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A review of hybridization of water and hydrogen production in solar multigeneration systems

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ABSTRACT

Multigeneration systems have huge potential in solving many of the energy and environmental challenges faced globally. This review investigated the production of power, freshwater, and hydrogen from multigeneration systems powered by solar energy. Furthermore, the hybridization of different production cycles and their effect on overall system performance was assessed. The investigation was also expanded to include systems utilizing differing energy sources in addition to solar. Most of the proposed processes underwent thermodynamic, economic, environmental, parametric, and optimization analyses to understand their performance. This included exploring the influence of various environmental and design factors such as solar radiation and wind speed on system performance. Comparing performance metrics across different studies was difficult due to the deployment of varying indicators by different studies and the site-specific nature of the results obtained. However, the levelized costs whose values are comparable across studies ranged between 16 and 20 $\frac{\$}{GJ}$ for solar multigeneration systems depending on various system attributes. Those included choice of energy sources, products, and components utilized which differed across studies due to a multitude of factors including climatic conditions, renewable energy availability, and demand patterns. To the best of the authors' knowledge, this is the first review to focus specifically on solar-driven multigeneration systems that concurrently produce power, freshwater, and hydrogen, synthesizing both thermodynamic and techno-economic perspectives across a range of configurations.

1. Introduction

With the ever-increasing focus on minimizing environmental impacts associated with various engineering systems, multigeneration systems emerged as an attractive potential solution. These integrated processes utilize different cycles to couple the production of multiple energy vectors and fuels such as electricity, hydrogen, heating load, and refrigeration within the boundaries of a single system [1–3]. Other essential products and their respective production cycles are also integrated within multigeneration systems such as freshwater, ammonia, methanol, and bitumen along with various chemicals, fuels, and value-added products [4–7]. While multigeneration systems may be fueled by fossil fuels, many systems proposed in the literature are fueled by renewable energy sources with solar energy being the most common.

Hybridization of multiple processes has been reported to improve thermodynamic efficiency, increase energy utilization, reduce waste production, and improve the environmental profile of the overall process [8,9]. Depending on the number of products produced, multigeneration systems are classified into cogeneration, trigeneration, and polygeneration as presented in Fig. 1. A well-known example of cogeneration systems are combined heating and cooling plants (CHP) which utilize waste heat from power production to provide district or industrial heating [10]. Coupling of cooling and heating production has been reported to increase the energy utilization factor from 15-30 % to 50–80 % [11].

Water is one of the most important products in most multigeneration

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systems. Water and power are linked together in many ways due to the dependence of the production of either one on the other. In the example of CHPs, steam turbines used for electricity generation have high water requirements; therefore, it is common to incorporate water production within these system [12]. Various other proposed multigeneration systems, irrespective of their size, include water desalination systems to provide freshwater as a product taking advantage of the potential synergies between power and water production processes. In addition, the high energy costs associated with desalination has led to the frequent inclusion of desalination systems within renewable multigeneration systems in the literature [13]. Lastly, the inclusion of hydrogen production cycles in multigeneration systems has been observed mainly due to the interest in its use as a fuel. Advantages of hydrogen when compared to conventional fuels include reduced emissions and increased efficiency [14]. Moreover, it is considered as an energy storage option for long-term applications [15].

Recognizing the importance of the power-water-hydrogen nexus, this review presents and discusses investigations of solar powered multigeneration systems that produce freshwater, power, and hydrogen. One of the most important reasons behind drawing the connection between these strategic production cycles is the potential for tackling the issue of intermittency associated with renewables [16]. In a future of low carbon economies, electric vehicles are poised to increase power demand and renewable energy utilization would be vital. Concurrently, water demand is estimated to increase with water scarcity already posing a challenge in many countries. Finally, hydrogen could potentially provide a clean fuel option for processes which cannot be powered by electricity. Therefore, including these three products in a single plant and leveraging the potential synergies and efficiency gains of combining multiple processes in one system could be a potential solution. This work focuses on synthesizing the most important conclusions of technological integration and performance trends in solar-powered multigeneration systems producing power, freshwater, and hydrogen. Literature was identified through targeted searches in ScienceDirect using combinations of keywords such as “solar multigeneration,” “hydrogen production,” “desalination,” “polygeneration,” and “hybrid systems.” The search covered recent peer-reviewed journal articles beginning in 2013. Inclusion criteria included reliance of the system on solar energy and the production of at least water and hydrogen. Systems which produced more products or relied on energy sources in addition to solar were included. However, studies focused solely on single-product systems and non-solar configurations were excluded.

The objective of this study is to review the different potential configurations of such multigeneration systems, their assessment metrics, feasibility, challenges, and future potential. After reviewing the literature, it was noticed that most renewable multigeneration systems which produced the target products rely on solar energy which explains the choice made in this paper. Other renewables utilized include geothermal and biofuel; however, these sources are often combined with solar energy as well and such systems are covered in this study. No other review to the authors knowledge has focused on water, power, and hydrogen producing multigeneration systems despite its aforementioned potential. Examples of multigeneration systems reviews included Mahmoud et al. [17] which reviewed geothermal powered multigeneration systems producing hydrogen. Meanwhile Kasaeian et al. [18] looked into solar polygeneration systems and Zhang et al. [19] reviewed green hydrogen production in polygeneration systems both without addressing water desalination.

2. Typical subsystems in multigeneration processes

2.1. Solar and energy storage systems

Solar radiation is either converted to thermal energy using solar collectors or to electrical energy using photovoltaic (PV) systems. Photovoltaic/thermal (PVT) systems are also investigated as a hybrid alternative with increased efficiency [20]. First, within a solar collector system, heliostat fields are utilized to reflect solar radiation towards a solar receiver using a single mirror or a set of independently controlled mirrors [21,22]. Moreover, concentrated solar power (CSP) systems use transmissive or reflecting components to focus radiation towards an area in which it is converted to thermal or electrical energy [23]. Heliostats in CSPs employ solar tracking systems to improve the performance of the overall system [24,25]. In the context of multigeneration systems, parabolic trough collectors (PTCs) are the most commonly encountered CSP system and are considered to be a well-established technology [25]. They utilize long tubes and concave trough shaped mirrors used to focus energy onto a linear collector [26,27]. Furthermore, flat plate collectors (FPC) are another commonly deployed collectors with a differing geometry than that of PTCs. The absorptance of a solar collector’s surface, in addition to other geographic and design factors, plays a pivotal role in its effectiveness [28,29].

Thermal energy storage (TES) systems are an integral part of a CSP system typically included to improve the system’s ability to deal with the intermittency of solar power [30,31]. A common example of such storage systems are hot molten salt tanks which work in conjunction with a steam generator [32]. Other renewable energy systems utilized in multigeneration systems along with solar energy systems include wind turbines (WT), single and double flash binary geothermal plants, and ocean thermal energy systems. In addition, biomass is typically converted to either power or fuel and sourced from animal manure, food waste, or agricultural waste among other sources [33].

2.2. Power cycles

Different power cycles may be used in multigeneration systems to convert renewable thermal energy to electrical power [34]. The most common example is the steam Rankine cycle (RC) and organic Rankine

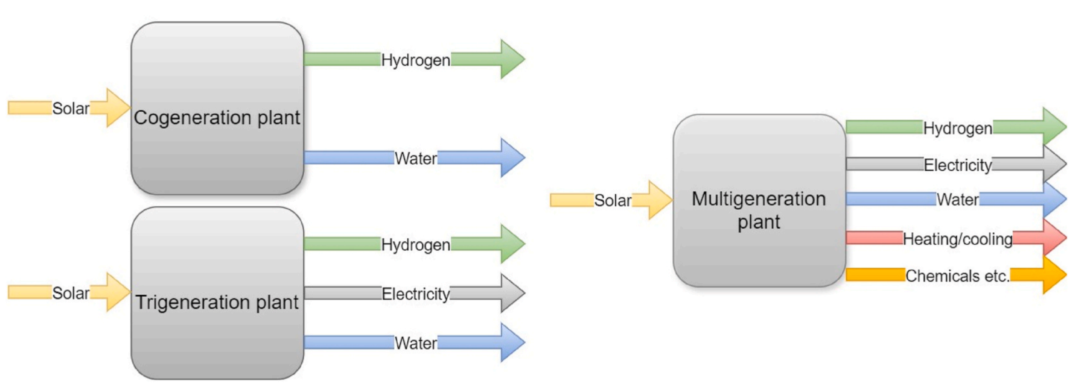

Fig. 1. Products of solar cogeneration (2 products), trigeneration (3 products), and multigeneration (more than 3 products) systems.

cycle (ORC). ORCs are better able to exploit low temperature heat extracted from sources such as waste heat from industrial processes in addition to geothermal and solar energy [35]. The Kalina cycle (KC) is employed for similar functions and utilizes a mixture of water and ammonia as its working fluid [36]. Other examples of power cycles include the Stirling engine, Brayton cycle (BC), and thermoelectric generators (TEG). Supercritical and transcritical CO_2 (TRCC) cycles are also employed and investigated as an alternative to water and organic based cycles to achieve better thermodynamic performance [37].

2.3. Hydrogen production

Multiple hydrogen production methods are utilized in solar multigeneration systems though some are more common than others. First, steam methane reforming (SMR) is currently the most commonly deployed hydrogen production method globally in standalone processes [38]. The process involves high temperature steam which is reacted with methane to produce hydrogen [39]. Alternatively, three distinct energy intensive water electrolysis processes may be deployed to produce hydrogen including proton exchange membrane electrolyzer (PEME), solid oxide electrolyzer (SOE), and alkaline water electrolyzer (AWE) [40]. One of the main differences between the three methods is the use of solid electrolytes in PEME and SOE as opposed to the liquid electrolytes utilized in AWE [41]. Moreover, SOE operates at high temperatures as opposed to the lower heat requirements of PEME and AWE [40].

Thermochemical cycles are another hydrogen production method considered in multigeneration systems, most common of which is the copper chlorine (Cu–Cl) cycle. Other cycles include sulfur bromide (S–Br) and magnesium chloride (Mg–Cl). These cycles involve a series of endothermic reactions utilizing continuously recycled chemicals and require lower temperatures as compared to direct water splitting reactions [42,43]. Similarly, electrolysis of brine and the water gas shift reaction (WGS) are two hydrogen production methods employed in renewable multigeneration systems. Brine electrolysis involves the production of chlorine as a byproduct while WGS is typically conducted in multiple step catalytic converters producing hydrogen from carbon monoxide and water [44,45]. The chemical energy within hydrogen may be converted to electricity and heat via fuel cells where the electrolysis processes mentioned above are reversed using units such as a proton exchange membrane fuel cell (PEMFC) or a solid oxide fuel cell (SOFC) among others [46]. Fuel cells have several advantages including durability and high efficiency; in addition, they allow for the use of hydrogen as an energy storage system increasing the overall system flexibility [47].

