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# A short recent review on hybrid energy systems: Critical analysis and recommendations

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## Abstract

Currently, the world is perceiving a change-over from its existing conventional energy sources to a future with optimized and inventive energy sources. Nowadays, the world is more and more oriented to the use of renewable energy sources to decrease the consumption from the conventional energy sources in particular the fuel energy. In addition, the use of renewable energy source decrease the impact of the conventional energy on the environment. For all these reasons, researchers are currently focusing on studies that implement and innovate methods for the purpose of optimizing and increasing the efficiency of existing renewable energy sources. Of the proposed methods are the hybrid systems. These systems are applicable in both residential and industrial sectors. However, hybrid systems can be applied to renewable energy, wind energy, fuel cell, Desalination, Heating, Ventilating, and Air Conditioning, Engines, Electric Vehicles, Heat Pump, Redrying, PV cells, Engines, Solar Cells, and many other systems. In this context, the aim of the present paper is to provide a short recent review focusing on the types and applications of hybrid renewable energy systems and hybrid recovery energy systems that are applied in industrial and residential sectors. Moreover, the environmental impact, cost and the efficiency will also be presented and discussed.

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**Keywords:** Short recent; Review; Waste heat recovery; Hybrid energy systems; Renewable energy; Critical analysis; Recommendations

## 1. Introduction

In a global attempt to keep in pace with the needs of industrial evolution accompanied with global population growth, both leading to more human dependency on energy, the world's attitude is optimizing and resourcing

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**Nomenclature**

GHG	Greenhouse gas emissions
PV	Photovoltaic
HPGHP	Hybrid power gas engine heat
HHO	Hydroxyl
HRES	Hybrid renewable energy systems
HVAC	Heating, ventilation, and air conditioning
RES	Renewable Energy Sources
HES	Hybrid energy storage system
HES	Hybrid energy system
ICE	Internal combustion engine
HHRS	Hybrid heat recovery systems
HEV	Hybrid electric vehicle
COP	Coefficient of performance

all types of energy resources [1]. Researchers estimation at 2010, assume that the energy demand will reach a 35% increase by 25 years [2]. The main reasons of the rise in demand of energy are the enormous industrial growth, and the depletion of fuel energy resources [3]. Moreover, multiple reports showed the considerable rate of growth in world's energy demand due to an increase in the population [4]. At least 50% of the applied energy is wasted in transportation, power generation, factories, housing sectors and many other activities [5]. Efficiency and greenhouse gas emissions (GHG) enhancement are considered as great challenges concerning global warming in engineering industries [6]. Thus, novel technologies for improving energy efficiency are urgently required to save energy and reduce emissions [7]. Hence, to save energy and condense emissions, innovative mechanisms for enhancing energy efficiency are instantly required [7]. On the other hand, energy production and fuel consumption are developed perfectly by increasing efforts on renewable energy and energy management [8]. For all these reasons, the present article is concerned with focusing on the types and applications of hybrid renewable energy systems and hybrid recovery energy systems that are applied in industrial and residential sectors. This review summarizes studies on Hybrid Energy Systems in four main sections including introduction. Section 2 deals with the types of hybrid systems. Section 3 deals with critical analysis and recommendations, and finally Section 4 draws the main conclusions of the work.

The novelty of this short review paper resides in:

1. Classifying hybrid energy systems into hybrid renewable energy systems and hybrid heat recovery systems;
2. Reviewing studies concerning hybrid systems and their applications in real life;
3. Reviewing comparatively the different types of hybrid systems, advantages and disadvantages and corresponding effects on the efficiency of hybrid systems.

## 2. Hybrid energy systems

Researchers are searching for novel ways reprocess the high amount of thermal energy being lost through exhaust gases [9]. Unfortunately, these methods capability of increasing efficiency and recovering heat is limited. This limitation obligates urgently combining methods in hybrid form to reach better efficiency. However, with lowering cost of renewable energy systems, small sectors, especially housings, can now benefit from renewable energy technologies to produce electricity. Yet, many efforts should be done on the development of renewable energy and storage technologies in order to achieve promising results [10]. By definition, a mechanism which combines multiple energy sources to give a corresponding energy output is called: Hybrid energy system (HES). Nevertheless, many factors are considered as challenges to HES. Environmental effect of exhausts in energy systems, high energy consumption, and amplified expenses are instances for these factors [11]. HESs can be divided into two major types: Hybrid Renewable Energy Systems (HRES) and Hybrid Heat Recovery Systems (HHRS). These systems along with their main recent studies will be exposed in the following subsections.

