresh air, whereas, in the cooling mode, it pre-cools the hot inlet fresh air. It was found that the optimal point is with the effectiveness of 0.774 and a total cost of $1474, with a return period of about 2.5 years [138]. Precooling or preheating air is considered to be very effective as Ahmadzadehtalatapeh M. [139] showed. The results revealed that, by reheating and pre-cooling, a total amount of 236.9 MWh energy could be saved yearly. This amount results in saving $24,572 annually.

Another study on thermosiphon THE heat recovery unit in shopping centers under different seasons was conducted. It was noticed that the seasonal temperature effectiveness of THE was 55.43% in summer and 66.08% in winter, with a payback period of about 2.5 years [142]. J. Wallin et al. [61] performed a study on improving heat transfer through a run-around coil. The results showed that the annual HR rate was improved from 47% to 66%. The system showed considerable and affordable results. For the three-stage heat pump design, the payback period was 5.7 years; for the variable heat pump capacity design it was 6.2 years.

As noticed from previous work, HR is an added value to HVAC systems under different conditions. Despite the additional cost that the recovery system requires, the system saves a remarkable amount of energy over time.

8. Discussion

Throughout the findings, the results have shown that it is worthwhile implementing the energy recovery system (ERS) in HVAC. As the ERSs could save a considerable amount of wasted energy, such an update has proven its effectiveness and efficiency through several studies.

In particular, RW and FPHE have the highest efficiency due to transferring both sensible and latent heat, which increases their efficiency among other systems. Consequently, they are mainly used in humid weather in order to benefit from the latent energy; where energy recovery increases when the temperature of fresh air and moisture content increases, subsequently the chance to recover heat using EW rises. Therefore, RW and FPHE are highly recommended for humid climates. On the other hand, the disadvantage of RW is that it may not be used for hospitals due to the contamination matter. As such, FPHE is a good alternative, especially because it has no moving parts. However, it has frosting problems, a high-pressure drop, and condensation build-up, and these issues should be taken into consideration. The ability of FPHE and RW to recover both latent and sensible energy gives them the credentials over the heat recovery devices, although HP is also considered to be one of the most commonly used in HVAC, besides the FPHW and RW.

Concerning the heat recovery devices, it is noticed that OHP in continental climates can save higher energy. However, the efficiency of THE in winter is higher than that in summer. Integrating a run-around coil with HVAC was not available as frequently as other heat recovery devices, however, this technology is recognized as being effective in cold climates. Thus, the most appropriate device depends on the location and weather.

Air-to-air HE considerably decreases the energy consumption, but there are some limitations according to its characteristics and specific configuration. As for air to water HE, it is considered to be more efficient due to the high heat capacity of water that allows it to conduct heat at about 25 times faster than air. The outlet temperature of the water increases as the load increases. This indicates that applying air to the water heat exchanger in buildings that have a high use of HVAC is very efficient.

EAHE is effective in severely cold/hot weather when the temperature is high, which results in a higher temperature gradient, which means higher heat transfer. In addition, it is noticed that the EAHE is most efficient in hot dry climates weather.

Some devices were remarkably noticed, however, they do not offer a significant output, such as TEG, where it may be used easily with no moving parts, which eliminates the maintenance cost. Yet, they offer only slight improvement due to their low efficiency.

Thermal energy storage systems represented by PCM provide a great opportunity for energy storage. Combining PCM with other systems is recommended, because PCM offers the opportunity of storing energy, and adding PCM slows the temperature rise and guarantees safe operation of the devices over years. Consequently, integrating more than one recovery device produces a significant output. For instance, combining TEG or PCM with other systems, where PCM possesses a significant effect in terms of energy-saving and storage. This opportunity of storing energy slows the temperature rise and guarantees safe operation of the devices over years. In addition, it prevents the other devices from overheating, which is considered to be a double phase benefit. As such, it is recommended that PCM is used as an aiding storage system to store the excess heat and discharge it gradually, such as PCM combined with HP, THE, or EAHE, where PCM offers the storage which helps in extending the lifetime of the system. In addition, PCM and EAHE system shows considerable results, mainly due to their reducing swings in temperature.

Smart systems in HVAC have provided good results in terms of facility, simplicity, and saving energy. Such systems are highly recommended, especially for large constructions due to their convenience and usefulness; however, they require high cost and accuracy in construction.

Based on the results obtained from the previous papers and the discussion made on the effect of heat recovery systems, heat recovery in HVAC systems is a must, not just for large buildings and industries, but also for residential buildings and houses. In addition, recovery systems based on smart systems are expected to be increasingly involved in large-scale manufacturing due to their effectiveness in facilitating the work process and saving energy.