2.4. Desalination systems

Water production in solar multigeneration systems generally employs two types of desalination systems. First, thermal desalination such as humidification dehumidification (HDH), multiple effect distillation (MED), membrane distillation (MD), thermal vapor compression (TVC) and multistage flash distillation (MSF) are usually used in solar multigeneration systems to produce freshwater using renewable thermal energy. Membrane desalination is the second type which operates by utilizing excess electrical energy produced within the system to produce water using technologies such as reverse osmosis (RO).

2.5. Cooling cycles

Various cooling cycles are typically deployed in renewable multigeneration systems to provide cooling. First, absorption cooling cycles (ACs) use liquid or solid sorption material in addition to low grade thermal energy making them ideal for solar powered systems [48,49]. In many multigeneration systems single effect absorption cycles (SEAC), double effect absorption cycles (DEAC), and triple effect absorption cycles (TEAC) are employed. They are powered by heat which makes them an attractive option to couple with thermal renewable energy [50]. In most cases, water is utilized as a refrigerant in those systems while lithium bromide is used as an absorber [51]. Alternatively, ejector refrigeration cycles (EJRC) which use high pressure motive steam as their energy source are in some instances coupled with power cycles using their waste heat as an energy source [52]. Different combinations of the above-mentioned systems and cycles are presented and analyzed in the studies reviewed. Fig. 2 summarizes the products, energy sources, and subsystems included in those studies.

3. Solar multigeneration systems for power, water, and hydrogen production

Investigations of solar powered multigeneration systems producing hydrogen and water differ in whether they solely rely on solar energy or include other renewables as well. Utilization of multiple sources generally increases a system's ability to deal with fluctuations in demand and the intermittent nature of any single source. It is important to note that assessing the efficiency of any proposed system is typically done in the literature using thermodynamic modelling and simulation. Other analyses such as parametric studies, optimization, and economic investigations among others are also carried out in many cases to provide more performance metrics and a deeper understanding of the system in question.

In the reviewed investigations, solar energy was mainly collected by solar collectors such as PTCs and converted to power using cycles such as RC, ORC, BC, and KC. Solar collector systems included TES units mainly to offset the intermittency of solar energy while battery packs were seldom considered to the same end. Another path for utilization of solar energy was PV systems; however, they were not as prevalent as solar collectors. Moreover, instead of solely powering their proposed systems by solar energy, many studies opted for the hybridization of other renewable and non-renewable energy sources to increase overall system reliability.

For hydrogen production, excess power was used in most studies to power PEMEs while other production methods such as thermochemical cycles, AWE, SMR, and SOE were utilized to a lesser extent. Moreover, very few studies opted for brine electrolysis and WGS. Also, a subset of the reviewed studies deployed HES systems whereby hydrogen fuel cells converted hydrogen fuel back to power.

For water production, desalination systems such as MED, RO, HDH, and MSF were included. Thermal desalination units were powered by waste heat from power cycles in most cases. Fig. 3 presents the various possible configurations for solar trigeneration systems producing power, water, and hydrogen in the literature. Following similar configurations, polygeneration systems producing additional products such as cooling, heating, and hot water among others are also presented in the literature with most utilizing similar configurations to trigneration systems in Fig. 3.

3.1. Single energy sourced solar multigeneration systems

Typically, trigeneration systems relying on solar energy utilize a solar collector, power cycle/s, thermal desalination system, and hydrogen production system. For multigeneration systems, other cycles are included such as cooling, heating, or chemical production cycles among others depending on the system products. Nearly all the systems encountered followed a general set up with small variations from one study to the next. Solar collectors are often deployed to provide thermal energy for a power cycle while energy from the power cycle is used by the electrolyzer as done by Delpisheh et al. [53]. Moreover, waste heat from the power cycles turbine effluent is utilized to power thermal desalination units such as MSF, MED, MD, and HDH. Desalinated water designated for the electrolyzer is often preheated by waste heat from the power cycle. In some instances, RO instead of thermal desalination was utilized utilizing electrical power generated by the system as presented

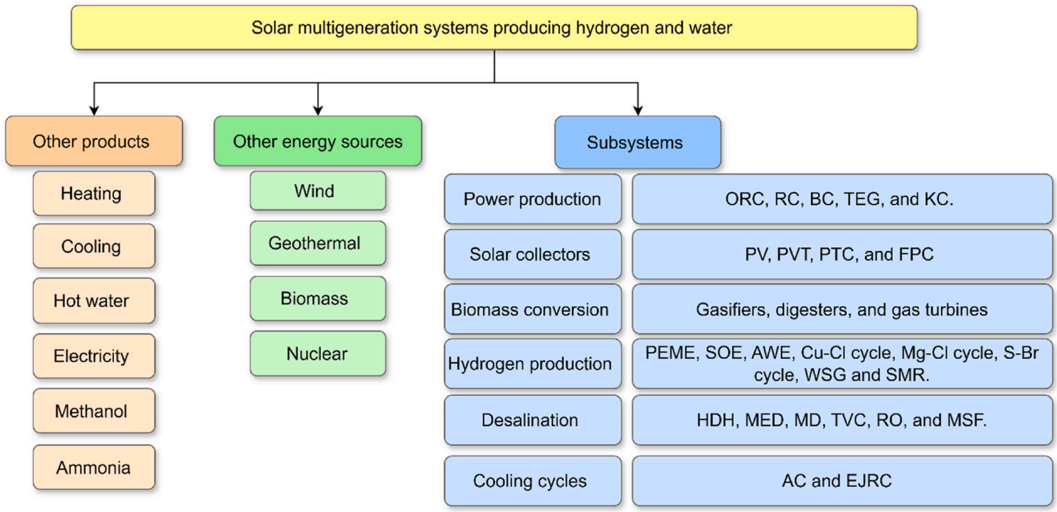

Fig. 2. Typical products, energy sources, and production units in solar multigeneration systems.
Abbreviations: ORC – Organic Rankine Cycle, RC – Rankine Cycle, BC – Brayton Cycle, KC – Kalina Cycle, PV – Photovoltaics, PVT – Photovoltaics/Thermal, PTC – Parabolic Trough Collector, FPC – Flat Plate Collector, PEME – Proton Exchange Membrane Electrolyzer, SOE – Solid Oxide Electrolyzer, AWE – Alkaline Water Electrolyzer, WSG – Water Gas Shift Reactor, SMR – Steam Methane Reactor, HDH – Humidification-Dehumidification, MED – Multi Effect Distillation, MD – Membrane Distillation, TVC – Thermal Vapor Compression, RO – Reverse Osmosis, MSF – Multi Stage Flash, AC – Absorption Cooling Cycles, EJRC – Ejector Refrigeration Cycles.

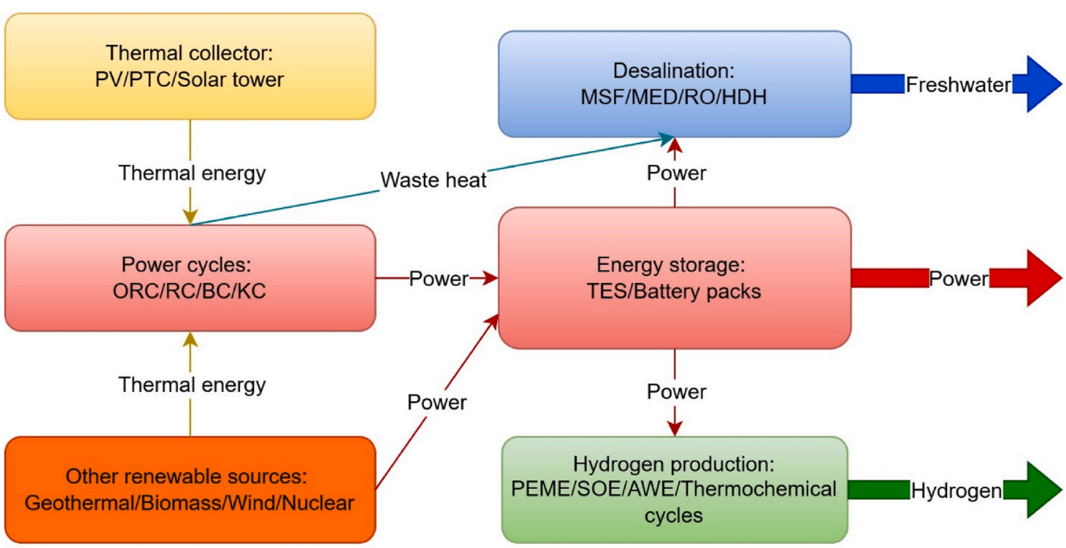

Fig. 3. Different configurations of solar trigeneration systems producing water, hydrogen, and power.

by Mohammadpour [54] et al. Meanwhile, polygeneration systems followed a similar design with the addition of other cycles such as SEAC which rely on low-grade heat as their power source.

3.1.1. Solar powered trigeneration systems

Six different studies of trigeneration systems producing power, water, and hydrogen based solely on solar power as presented in Table 1. Delpisheh et al. [53] proposed a PTC based system which also employed PEME, ORC, and HDH. The system was analyzed for low, high, and no radiation scenarios during which solar, solar-storage, and storage only operational modes were simulated. Optimization of system design parameters increased efficiencies by 4.2 %–10.8 % and hydrogen production rates by 14.7 %–48.7 % in solar and solar-storage modes. Energetic and exergetic efficiencies were 81.46 % and 5.22 % in solar mode, 27.73 % and 1.86 % in solar-storage mode, while values for storage only mode were 50.61 % and 3.55 %. Similarly, Siddiqui and Dincer [55] analyzed a novel solar tower-based trigeneration system which coupled RO, RC, ORC, and PEME subsystems. Findings of the study include an overall system energy efficiency of 23.2 %, and an exergy efficiency of 6.2 %. Moreover, it was found that the low-pressure turbine was the highest contributing component towards exergy destruction. Furthermore, results indicated that increased radiation reduces the overall system energy and exergy efficiencies. Finally, the thermodynamic performance of the PEME was found to be negatively correlated with its area.

Another trigeneration system was proposed by Farajollahi et al. [56] where a solar chimney system, MED unit, and PEME were coupled. Solar chimneys operate by solar induced air convection current which is used to power a turbine at the bottom of the systems as presented in Fig. 4. Energy and exergy efficiencies of 31.08 % and 7.08 % were reported, respectively. In addition, the power production cost was found to be 16.86 $/GJ. Finally, the solar chimney system was identified as the

Table 1
Summary of literature works investigating solar powered trigeneration systems producing power, water, and hydrogen.