## 2.1. Hybrid renewable energy systems

Currently, coupled with government and community support, renewable energy resources (RES) play a substantial role as a choice to meet industrial demands for power generation [12]. Countries over the world depend on fossil fuels for energy generation. Yet, the perpetual reduction of fossil fuel and its environmental effects become a great alarm on economic growth in these countries. Renewable energy sources are now a necessity for the world as a substitute source of energy [13]. Universally, there are many zones with both high geothermal heat flux and surface radiation, which makes incorporation of geothermal and solar energies conceivable. Usually, geothermal industries tend to target resources with high temperatures. Yet, most of geothermal resources can be used for moderate temperatures (less than 150 °C). On the contrary, solar systems is incapable of feeding peak power demand during night hours, opposite to its performance during daylight hours. Thus, when combining both systems, geothermal fluids could be used as storage systems for excess of solar energy, while solar systems could be used to rise the temperature of geothermal fluids, therefore refining the efficiency of geothermal power generation. This combination is named as Hybrid Renewable Energy systems (HRES) [14]. Fig. 1 shows main sources of HRE systems.

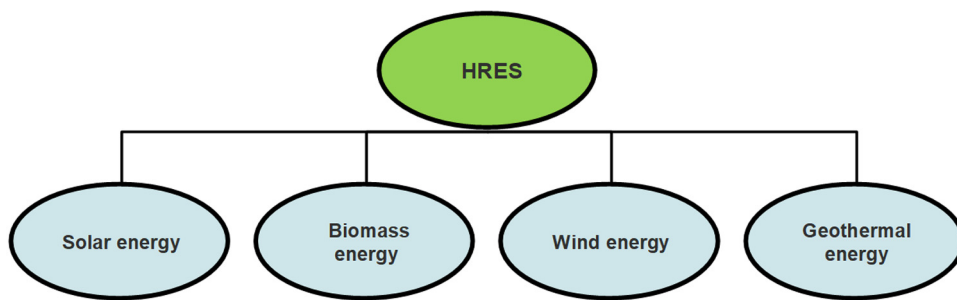


Fig. 1. Main sources of HRE systems.

On the other hand, certainly, global current work in energy market is on gradual change from conventional systems based on coal and natural gas to systems based on renewable energy sources, including existing solar energy and wind energy which lack continuity throughout the year. However, energy storage systems will be a requisite element of the energy systems of the future [15]. Else ways, energy storages present several superiorities such as power quality enhancement, lessening from the intermittency of renewable sources, enabling regulations in microgrid (MG) operation and balancing generation and demand. Hybrid energy storage systems (HESs) specified by coupling two or more types of energy storage systems are developed as a solution to attain the desired performance [16]. Fig. 2 shows different applications of HRESs.

In electrical power system, HRESs based on power generation has arisen as a major revolution because of their ability of providing inexpensive and carbon free electricity to the customers [14]. For instance, a study using various types of biomass gasifiers in an off-grid renewable hybrid system composed of photovoltaic energy, hydrokinetic turbines and batteries, shows that the change of the cost in the apparatuses impacts the total cost of the system. However, the photovoltaic and fuel system have the highest sensitivity among other systems [17]. In addition, a hybrid-energy system proposed on a steam-turbine power plant, allows applying variety of conventional sources (electricity, natural gas or coal) and RES (geothermal and solar heat, and/or waste biomass). This study shows that with waste biomass, gross power can be entirely derived from renewable sources, while with fossil fuel up to 35% can be derived from renewable sources [18]. Table 1 shows a summary for some recent HRES applications, technologies used and corresponding key results.

HRES systems applications summary shows high dependency on PV cells. Solar systems play a significant role in most of the HRESs. However, these systems are more applicable on large industrial sectors. This combination can happen by adding wind power, biomass, bio generators, hydrogen systems and many other systems. Optimization attempts on reducing GHG, reducing the size of PV, reducing CO<sub>2</sub> emissions, increasing RES fraction and lessening generators working hours. These attempts aim for reducing size and cost, increasing efficiency, and reducing GHG. Thus, savings are revolved around economic, environmental and energy. However, challenges for HRES systems are summarized in Fig. 3.