Interestingly, a noteworthy observation to emerge from the outcomes is that hybrid heat recovery systems are very promising systems due to the advantages that these systems offer when combining more than one device together, such as avoiding overheating. Thus, it is highly recommended such systems are investigated and that the effect of each device alone and when it is combined with other different devices is studied.

9. Conclusions

This review covered the main methods of energy management in HVAC by investigating around 190 papers, and then classifying them into specific categories to conclude that heat recovery (HR) is an important issue in HVAC. The challenge is not just to recover the wasted heat, but the challenge is also to recover the maximum wasted heat possible. This paper also presented historical notes on the main energy recovery devices. This paper then discussed HR systems and their effects from already published papers. In addition, it provided a table displaying the working process, pros, and cons of each device. Finally, it presented the best weather conditions for each system. From this review, the following outcomes were concluded:

- Air-water HE is a very effective method to save energy. This is due to the thermal properties of water, which has a higher thermal conductivity and specific heat capacity than air. As the load increases the outlet temperature of water increases. This indicates that applying air-water heat exchangers in buildings that have a high use of HVAC is very efficient.
- TEG has low efficiency due to its design. However, it shows significant results in HVAC applications due to its main advantage, which is generating electricity from even small grade waste heat. Accordingly, this is considered a great solution in the future for decreasing the cost of power generation. However, the main challenge in TEG is to increase its efficiency.
- Smart systems have acquired high attention in HVAC for their ease of use and their significant positive effect on saving energy, but they have a high cost and require accuracy in construction.
- The most commonly used types of heat recovery are heat pipe, fixed plate, and rotary wheel devices, due to their advantages over the other devices.
- PCM provides a great opportunity for energy storage since it possesses a significant effect in terms of energy-saving and storage. Besides, the PCM + EAHE system showed significant results, which widen the research for involving PCM more in other systems, especially in regions with hot climates.
- Systems that recover sensible and latent energy (RW, FPHE, and PCM) are efficient in a humid climate. Thus, they are most efficient in a non-arid climate. However, RW

and FPHE are efficient in humid climates because there is a limitation on very low temperatures that cause freezing and condensation problems. It is concluded that GHP and EAHE are applicable in hot dry-climate regions.

- Papers on integrating run-around coil with HVAC were not as commonly available as papers detailing other heat recovery devices, however, it is concluded that this technology is recognized as effective in cold climates.
- Finally, some recommendations appear:
- It is recommended that further research is undertaken that involves the smart system in heat recovery devices, where smart systems reduce energy consumption and heat recovery (HR) systems recover waste heat.
- It is recommended that hybrid heat recovery (HHR) systems are used, which means applying more than one heat recovery system at the same time.
- It is recommended that TES systems are involved more often with other HR systems, because TES system offers the storage opportunity which helps in extending the lifetime of the system. These hybrid systems could be:
    - PCM combined with HP, THE, TEG, or EAHE.
    - TEG combined with HP where HPs provides higher gradient temperature.
    - TEG combined with PCM, and HP.
- It was found that there was a lack of information concerning the best climatic conditions for HP. Therefore, it is recommended to do some experimental studies:
    - that compare the use of HP in a cold dry climate and cold humid climate;
    - for OHP effectiveness in a hot dry climate and compared it to a hot humid climate.
- It is recommended to design HR in the HVAC system at the beginning of the construction steps, which take into consideration the geometrical parameters of the building, location, climate, and occupants.
- The comparison was not very efficient, as there was not sufficiently consistent research that leads to more reliable results.

Author Contributions: Conceptualization, M.K.; methodology, R.A. and M.K.; validation, R.A.; formal analysis, R.A., J.F., S.A., M.G.E.-R., T.L. and M.K.; investigation, R.A., J.F., S.A., M.G.E.-R., T.L. and M.K.; data curation, R.A.; writing—original draft preparation, R.A.; writing—review and editing, J.F., S.A., M.G.E.-R., T.L. and M.K.; supervision, M.K.; project administration, M.K. All authors have read and agreed to the published version of the manuscript.

Funding: The APC was funded by the International University of Beirut.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

COP	Coefficient of Performance
EMS	Energy Management System
EW	Enthalpy Wheel
EAHE	Earth to Air Heat Exchanger
FPHE	Fixed Plate Heat Exchanger
HR	Heat Recovery
HHR	Hybrid Heat Recovery
HVAC	Heating, Ventilating, and Air Conditioning
OHP	Oscillating Heat Pipe
PCM	Phase Change Material
PHP	Pulsating Heat Pipe

RA	Return Air
RH	Relative Humidity
RW	Rotary Wheel
SA	Supply Air
TE	Thermoelectric
TEG	Thermoelectric Generator
TES	Thermal Energy Storage
THE	Thermosiphon
WHR	Waste Heat Recovery
WLHP	Wraparound Loop Heat Pipes

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