Ref.	H2 prod.	Desal.	Solar collector	Prime movers	Energy/exergy efficiency (%)	Main points and results
[53]	PEME	HDH	PTC	ORC	Solar mode: 81.46/5.22 Solar-storage mode: 27.73/1.86 Storage only mode: 50.61/3.55	• Optimization increased efficiencies by 4.2–10.8 % for solar and solar-storage modes. • Also increased hydrogen production rates by 14.7–48.7 % in solar and solar-storage modes
[55]	PEME	RO	Solar tower	RC ORC	23.2/6.2	• PEME area and thermodynamic performance are negatively correlated.
[56]	PEME	MED	Solar chimney	–	31.08/7.08	• Power production cost estimated at 16.86 $\frac{\$}{GJ}$. • Solar chimney was the highest contributor to exergy destruction.
[57]	PEME	MSF	Heliostat field	TEG-Gas turbine	42.5/40.5	• Daily production of 1210 tons freshwater, 50.6 GJ power, and 129.9 kg hydrogen.
[54]	SMR	RO-HDH	Heliostat field	RC ORC TEG	-/11.32	• Uniquely chose to hybridize RO and HDH desalination. • Overall system cost of 78.18 $\frac{\$}{h}$. • 57.59 $\frac{kg}{h}$ oxygen production, 7.13 $\frac{kg}{h}$ hydrogen production, and 15.97 $\frac{kg}{s}$ freshwater production.
[58]	SMR	RO	Solar tower	HGT	50.18/51.91	• Solar energy was utilized exclusively to provide hot air for combustion in HGT. • Production of 12.9 MW of electricity, 96.18 $\frac{kg}{s}$ of freshwater, and 5.2 $\frac{kg}{s}$. • Irradiation increase led to higher efficiency for the solar tower and by extension, the overall system. The opposite effect was observed for exergy efficiency.

Abbreviations: ORC – Organic Rankine Cycle, RC – Rankine Cycle, PEME – Proton Exchange Membrane Electrolyzer, PTC – Parabolic Trough Collector, TEG – Thermoelectric Generator, SMR – Steam Methane Reforming, HGT – Hydrogen Gas Turbine, RO – Reverse Osmosis, MED – Multi Effect Distillation, MSF – Multi Stage Flash, and HDH – Humidification-Dehumidification.

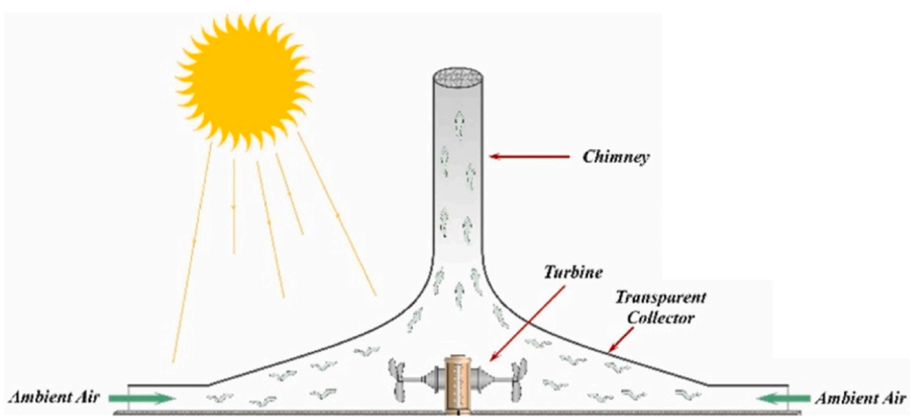

Fig. 4. Solar chimney system presenting air convection currents and turbine (taken with edits from Ref. [56]).

largest contributor to exergy destruction followed by the MED unit. Similarly, a system was analyzed by Demir and Dincer [57] where an MSF, PEME, heliostat field, TEG, and gas turbine were coupled. The overall system was reported to achieve 42.5 % and 40.5 % energy and exergy efficiencies respectively. Meanwhile, the system produced 1210 tons/day of freshwater, 50.6 GJ/day of power, and 129.9 kg/day of hydrogen.

Unlike the previous studies discussed where PEME was utilized for hydrogen production, Mohammadpour [54] et al. and Javadi et al. [58] uniquely opted for the utilization of SOE and methane fed SMR, respectively. Mohammadpour et al. [54] proposed a system which included a heliostat solar field to collect solar energy and included an ORC, RC, TEG, and RO-HDH desalination system. Unlike other investigations, this analysis chose to hybridize two desalination technologies whereby brine output from the RO plant is further treated in the HDH unit aiming to increase overall desalination efficiency. While the RO plant was fed electrical power produced within the ORC, the HDH unit employed waste heat from the low-pressure turbine effluent as presented in Fig. 5. Parametric analysis for the impact of different input parameters was performed such as presented in Fig. 6 for the impact of heliostat concentration ratio on various performance indicators. Moreover, results indicated a maximum exergy efficiency of 11.32 % and a minimum total cost rate of 78.18 $\frac{\$}{h}$. At optimal system operation, the system generated around 57.59 kg/h of pure oxygen, 7.13 $\frac{kg}{h}$ of hydrogen, and 15.97 $\frac{kg}{s}$ of freshwater.

Javadi et al. [58] proposed a system employing a solar tower, hydrogen gas turbine (HGT), SMR, and RO. The system investigated in this study was different in two main ways. First, power was produced by the HGT while solar energy was used to heat air for HGT combustion instead the typical reliance on renewable energy for power cycles. Second, the utilization of methane fueled SMR for hydrogen production in this study was unique as opposed to the typically deployed water splitting methods. Heat from the HGT exhaust gas was used in the SMR cycle; meanwhile, electricity generated by it was used for two consecutive RO cycles. Moreover, the hydrogen produced in the SMR cycle was used as part of the HGT syngas. Results indicated that direct normal irradiation positively influences the efficiency of the solar tower and the overall system; however, it had the opposite effect on exergy efficiency. The overall system produced 12.9 MW of electricity, 96.18 $\frac{kg}{s}$ of

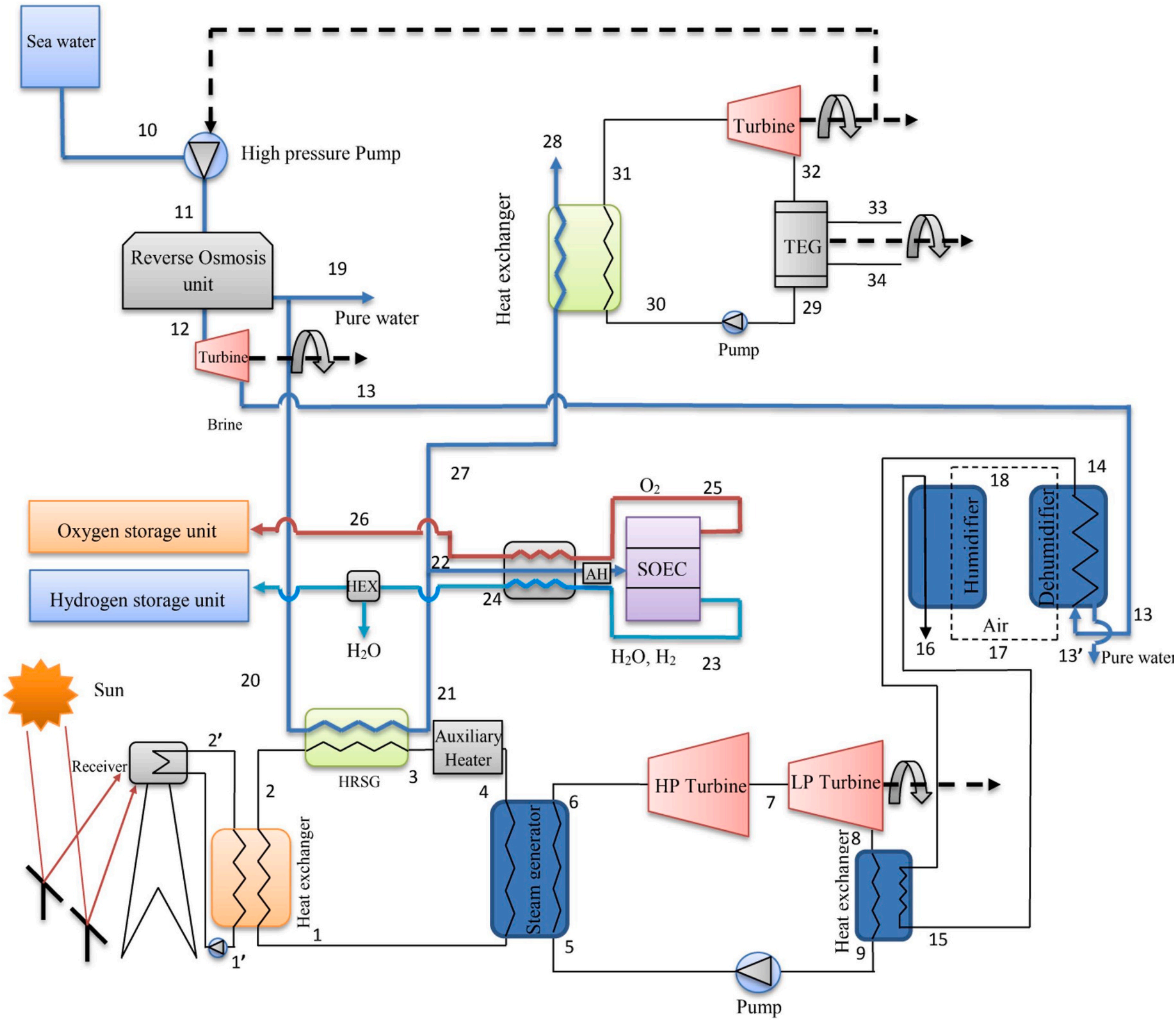

Fig. 5. SOE, RO-HDH, TEG, heliostat field, and ORC-RC based multigeneration solar energy powered system [54].

freshwater, and 5.2 $\frac{kg}{s}$ of hydrogen while the overall energy and exergy efficiencies were found to be 50.18 % and 51.91 %, respectively.

3.1.2. *Solar powered polygeneration systems*

Some studies opted to also include heating and cooling as products. These products were included in addition to electricity, freshwater, and hydrogen. For example, Hai et al. [59] integrated heating and cooling cycles among other systems to supply a building with its power, water, heating, and cooling requirements. In addition to the deployment of a PV system supplying power, the proposed design was also uniquely grid connected for energy supply stabilization. During periods of excess power generation, hydrogen was produced by both PEME and AWE units. Meanwhile, water was produced in a separate cycle where an HDH system was powered by solar collectors. Findings indicated that water production rates varied greatly depending on the ambient temperature reaching 14,200 kg on the hottest day and almost zero on the coldest. System efficiency demonstrated a similar pattern reaching 40.23 % during July and 18.5 % during January. Meanwhile, reductions in carbon emissions as compared to a fossil fuel powered system varied between 32.57 and 125.93 $\frac{tons}{day}$. Another study with the same products was conducted by Hai et al. [60] employing RC, BC, ORC, MSF, solar heliostat, and AWE subsystems. The energy and exergy efficiencies were determined as 78.93 % and 47.56 %, respectively. Also, the proposed system generated 18,992 kW power, 0.04663 $\frac{kg}{s}$ hydrogen, and 0.8862 $\frac{kg}{s}$ freshwater.