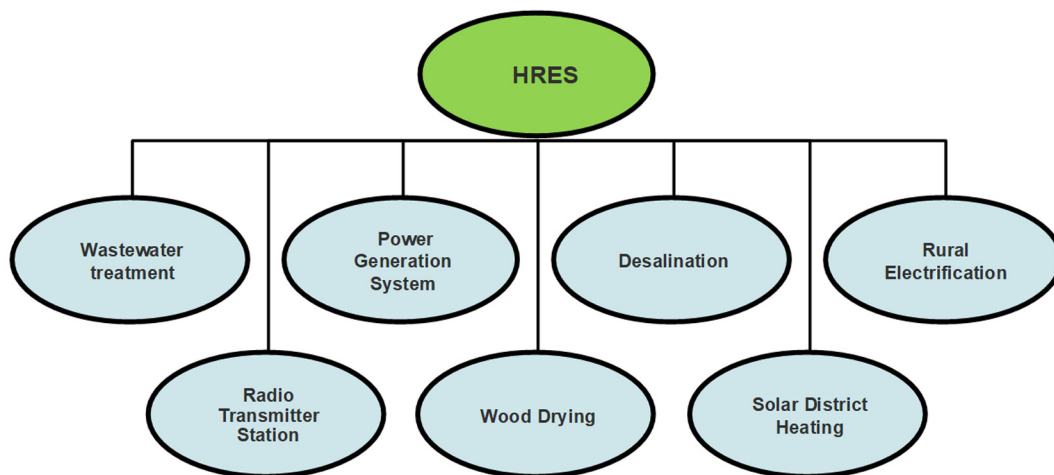


Fig. 2. Applications of HRESs.

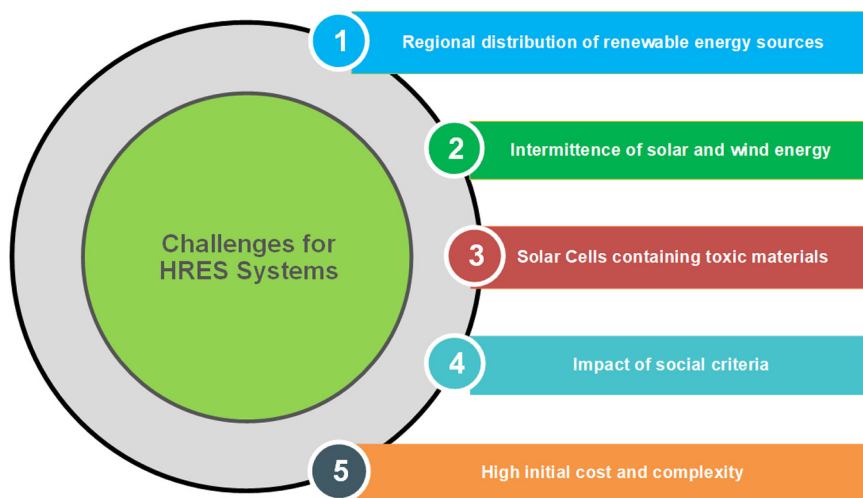


Fig. 3. Challenges for HRESs.

### 2.2. Hybrid heat recovery systems

Due to population and industrial growth globally, pollutants of transportation division present a main source of pollution. Yet, 80% of Carbon and 90% of Nitric oxide are contributed by this division. Currently, Battery electric vehicles are used as an option to decrease environmental pollution. Yet, the driving range and battery lifespan are still a great challenge due to its large-scale commercialization [32]. However, conventional ICE has only 30%–40% efficiency. Most of the lost energy is in the form of exhaust heat, where some can be recovered by Thermoelectric generators, thus reducing CO<sub>2</sub> emissions and fuel consumption [33]. Hybrid power gas engine heat pump (HPGHP) is an innovative air conditioning system that uses a power battery as an secondary power source to attain efficient engine functioning [34]. On the other hand, environmental calamity necessitates using cleaner energy sources for many sectors. Hydrogen is used for transportation as a main or secondary source of energy (fuel) in vehicles. It is the conversion of the automotive industry from petrol and diesel into a sustainable fuel [35]. Fig. 4 shows different applications of HHRSs. However, Fig. 5 shows the main challenges which face HHRS systems globally.