Yilmaz et al. [61] presented polygeneration systems which utilized solar towers instead of PTCs as a solar collector system. In addition to the solar tower, the study included a supercritical BC, transcritical RC, MED, PEME, and EJRC. Carbon dioxide was chosen as the working fluid for the power cycles while ammonia was chosen for the EJRC. The net power production was 653.4 kW, while heating, cooling, hydrogen, and freshwater production rates were 1748 kW, 1013 kW, 2.821 $\frac{kg}{h}$, and 2.951 $\frac{kg}{s}$, respectively, as presented in Fig. 7. Thermodynamic efficiencies were reported as 43.77 % and 19.61 % for energy and exergy respectively; meanwhile, the solar collector system demonstrated the highest exergy destruction rate of all the system components. Finally, it was found that an increase in solar irradiation improved overall performance while an increase in wind speed negatively affected it. Analyzing the effect of wind speed on performance of a solar system was unique to this study. Wind speed directly corresponded to the rate of convective heat loss from the surface of the heliostats within the solar tower explaining its negative impact on the overall performance.

Similar in its utilization of a solar tower, Yilmaz [62] analyzed a design which included a BC, RC, ORC, SEAC, PEME, and MSF and its products included power, freshwater, hydrogen, heating, and cooling. A thermodynamic assessment demonstrated efficiencies of 78.93 % and 47.56 % for energy and exergy. Moreover, the overall power generation capacity of the system was 18,992 kW and the system produced hydrogen and freshwater at rates of 0.04663 and 0.8862 kg/s respectively.

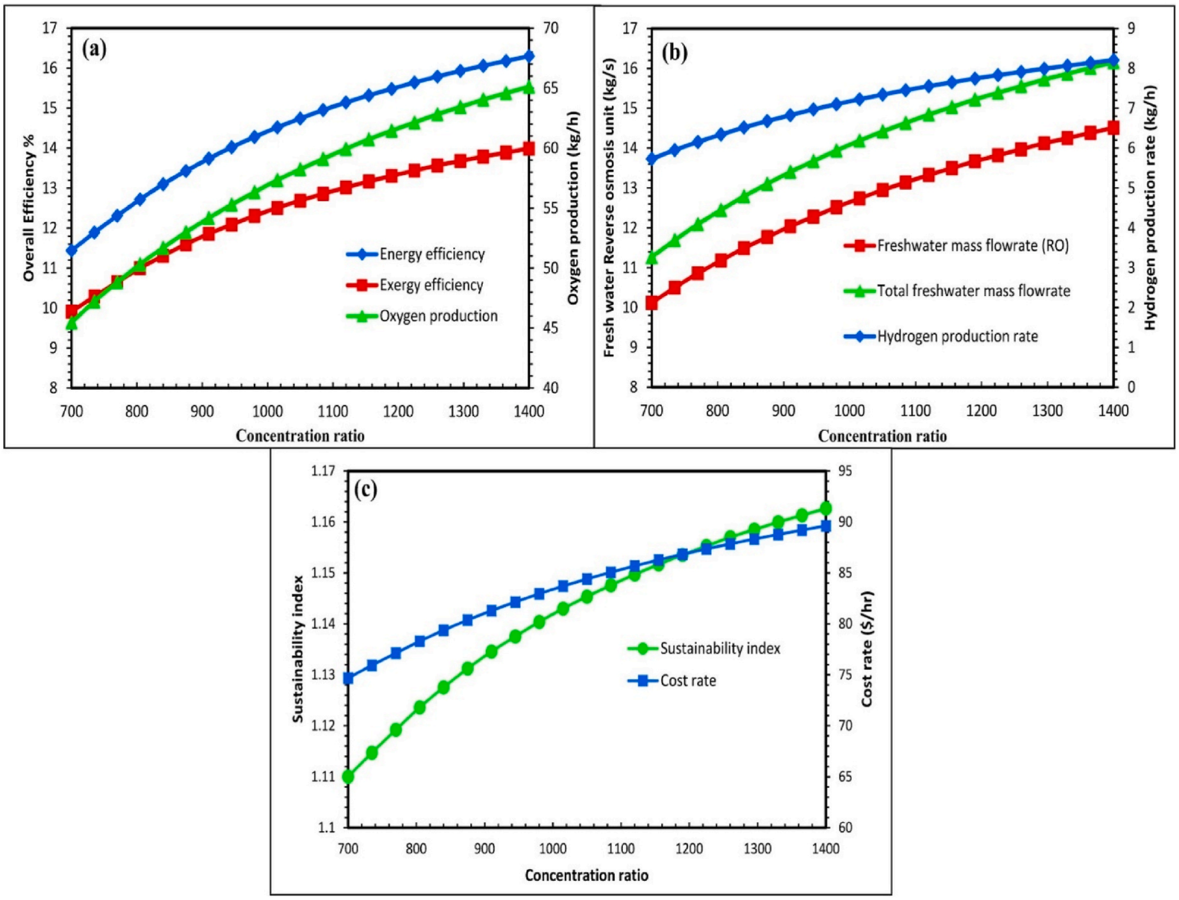

Fig. 6. Results of parametric analysis on the effect of heliostat concentration ratio over (a) oxygen production and overall system efficiency, (b) production rates of water and hydrogen, and (c) sustainability index and cost for overall system [54].

Three more solar tower-based systems were investigated in separate studies. First, the system investigated by Colakoglu and Durmayaz [63] included a BC, ORC, MED, PEME, and lithium bromide AC producing electricity, freshwater, hydrogen, heating, cooling, and hot water. The proposed system was unique in its inclusion of an ammonia-water based Goswami cycle as a bottoming cycle producing power, refrigeration and hot water for the overall system utilizing low grade waste heat from other cycles. The optimum system produced 927.3 kW power, 5.748 kg/h hydrogen, 0.6165 kg/s potable water, 3.73 kg/s domestic hot water, 10.39 kW refrigeration, 135.3 kW space cooling, and 187.3 kW water heating. Moreover, energy and exergy efficiencies were found to be 51.99 % and 36.99 % with solar collectors identified as the largest contributor to exergy destruction. Producing all of the same products except for heating, El-Emam and Dincer [64] designed a polygeneration process which also coupled a solar tower in addition to RO, AC, steam turbine, reheat steam power cycle, and PEME. The system was optimized and found to generate 4 MW of power, 1.25 kg/h of hydrogen, and 90 kg/s of fresh water. The optimized system configuration included 396 heliostats and a tower height of 63.3 m. Lastly, the system proposed by Yuksel et al. [65] incorporated a solar tower, SOE, RC, quadruple effect absorption cycle (QEAC), and MD producing both hot water and drying in addition to electricity, freshwater, hydrogen, cooling, and heating. The analysis demonstrated that the parameter with the highest impact on system performance was solar irradiation while the solar tower contributed the most to the energy destruction within the system. Lastly, the overall energy and exergy efficiencies were found to be 42.18 % and 46.93 % respectively.

Two systems producing electricity, freshwater, hydrogen, heating, cooling, and drying were investigated by Tukenmez et al. [66] and Anamaq et al. [67]. The study by Tukenmez et al. [66] coupled PTC, ORC, PEME, EJRC, MED, and KC subsystems. Thermodynamic efficiencies were 59.34 % and 56.51 % for energy and exergy, while the desalination unit demonstrated the best thermodynamic performance of all system components. The same components were integrated in the system proposed by the Anamaq et al. [67] study except for the use of thermosyphon-assisted refrigeration cycle instead of EJRC. The overall energy and exergy efficiency of the system were 61.34 % and 58.08 %, respectively, according to thermodynamic analysis. Moreover, the dryer unit was the component with the highest efficiency while the PTC system had the highest share of exergy destruction.

Ozlu and Dincer [68], Bozgeyik et al. [69], and Yilamz et al. [70] all utilized PTC's to capture solar energy for their proposed multigeneration systems. Ozlu and Dincer [68] proposed a system which integrated MSF, RC, ammonia-water RCs, and PEME while Bozgeyik et al. [69] employed the same subsystems except for using a single ORC instead of multiple RCs. In addition to the main products, waste heat was utilized to provide hot water and heating for the first study and only hot water for the second. The optimum energy and exergy efficiencies for the proposed system were 36 % and 44 % for the first study while the values were 78 % and 25.50 % for the second. Results from the first study reported a freshwater production rate of 0.04 $\frac{kg}{s}$ and carbon dioxide emissions reduction of 830 $\frac{tons}{year}$ when compared with a natural gas driven system. Meanwhile, the second study investigated the effect of coupling the MSF unit and found no significant effect on the overall process from a thermodynamic point of view. Their results also indicated that the exergy destruction for the PTC was 331 kW which was the highest value of all the different system components. Meanwhile, the ambient temperature had a positive impact on the overall system's thermodynamic performance. Lastly, the polygeneration system investigated by Yilamz et al.

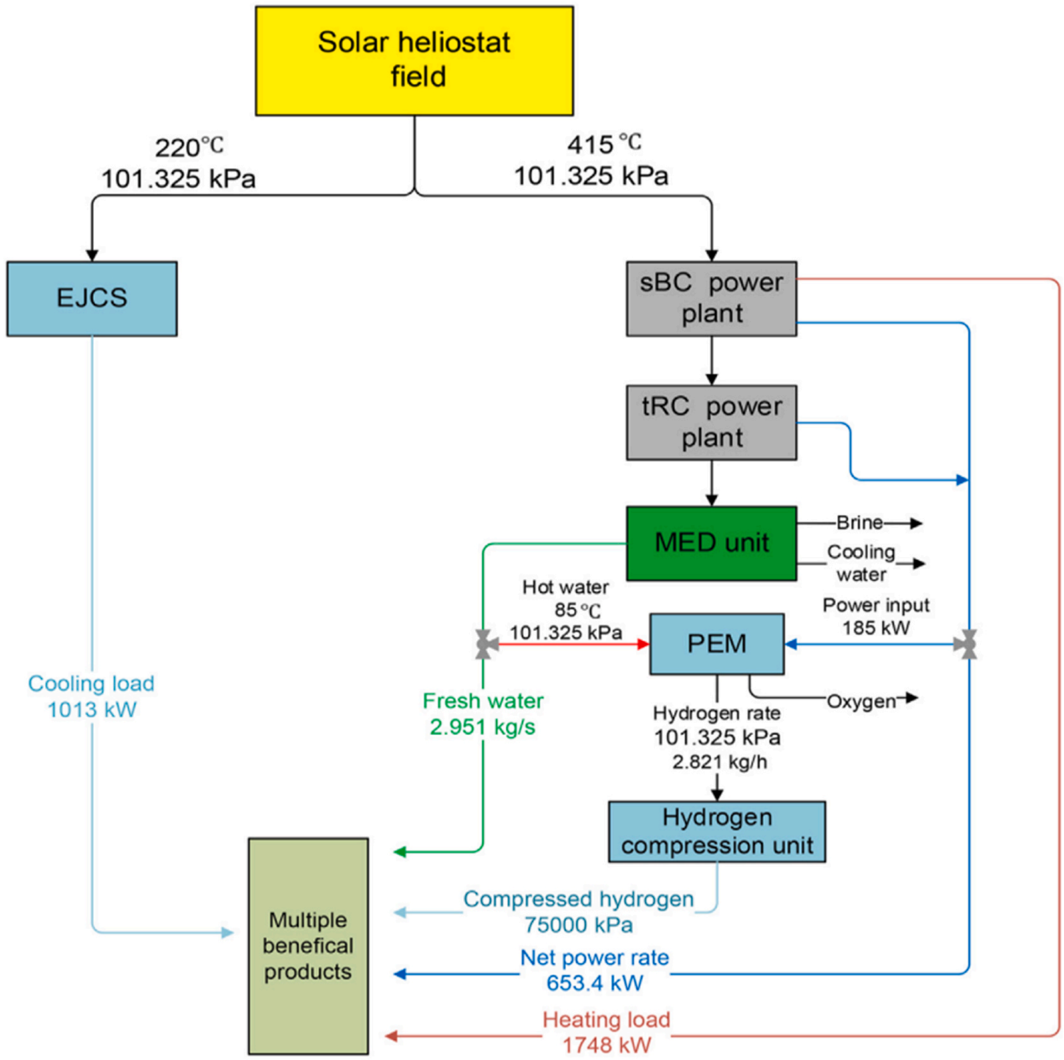

Fig. 7. Block flow diagram of solar polygeneration system showing the flow of water through RC, EJCS, PEME, and MED producing power, cooling, hydrogen, fresh water, and heating [61].

[70] incorporated a PTC, RC, ORC, drying cycle, parabolic dish solar collector, heat pump, MD, PEME, and AC to produce cooling, heating, hot water, hydrogen, freshwater, drying, and electricity. The production rates of power, hydrogen, freshwater, and cooling were 11473 kW, 0.0682 kg/s 0.124 kg/s, and 3842 kW respectively. Finally, the overall energy and exergy efficiencies were reported as 58.43 % and 54.185 % respectively.

Unlike previously mentioned investigations, multiple studies proposed systems that produced only cooling in addition to electricity, freshwater, and hydrogen. For example, Musharavati et al. [71] proposed a solar tower based system which coupled RO, ORC, EJRC and PEME. Three different working fluids for the ORC were compared and n-octane demonstrated the best performance when compared to propane and iso-butane. Moreover, solar radiation intensity was found to have a negative impact on the overall system exergy efficiency while the turbine inlet temperature had the opposite effect. Producing the same products, Khalid and Kumar [72] employed an ORC, PEME, vapor compression cycle, and freezing desalination unit in conjunction with a PTC in their presented system. The energy and exergy efficiencies were found to be 17.5 % and 10.9 % respectively. Similarly, the polygeneration system proposed by Nedaei et al. [73] integrated a supercritical BC, AC, HDH, PEME, and a solar tower. The solar irradiation and estimated costs were used to perform a thermodynamic, economic, and parametric analysis as presented in Fig. 8. Results demonstrated an exergy efficiency of 38.7 %, power output of 7.4 MW, and unit cost of products of 9.7 $\frac{\$}{GJ}$ during the month of May. Lastly, the solar tower was found to be the largest contributor of exergy destruction within the system. Another polygeneration system producing freshwater, hydrogen, cooling, and electricity was proposed and analyzed by Hadelu et al. [74]. Components of the system included a supercritical EJRC, SOE, PTC, and a solar still. Moreover, seven different phase changing materials (PCM) were tested for the energy storage system of the PTC. Study findings indicated that Cu–Si metal alloy has a superior thermodynamic profile as a PCM while inorganic salts lead to lower costs, emissions, and water requirements.

Similar studies of polygeneration systems producing electricity, freshwater, hydrogen, and cooling were also carried out by Khan et al. [75] and Mehrenjani et al. [76]. The former employed parabolic dish collectors, supercritical BC, PEME, DEAC, and single flash distillation. The performance of a novel PCM (Li_2CO_3–Na_2CO_3) was investigated and its utilization was found to reduce the levelized electricity cost. Overall energy and exergy efficiencies were 31.59 % and 30.02 %; meanwhile, water and hydrogen production rates were 1.564 $\frac{kg}{s}$ and 0.0024 $\frac{kg}{s}$. Mehrenjani et al. [76] put forth a polygeneration system producing the same products while coupling an ORC, TEG, PEME, SEAC, RO, and PTC. The coupling of SEAC and TEG utilizing waste heat from the power cycle was determined to increase power production by 29 %. Three modes of

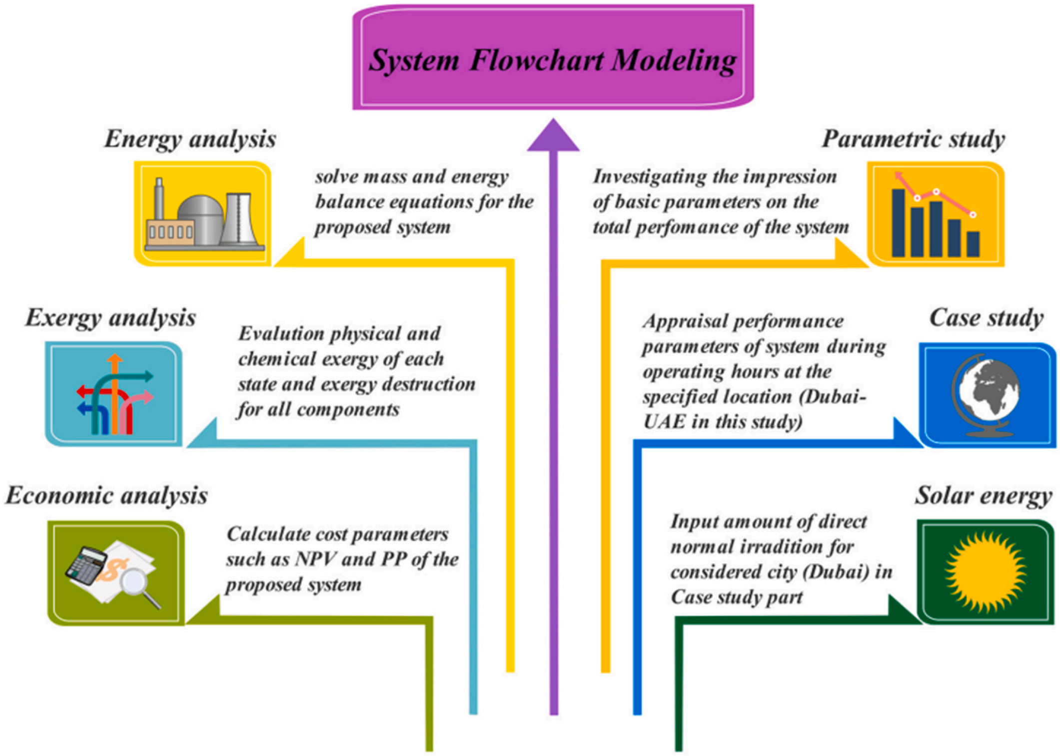

Fig. 8. Simulation process for parametric, economic, exergy, and energy analyses of a multigeneration system [73].

operation were modelled which accounted for the different radiation levels throughout a typical day. The results indicated that the highest efficiency levels were obtained when the system operated at solar only mode with energy and exergy efficiencies of 45.31 % and 10.85 % respectively.

Finally, production of chemicals was observed in two studies of solar powered polygeneration systems producing hydrogen and water. Firstly, Esmaeilion et al. [77] presented a system incorporating a solar tower, carbon dioxide RC, combined cooling heat and power plant (CCHP), and MSF to produce electricity, hydrogen, cooling, heating, sodium hypochlorite, and freshwater. In addition, this system was unique in its utilization of brine electrolysis which also served the function of reducing the environmental impact of brine disposed by the MSF unit. Energy and exergy efficiency were calculated as 22.39 % and 40.24 % respectively and the net present value for the overall system was found to be 1.44×10^9 \$. Secondly, Yilmaz et al. [78] proposed a system which produced ammonia in addition to electricity, freshwater, and hydrogen at rates of 0.004842 $\frac{kg}{s}$, 1654 kW, 1.182 $\frac{kg}{s}$, and 0.0025 $\frac{kg}{s}$ respectively. The polygeneration system coupled a PTC, transcritical RC, PEME, ammonia synthesis reactor, and MED with overall system energetic and exergetic efficiencies of 29.04 % and 27.43 %.

3.2. Solar and geothermal multigeneration systems

As previously mentioned, coupling of other renewable energy sources with solar increases a system's overall reliability. Therefore, most investigations of hydrogen and freshwater production through solar multigeneration systems also included other renewables with geothermal being the most common. Unlike the intermittent nature of solar energy, geothermal energy is continuous which in theory should improve the overall performance of the proposed systems [79,80]. Except for two trigeneration systems, all the solar and geothermal powered systems produced more products than three.

Two main approaches to the utilization of geothermal energy in multigeneration systems were observed in the literature. First, systems such as the one presented by Ahmadi et al. [81] among others opted to exclusively use the geothermal source to provide heat for the working fluid of the solar collector. Meanwhile, other studies such as Cao et al. [82] utilized geothermal heat to power various other system components including power cycles. Lastly, all the solar and geothermal systems discussed below are summarized in Table 2 at the end of this section.