**Table 1.** Summary for some recent HRES applications.

Reference	Main objective	Technology used	Key results	Improvement & savings
[19]	Sizing and energy management of hybrid energy systems using finite automata.	Solar system.	–80 kW reduction in size of PV –50% reduction in the size of Electrolyze and the hydrogen tank –35% decrease in the diesel generator working hours.	Energy & Economy
[13]	Analysis of the effectiveness of a hybrid PV–wind–diesel–battery energy system applied in a remote community.	Solar and Wind systems.	-Cost of energy: 0.110\$/kWh; -Present cost: 1.01\$; -Operating cost: 4723\$; -Renewable fraction: 98.3%; -Greenhouse gas emission: 2889.36 kg/year;	Environment & Economy
[14]	Capacity optimization of grid connected solar/fuel cell energy system using hybrid ABC-PSO algorithm.	Solar-fuel cell.	- Total electricity demand could be met with a: –106 kW solar photovoltaic; –8 kW fuel cell; –45 kW electrolyze; –150 kg of hydrogen tank; -Levelized cost of energy of 0.104 \$=kWh.	Energy
[20]	Studying of a hybrid solar–biomass coffee bean drying system.	Solar–biomass system.	–80% reduction in operation cost.	Economy
[21]	Proposing and enhancing a Hybrid PV–Wind Turbine–Pumped Hydro Storage Energy System in Coastline Communities.	Solar, wind turbine and Pumped Hydro Energy Storage systems.	-The minimum storage capacity of the system: 3930615 kWh; -Levelized Cost of Energy 0.27 \$/kWh;	Energy
[22]	Optimum sizing of a hybrid system for electric and thermal loads using excess energy and waste heat.	Solar, wind turbine, Micro Gas Turbine and Li-ion battery.	–40% Drop in CO <sub>2</sub> emissions –33% rise in renewable energy system fraction	Environment
[23]	Optimizing hybrid energy system to provide thermal and electrical operation.	Solar, fuel cell and battery system.	–5.52% lessening in total increase of operation cost with demand response program. –13.28% lessening in Cost deviation with demand response program.	Economy
[24]	Proposing and estimating different working approaches for rural electrification using a hybrid renewable energy system	Solar, wind turbine and bio generators system.	-Percentages of generated power: - solar power: 86.8% - wind power: 12.7% -bio generators power: 0.5%. Losses: 6.8% battery bank losses. And 1.78% converter losses.	Not specified

*(continued on next page)*

Due to the depletion of fossil fuels and serious pollution emissions, hybrid electric vehicles (HEVs) are gradually replacing internal combustion engines (ICE) vehicles as people's walking tools [36–39]. A super capacitor-based HESS is wild becoming the automotive industry trend. However, many attempts of integrating multi-speed

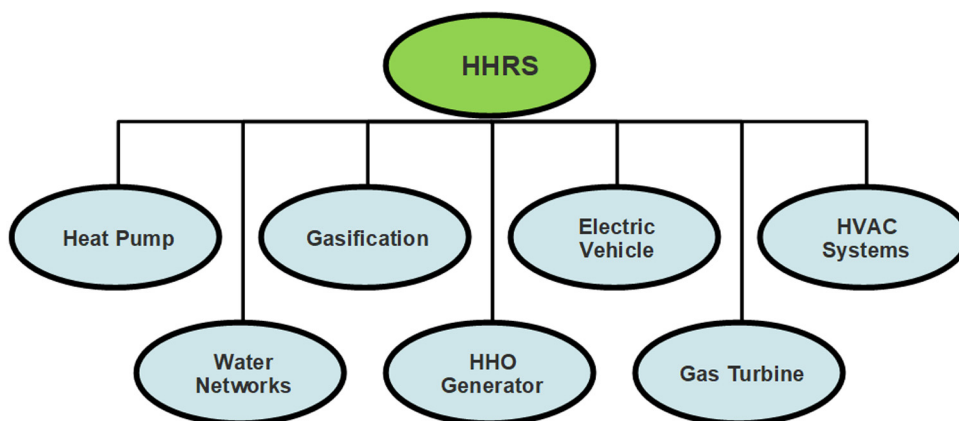
Table 1 (continued).