3.2.1. Solar and geothermal trigeneration systems

Trigeneration systems producing electricity, freshwater, and hydrogen and relying on solar and geothermal energy were presented twice in the literature. The first analysis was performed by Balali et al. [83] which integrated a geothermal plant, PTC, RC, ORC, PEME, HDH, and TEG. The system was analyzed in four modelling and optimization steps as presented in Fig. 9. MATLAB was used to simulate the system, and results were utilized to train an artificial neural network (ANN) to generalize the simulation results. Also, a genetic algorithm (GA) was utilized in conjunction with the ANN to optimize system parameters. The hybridization of GA and ANN was done since ANNs can provide accurate estimates for the fitness of a potential solution suggested by the GA thereby avoiding the high computation requirements of MATLAB simulations. Finally, linear programming technique for multidimensional analysis of preference (LINMAP) was utilized to find preferrable solutions from the pareto front obtained by the GA for the multi objective optimization problem. Results indicated power, hydrogen, and freshwater production rates of 429.29 kW, 2.49 $\frac{kg}{h}$, and 907.16 $\frac{kg}{h}$ respectively. Moreover, the solar power plant and RC were the highest exergy destruction contributors; meanwhile, PTCs and steam generators had the highest costs of all system components. Similarly, Li et al. [84] coupled a TRCC, ORC, TEG, HDH, PEME, solar collectors, and single flash geothermal (SFG) system. The study found that increased reliance on solar energy as opposed to geothermal energy improved efficiency, production rates, and costs. After a multi-objective optimization analysis was undertaken, energy efficiency was found to be 23.35 % and the levelized cost of power was 17.07 $\frac{\$}{GJ}$.

Table 2
Summary of solar and geothermal trigeneration and polygeneration systems producing hydrogen, freshwater, and electricity investigated in the literature.

Ref.	H2 prod.	Desal.	Solar collector	Prime movers	Other Components	Other products	Energy efficiency	Exergy efficiency
[83]	PEME	HDH	PTC	RC ORC	TEG	–	–	–
[84]	PEME	HDH	PTC	TRCC ORC	TEG SFG	–	23.35 %	–
[88]	Cu–Cl cycle	MED	PTC	TARC	Heat pump	Heating	–	–
[91]	PEME	MED	Greenhouse	KC ORC	Dryer TEG	Heating Drying Hot water	–	–
[92]	PEME	HDH	PTC	ORC	ICE	Hot water	23.87 %	28.21 %
[96]	Mg–Cl cycle	MED	Solar tower	ORC	–	Heating Hot water	45.45 %	52.32 %
[97]	Cu–Cl cycle	MED	PTC	BC	–	Heating Hot water	52.6 %	47.1 %
[89]	Cu–Cl cycle	MED	PTC	TARC	Heat pump	Hydrogen Heating	–	–
[90]	Cu–Cl cycle	MED	PTC	TARC	Heat pump	Heating	–	–
[85]	PEME	RO	PTC	RC ORC	AC	Cooling	–	32.39 %
[93]	PEME	RO	PTC	RC ORC	AC	Heating Cooling Hot water	31.66 % at night	60.56 % at night
[82]	PEME	HDH	PTC	TRCC	Modified transcritical RC	Cooling	19 %	–
[87]	Cu–Cl cycle	MED	Bifacial PV	RC	Heat pump	Heating	22.7 %	18.2 %
[86]	PEME	RO	Solar tower	ORC	Fuel cell AC	Cooling	42.3 %	21.3 %
[81]	PEME	HDH	PTC	ORC Regenerative ORC	SEAC	Cooling	–	–
[94]	PEME	RO	PTC	ORC Steam cycle	AC TEG	Cooling Hot water	–	–
[95]	PEME	RO	PV Dish collectors FPC	ORC	EJRC Air dryer unit	Cooling Heating Dry air Oxygen	–	–

Abbreviations: PEME – Proton Exchange Membrane Electrolyzer, HDH – Humidification-Dehumidification, PTC – Parabolic Trough Collectors, RC – Rankine Cycle, ORC – Organic Rankine Cycle, TEG – Thermoelectric Generator, TRCC – Trans Critical CO2 Cycle, SFG – Single Flash Geothermal, MED – Multi Effect Distillation, TARC – Trilateral Ammonia Rankine Cycle, KC – Kalina Cycle, ICE – Internal Combustion Engine, BC – Brayton Cycle, RO – Reverse Osmosis, AC – Absorption Cooling Cycles, SEAC – Single Effect Absorption Cycle, FPC – Flat Plate Collector.

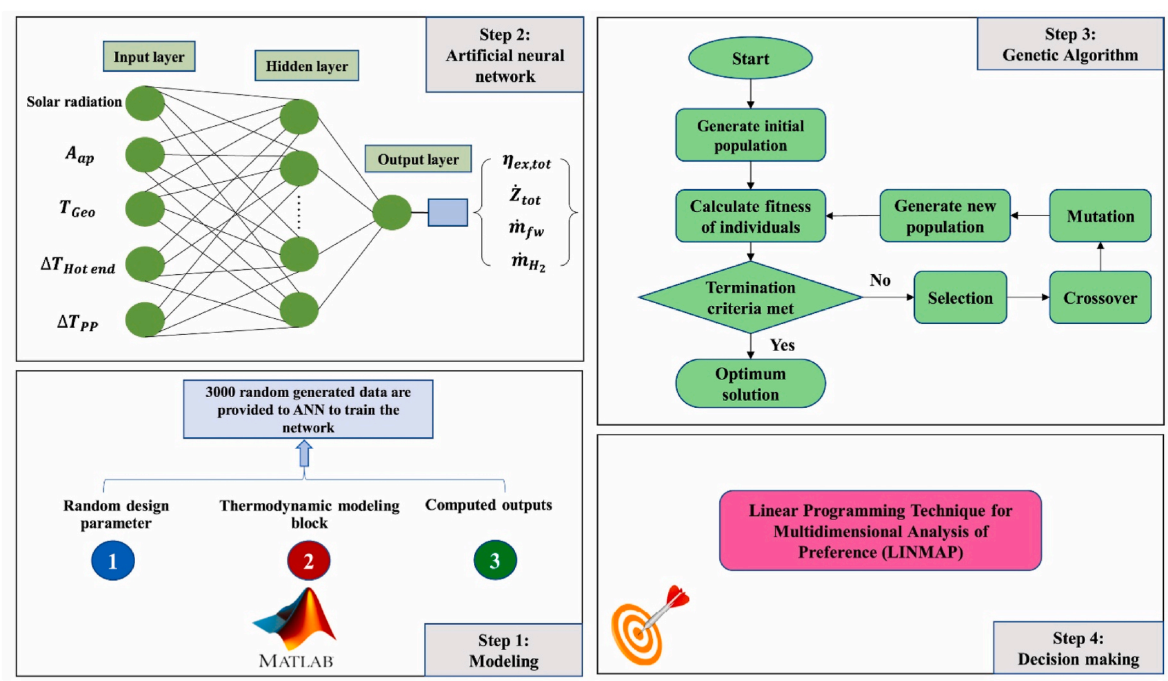

Fig. 9. Optimization process of trigeneration system using MATLAB simulation, ANN regression, GA optimization, and LINMAP decision making analysis [83].

3.2.2. Solar and geothermal polygeneration systems

Some of the studies proposed polygeneration solar and geothermal systems which produced electricity, freshwater, hydrogen, and cooling. For example, Assareh et al. [85] looked into a system which integrated a PTC, RC, ORC, PEME, RO, and AC. The proposed system was simulated and optimized to increase the exergy efficiency and decrease costs. The analysis determined that the best PTC heat transfer fluid was Therminol 59. Results also revealed that PTCs had the highest contribution to exergy destruction. The system was found to annually produce 5,741, 637 kWh of electricity, 1,935,794 kWh of cooling, 169,803 m^3 of freshwater, and 15,371 kg of hydrogen. Lastly, the optimum overall system was found to have an exergy efficiency of 32.39 % and levelized cost of 36.32 $\frac{\$}{GJ}$. Another example was presented by Cao et al. [82] utilizing PTCs, transcritical CO2 ORC, steam turbine, modified transcritical refrigeration cycle, PEME, and HDH. As presented in Fig. 10, the geothermal source was separated into steam and water streams using an expansion valve and separator. Steam was used to power the steam turbine while the high temperature water provided heat to the transcritical CO2 ORC. In addition, heat from the solar field also functioned as a heat source for the ORC while waste heat from its turbine effluent was utilized as heat source for PEME water input preheating, HDH, and refrigeration cycle. A multi objective optimization analysis resulted in as system with 19 % energy efficiency, 1316 kW total exergy destruction rate, 53.02 $\frac{m^3}{day}$ freshwater production rate, 1.733 $\frac{kg}{h}$ hydrogen production rate, 132.7 kW cooling rate, and net output power of 316.3 kW. Finally, levelized costs were found to be 14.5 $\frac{\$}{GJ}$ and 18.7 $\frac{\$}{GJ}$ for total products and electricity, respectively.

Other studies of systems producing the same products include Ahmadi et al. [81] which proposed a system incorporating a PTC, ORC, regenerative ORC, PEME, HDH, and SEAC. The system was simulated for different radiation intensity periods with solar, solar-storage, and storage modes. Therminol 66 oil was used as a working fluid of the PTC, n-octane for the regenerative ORC, and isopentane for two separate ORCs. As presented in Fig. 11, two consecutive evaporators transferred heat from the PTC to the power cycles, each of which was coupled with HDH units utilizing their waste heat. A third evaporator raised the temperature of the oil returning to PTC using geothermal heat which was subsequently used to preheat PEME water input and provide energy for the SEAC. The net power production rates for the solar, solar-storage, and storage modes were found to be 1118, 807.9, and 773.4 kW, respectively. Furthermore, the energetic efficiencies of the three modes were calculated to be 121.9, 57.28, and 77.68 % with a similar trend observed for exergetic efficiencies at 7.696, 3.374, and 4.922 %. In a similar analysis, Siddiqui and Dincer [86] coupled RO, ammonia fuel cell, PEME, solar tower, AC, ammonia fuel cell, and ORC. Results indicated exergy and energy efficiency values of 21.3 % and 42.3 %, respectively. Moreover, the geothermal system and AC generator had the highest exergy destruction rates at 643.3 kW and 2370.2 kW, respectively.

Temiz and Dincer [87] presented a system which uniquely utilized a bifacial PV system instead of a solar collector. Additionally, the system combined a Cu–Cl cycle, RC, and MED producing electricity, hydrogen, freshwater, and heating. Results indicated energy and exergy efficiencies of 22.7 % and 18.2 %, respectively. Also, the energy gain of the PV system proposed for the case study was found to be 25.49 %. Another system investigated by Temiz and Dincer [88] employed MED, Cu–Cl cycle, trilateral ammonia Rankine cycle (TARC), PTC, and heat pump. The study presented results including production capacities for electricity, heat, hydrogen, and freshwater of 47.6 GWh, 452.6 GWh, 296.9 $\frac{tons}{year}$, and 160,392.1 $\frac{tons}{year}$. Furthermore, November had the highest overall energy efficiency of 27.56 %, while January had the highest exergy efficiency of 18.39 %. Lastly, the unit costs of hydrogen and electricity were found to be 2.84 $\frac{\$}{kg}$ and 0.029 $\frac{\$}{kWh}$ respectively.

The analysis performed in Temiz and Dincer [88] was later expanded

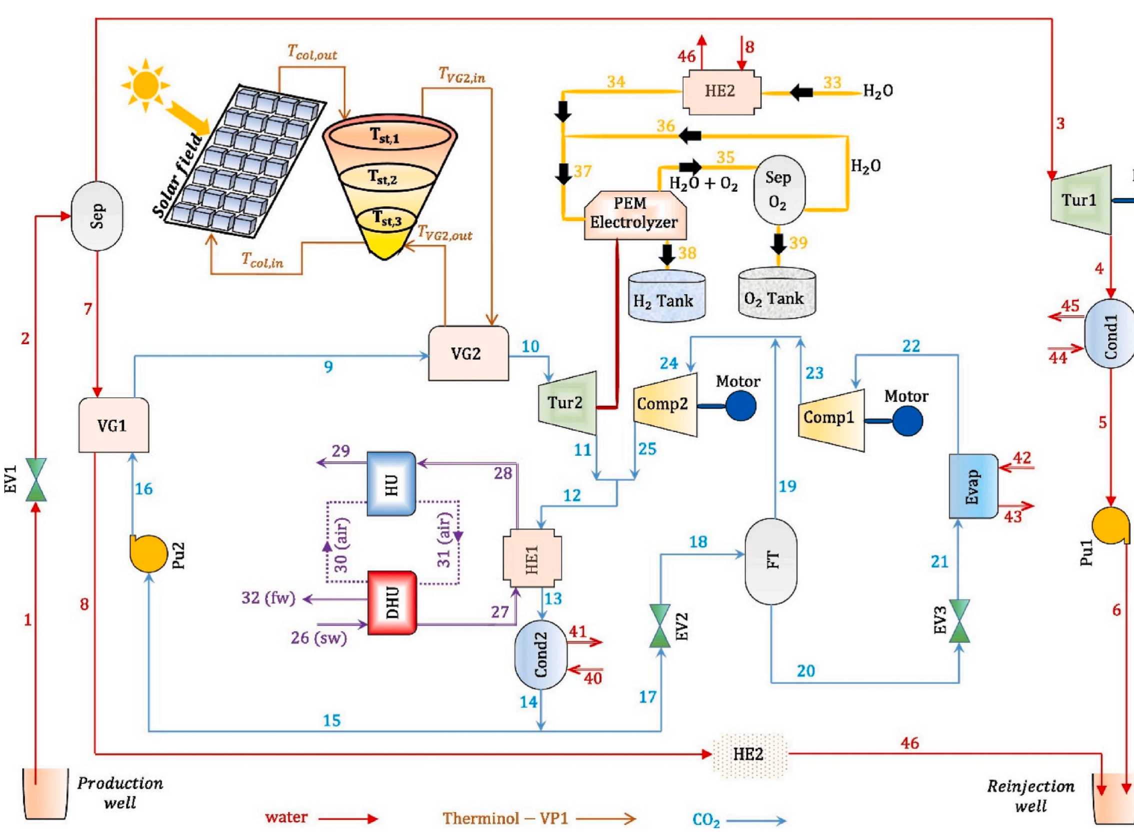

Fig. 10. Process flow diagram of solar and geothermal powered polygeneration system including a solar collector, power cycles, refrigeration cycle, desalination unit, and geothermal well extraction [82].

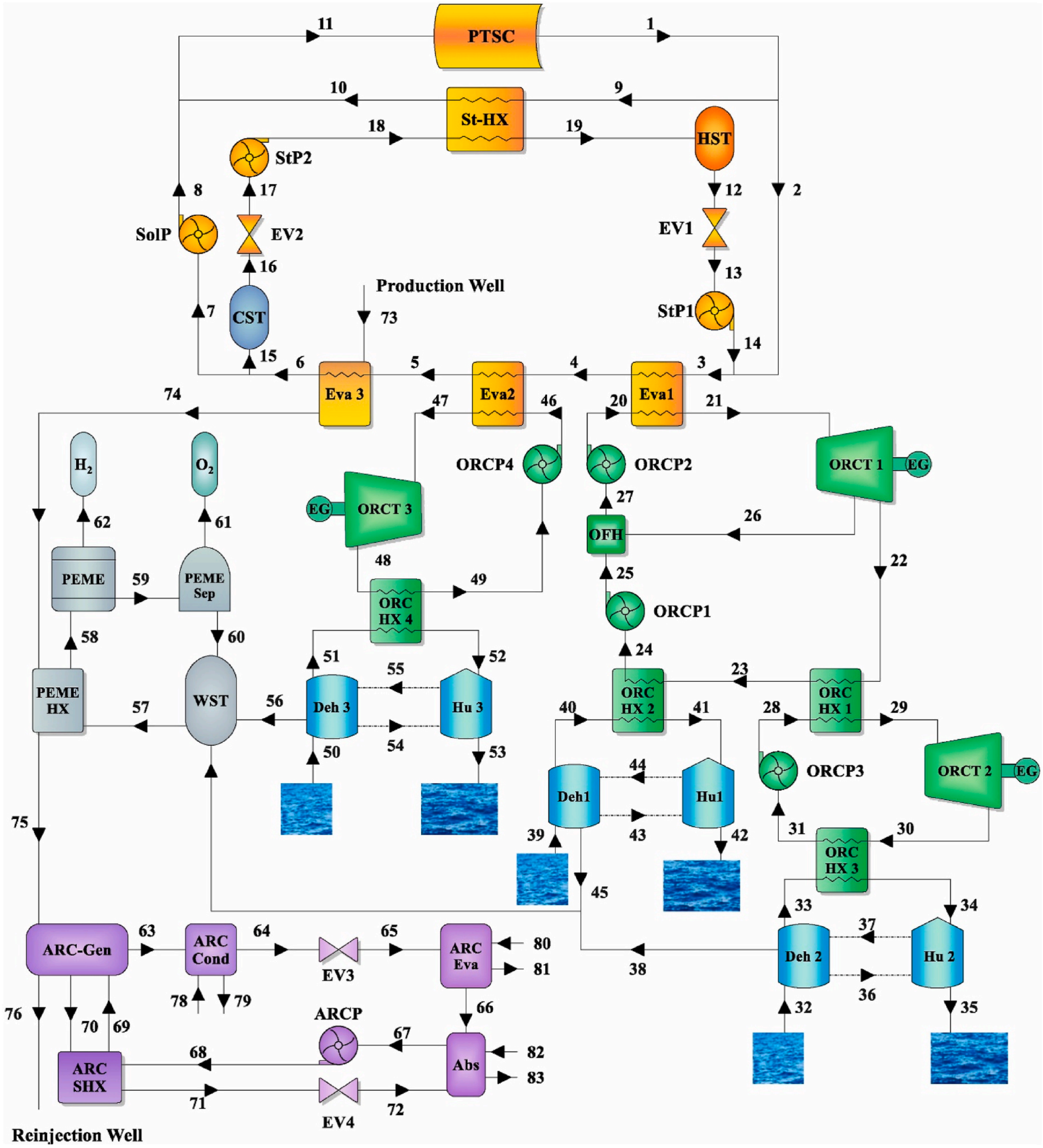

Fig. 11. Process flow of multigeneration system powered by geothermal and solar energy [81].

by Sohani et al. [89] to compare static and dynamic multi-objective optimization approaches in the same system. It was found that dynamic multi-objective optimization increased annual production of electricity, heating, hydrogen, and freshwater by 14.4 %, 16.1 %, 13.5 %, and 14.3 % respectively, proving much more effective when compared with static optimization. Furthermore, Sohani et al. [90] presented another study of the same system mainly focused on the effects of price inflation on multi-objective optimization decision variables and overall results and found that higher inflation rates led to higher rates of solar energy utilization instead of geothermal. For example, a 0.15 increase in inflation rate, from 0.05 to 0.2, led to a 14.4 % increase in the solar collector area and 20.1 % decrease in the mass of extracted geothermal water. This result was attributed to the high investment costs of solar collectors compared to geothermal energy whose costs are distributed over the project's life cycle making them more sensitive to inflation. Simultaneously, annual production of hydrogen increased by 9.9 %; however, freshwater, electricity, and heat production decreased by 15.0 %, 12.2 %, and 12.0 %, respectively.

Production of heating and hot water was observed in multiple studies such as Yilmaz and Ozturk [91] which integrated a KC, ORC, MED, dryer, TEG, greenhouse, and PEME to produce power, cooling, freshwater, compressed hydrogen, drying, hot water, and heating. Optimum KC, ORC, and TEG capacity was found to be 358.2 kW, 160.4 kW, and 182.62 kW. Moreover, heating and cooling rates were determined to be 1783 kW and 1169 kW while the geothermal powered greenhouse had a heating capacity of 4825 kW. Production capacity for freshwater and hydrogen were 2.777 $\frac{kg}{s}$ and 0.000392 $\frac{kg}{s}$. Lastly, the results were validated by comparing the effect of ambient and geothermal water temperatures on results to their effects in similar studies as presented in Fig. 12.

Also, Manesh et al. [92] analyzed a system which produced electricity, freshwater, hydrogen, and hot water by coupling an ORC, PTC,

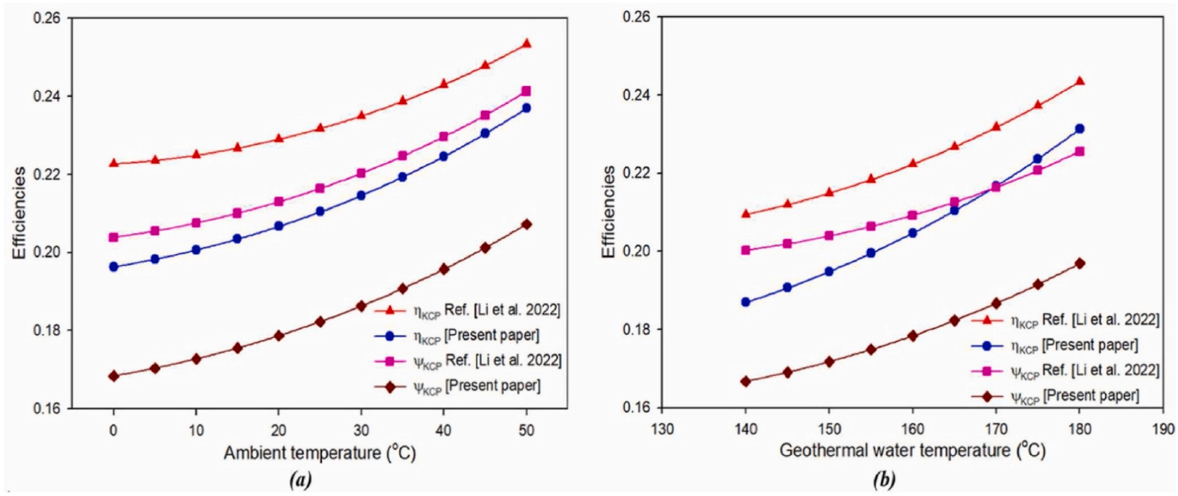

Fig. 12. Comparative analysis of the influence of a) ambient temperature, b) geothermal water temperature on overall system efficiency values for solar and geothermal powered polygeneration systems [91].

internal combustion engine (ICE), PEME, and HDH. Natural gas was used to augment power production during low solar radiation periods. Moreover, nine different organic fluids were investigated for use in the power cycle. Overall energy and exergy efficiencies were found to be 23.87 % and 28.21 % while production rates of freshwater, hot water, and hydrogen were 4.67 $\frac{m^3}{day}$, 1.31 $\frac{kg}{s}$, and 1.85 $\frac{kg}{h}$. Furthermore, ICE had the highest exergy destruction and environmental impact; meanwhile, the HDH unit had the lowest exergy efficiency. Lastly, the thermodynamic performance, operating costs, and environmental impact of the overall system were lower during summer months.