Ref-er-ence	Main objective	Technology used	Key results	Improvement & savings
[25]	Economic and technical study of a heat and power combination system based on hybrid photovoltaic-fuel cell systems	Solar system, fuel cell and thermal system.	-The net present cost of the optimized system is \$1,006,293; -The cost of energy \$0.8399/kWh; -The system is not economically viable at present; it is technically possible.	Energy
[26]	Study of hybrid renewable energy system with solar heating for net zero energy community.	Solar system, Thermal energy and heat pump	-Payback period: 6-year. -Benefit-cost ratio: 1.7.	Economy
[27]	Economic and technical enhancement of an off-grid hybrid renewable energy system using metaheuristic optimization approaches — Case of a radio transmitter station in India.	Solar, biogas generator, pumped hydro energy storage and battery system.	-Panel area of solar photovoltaic system: 548.67 m <sup>2</sup> -Biogas generator size of 16 kW, battery bank of 21 units, -Converter size of 30 kW -Upper reservoir volume of 2081.5m <sup>3</sup> -Total net present cost: \$0.813 million.	Economy
[28]	Waste heat recovery system based on steam ejector and WTA pre-drying in solar/lignite hybrid power plants.	Solar aided+ pre-drying systems.	For 1000 MW lignite-fired power plant: -21.6 from 46.6 MW of steam waste heat recovered; -1.62% of thermal efficiency increase; -cost is lower than conventional systems: 0.028 USD/kWh.	Energy & Economy
[29]	A hybrid renewable energy system for water desalination using reverse osmosis: A review.	Replacement of fossil fuel with renewable energy for desalination.	-Size: Photovoltaic Energy plants: 0.8 m <sup>3</sup> /d to 60,000 m <sup>3</sup> /d Wind energy plants: 1 m <sup>3</sup> /d to 250,000 m <sup>3</sup> /d Wind–PV hybrid energy plants: 3 m <sup>3</sup> /d to 83,000 m <sup>3</sup> /d -Cost: Photovoltaic Energy plants: 34.21 \$/m <sup>3</sup> to 0.825 \$/m <sup>3</sup> . Wind energy plants: 15.75 \$/m <sup>3</sup> to 0.66 \$/m <sup>3</sup> . Wind–PV hybrid energy plants: 6.12 \$/m <sup>3</sup> to 1.4 \$/m <sup>3</sup> .	Economy
(33)	A hybrid system of HHO generator-TEG waste heat recovery for CO reduction of a gasoline engine	Waste heat recovery on powering the HHO unit	For the case study: -Energy provided between 91 kJ and 169 kJ -Energy consumption of the HHO generator: 22.5 kJ.	Energy
[30]	A hybrid system using direct contact membrane distillation for water production to harvest waste heat from the proton exchange membrane fuel cell.	proton exchange membrane fuel cell and direct contact membrane distillation.	Compared with the single PEMFC system, as operating temperature varies from 328.15 K to 348.15 K, the energy utilization degree can be increased by 201%–266%.	Energy

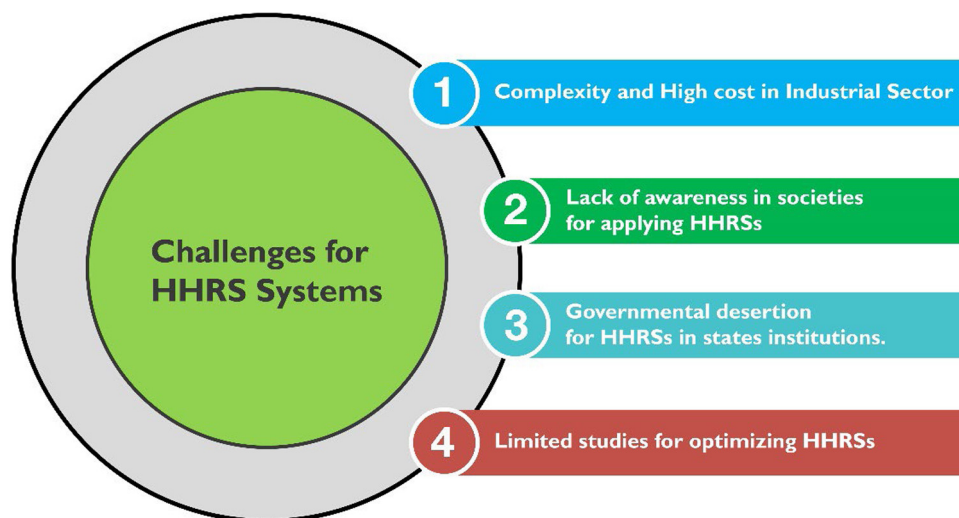
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**Table 1** (continued).

Ref-er-ence	Main objective	Technology used	Key results	Improvement & savings
[31]	Designing a desalination with hybrid renewable energy systems using persistent neural systems.	Solar, wind and reverse osmosis systems.	-HRES with optimized installation contains: 111 photovoltaic panels and 5 wind turbines The designed system reduced potential loss of power supply probability by 18.3% compared with the base case.	Energy



**Fig. 4.** Applications of HRESs.



**Fig. 5.** Challenges for HRSs.

transmission in HEVs are applied to enhance electric machine efficiency [33,38]. Fig. 6 shows some advantages of HEV.

Though researches on HEVs present many advantages, more researches should be done on these systems in order to achieve higher efficiency of the engine, longer life span, cheaper maintenance and better green systems. On the

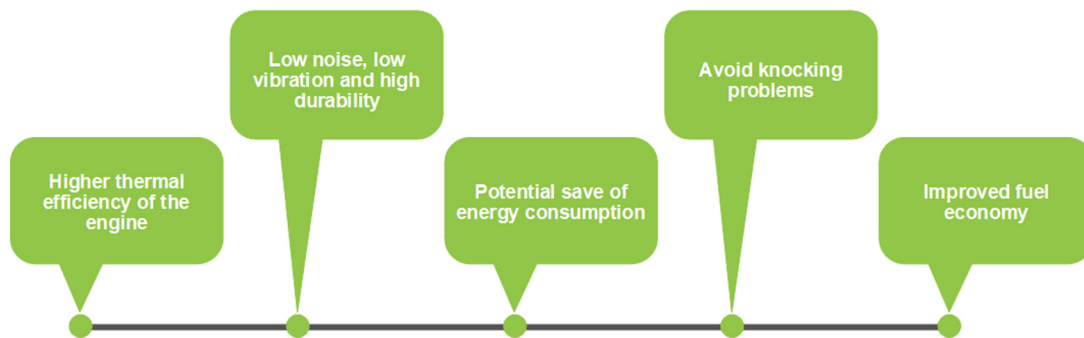


Fig. 6. Advantages of HEV.

other hand, absorption–compression heat pump is an efficient system for recovering low-temperature waste heat leading to the enhancement of efficiency in industrial sector [40,41]. Table 2 shows applications on HHRSS further remarkable outcomes.

Table 2. Applications on HHRSSs.

Reference	Applied technology	Boundary condition(s)	Remarkable outcomes
[40]	Absorption–compression heat pump.	-Sensible heat of flue gas below 150 °C. -Generate saturated steam at 0.5 MPa (151.8 °C).	-Exergy output of the system is 55.82 kW - COP reach 5.49; - Exhaust flue gas Temperature 94.7 °C -Payback period: 6.26 years.
[42]	Parallel hybrid powertrain -Organic Rankine cycle on a Diesel Engine	–900 kW fast passenger ferry Diesel engine	-No extra load on the engine -Increased fuel consumption -Local emissions could be reduced
[43]	A new hybrid air conditioning system (HAC)	Heat exchangers, including a packed bed and three 3/39 air–water finned coils	-Average energy saving rate of 44.0%. -Average power saving per hour is 13.41 Wm <sup>2</sup> .
[44]	A hybrid air treatment cooling system	-Intake rate of outdoor air: 15 to 2.5 L/s per person	-Chilled water supply temperature can be raised from 7 °C to 12 °C - COP of chiller reaches 19% increase
[45]	Proton exchange membrane fuel cell integrated with a hybrid-energy heat pump.	- Supply temperatures of 10 °C for cooling. - Supply temperatures of 40–60 °C for heating.	-Maximum power density of 4.341 kW/m <sup>2</sup> in cooling mode; - Maximum power density of 5.357 kW/m <sup>2</sup> in heating mode;
[46]	Novel ejector boosted hybrid heat pump.	Not specified.	-Unit product cost of heat pumps increase is linked with two factors: Increasing the pinch point temperature difference Reducing the weak solution concentration.
[47]	Hybrid heat recovery system based on vapor compression refrigeration and liquid desiccant dehumidification	–60 °C return water temperature - liquid–gas mass flow rate ratio of 3.2–3.4 -boiler heating capacity: 7 MW	-Thermal efficiency of a boiler can be increased from 90% to 104% - R134a as a refrigerant. - White smoke can be avoided.
[48]	hybrid absorption–compression heat pump.	-High-temperature saturated steam production (> 130 °C) –160 °C supplied heat temperature	-Better choice for the hybrid system in actual application: Ammonia-rich solution mass fraction <0.6 circulation >0.7 is a

Analysis show that sensible heat of flue gas and supply temperatures are the main boundary conditions to be specified in most of the research studies in heat pump. Nevertheless, remarkable outcomes can be summarized by: increasing payback period, increasing coefficient of performance (COP), and decreasing exhaust flue gas

temperatures [40,46,48]. However, some studies on HHRs based on vapor compression refrigeration and liquid desiccant dehumidification (HVAC) are reviewed [43,44,47], main outcomes are presented in Fig. 7.

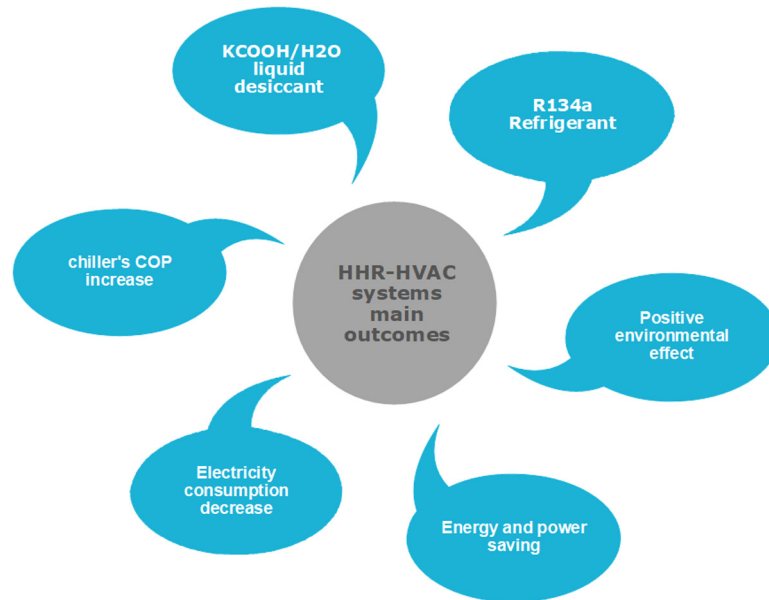


Fig. 7. Main outcomes of HHR for HVAC systems.

### 3. Critical analysis and recommendations

In line with the worldwide fears for increased GHG emissions, the industrial market tends to shift towards more environmentally methods to meet strict emission standards. However, future energy generation will be depending strictly on renewable energy sources due to the rapid reduction of conventional sources of energy. Moreover, HRESs drawbacks are being marginalized by many researchers, and it is not capable of eliminating the need for conventional sources of energy. Then, after analyzing studies on HRSs with its types and applications, it is recommended to:

- Focus on decreasing the cost of HRESs to meet the commercial market capacity.
- Enhance the efficiency of HRESs by optimizing these systems.
- Increase efforts HRESs to become more mature and applicable in daily life residential and industrial needs, which in return will decrease the demand on fossil fuels, and thus the HHRs.
- Emphasize on HHRs applications in industrial sectors.
- Approach studies to focus on enhancing HHRs, thus decreasing the cost of these systems which will meet the market needs, and therefore reducing the usage of fossil fuels.
- Apply multiple HHRs on the same application, to recover the exhaust after previous recovery.
- Study coupling HHRs with HRESs to meet highest efficiencies, with best environmental and economic results.
- Facilitate legal transactions in countries that set restrictions on HRESs
- Work on combining HRES and HHRs which will profit promising results.

### 4. Conclusions

The present manuscript concerned a short recent review on hybrid renewable and heat recovery systems in residential and industrial applications. Based on the literature presented, studies show that renewable energy systems became a necessity due to the decay of non-renewable sources. However, Hybrid energy systems are classified into Hybrid Renewable Energy Systems HRESs and Hybrid Heat Recovery Systems HHRs. For HRESs, the main sources of energy are: solar, biomass, wind and geothermal energy, while the main challenges are: sustainability, social criteria, environmental and economic factor. On the other hand, for HHRs, studies show that HVAC systems optimization focuses on increasing payback period, increasing COP, and decreasing exhaust flue gas temperatures.

Nevertheless, the enhancement of HEV should work on attaining higher efficiency of the engine, longer life span, cheaper maintenance and better green systems. Moreover, the sensible heat of flue gas and supply temperatures are the main boundary conditions to be specified in most of the research studies in heat pump. Finally, HHRS and HRES combination presents the largest promising challenge for future work.

### Declaration of competing interest

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

### Data availability

The data that has been used is confidential.

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