An almost identical system was investigated by Alirahmi and Assareh [93] integrating an ORC and RC to produce electricity, PEME to produce hydrogen, RO to produce freshwater, PTCs as solar collectors, and an AC for cooling. Heating and hot water were also produced, and the system was optimized using machine learning and metaheuristic algorithms. The maximum outlet work of the system was 1109 kW; moreover, the cost rate was 21.9 $\frac{\$}{GJ}$ with an energy efficiency of 31.66 %. Exergy efficiency was found to be 60.56 % at night while the PEME, AC, and solar collector had the highest rates of exergy destruction, in that order. Additionally, Alirahmi et al. [94] proposed a polygeneration system which coupled a PTC, AC, ORC, TEG, steam cycle, RO, and PEME producing hydrogen, freshwater, electricity, cooling, and hot water. The effect of increasing the solar collector area was investigated. It was found that power production grew from 702 kW to 3512 kW and overall system costs from 34.72 to 151.5 $\frac{\$}{h}$ when the solar collector area was expanded from 5000 to 25,000 m^2. Moreover, PTC was found to be the largest cost and exergy destruction contributor. Lastly, Dong et al. [95] analyzed a system which integrated PEME, ORC, EJRC, RO, PV, solar dish collectors, FPC, and air dryer unit to produce electricity, freshwater, hydrogen, oxygen, dry air, and heating. Results indicated that the number of FPCs has a large impact on the system's overall performance. In addition, the solar subsystem, including the collectors and PV systems, accounted for around 90 % of the total exergy destruction. Lastly, the optimum unit exergy cost of products, cooling load, and freshwater production rate were 19.77 $\frac{\$}{GJ}$, 38.89 kW, and 23.02 $\frac{kg}{s}$.

In all of the studies discussed up to this point, thermochemical cycles for hydrogen production were only deployed by Temiz and Dincer [87]. Two more studies by Gevez and Dincer [96] and Temiz and Dincer [97] utilized thermochemical cycles. First, Gevez and Dincer [96] presented a system producing freshwater, electricity, hydrogen, hot water, and space heating by coupling MED, Mg–Cl cycle, solar tower, and ORC. Production capacities were 8519 kW net power, 48.0212 $\frac{kg}{s}$ fresh water, and 8.70880 $\frac{kg}{h}$ hydrogen. Moreover, thermodynamic analysis revealed energy efficiency, exergy efficiency, and total energy destruction values of 45.45 %, 52.32 %, and 163,967.0353 kW, respectively. Additionally, Temiz and Dincer [97] opted for the same choice; however, utilizing different power and hydrogen production cycles. The system incorporated BC, Cu–Cl cycle, PTC, and MED and had an annual production capacity of 420.05 GWh of electricity, 11,983.68 tons of freshwater, 136.51 GWh of thermal energy, and 1034.18 tons of hydrogen. Overall energy and exergy efficiency rates were found to be 52.6 % and 47.1 % respectively.

3.3. Solar and biomass multigeneration systems

Another common renewable energy source utilized for multigeneration systems producing hydrogen and water in combination with solar is biomass. Only two studies of solar and biomass powered multigeneration systems producing freshwater and hydrogen encountered were of trigeneration systems producing electricity, water, and hydrogen. Modabber and Rabeti [98] proposed one such system, so did Rabeti et al. [99] with both utilizing municipal solid waste (MSW) as the biomass source. The first study investigated a system with an incineration unit, steam cycle, gas cycle, ORC, PTC, RO, and AWE. In addition to the typical thermodynamic, exergy, sensitivity, and optimization analyses, the study uniquely performed both and emergy and thermo-risk analyses. Emergy which is also called embodied energy involves the transformation of parameters for all system units and flows into units of solar emergy jouls (sej) using established conversion factors. Results for the emergy and thermos-risk analyses are presented in Figs. 13 and 14 respectively. Furthermore, results presented production rates of were 5.3 MW of electricity, 10.52 $\frac{kg}{h}$ of hydrogen, and 27.44 $\frac{kg}{s}$ of potable water. Moreover, energy and exergy efficiency were 21.72 % and 16.94 % while the overall and levelized electricity costs were determined as 653.03 $\frac{\$}{h}$ and 0.072 $\frac{\$}{kWh}$. Finally, results indicated that the incineration unit had the highest cost of all subsystems.

Meanwhile, Rabeti et al. [99] analyzed a system which coupled a KC, ORC, MED-TVC, RO, PEME, PTC, gas turbine, and double pressure steam cycle. In addition to MSW, mixed paper waste (MPW) and date palm waste (DPW) were considered and the performances of the three were compared. Results indicated that MSW was the most economically viable option while MPW had the best thermodynamic performance. Energy and exergy efficiencies when MSW was used as a source were 39 % and 32.01 % respectively; furthermore, the PTC subsystem had the highest investment costs.

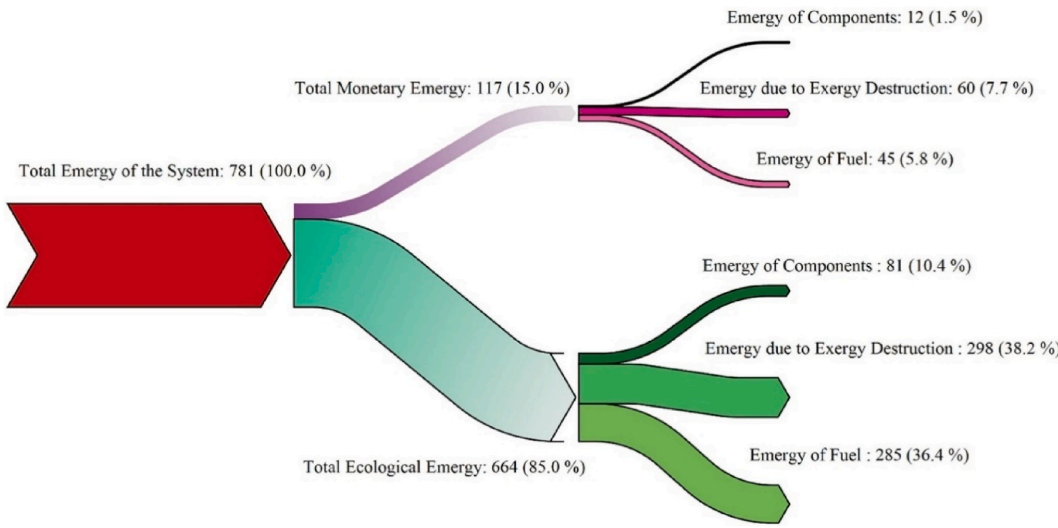

Fig. 13. Results of emergy analysis for solar and biomass powered trigeneration system producing water, hydrogen, and power [98].

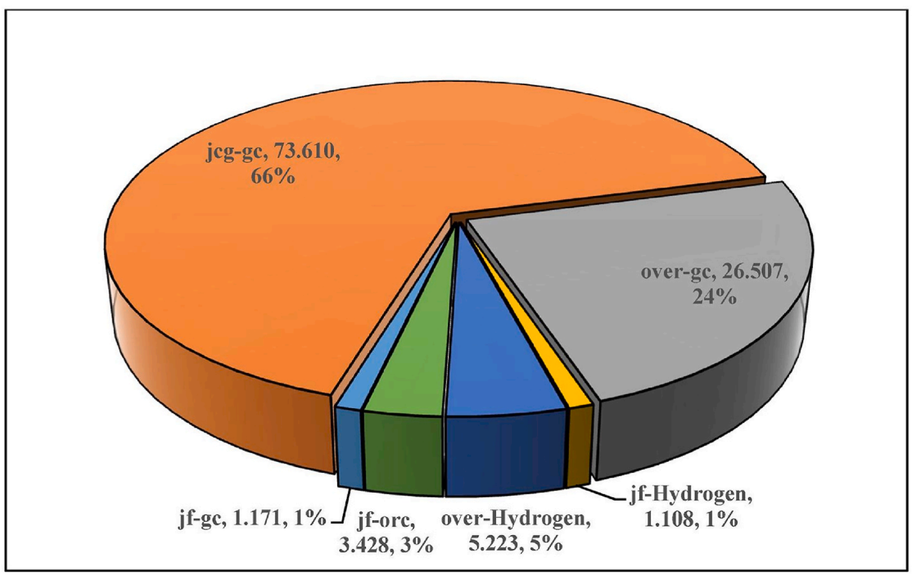

Fig. 14. Results of analysis presenting risks of various potential hazards identified for a trigeneration system [98].

Many investigations of polygeneration systems producing products such as cooling, heating, and hot water are presented in the literature. For example, Zhou et al. [100] analyzed a solar and biomass powered system which included a solar tower, AC, TEG, PEME, RO, RC, organic flash cycle, and gas turbine. The exergy efficiency was reported as 24.34 % while the solar tower was the largest contributor to exergy destruction. Moreover, Production capacities were 26,599 kW of power, 13, 015 kW of heating, 8401 kW of cooling, 16.18 $\frac{kg}{h}$ of hydrogen, and 67.93 $\frac{kg}{s}$ of freshwater. Another system producing those products was proposed by Hashemian and Noorpoor [101] employing RC, DEAC, PEME, MED, and PTC. With a 188,000 m^2 PTC area and 6.2 $\frac{ton}{h}$ of biogas consumption, the proposed system had the capacity to generate 26.3 MW electricity, 137.3 MW cooling load, 21.4 MW heating load, 72 $\frac{kg}{h}$ hydrogen, and 3927 $\frac{m^3}{h}$ potable water with an exergy efficiency of 16.53 %.

Two different studies investigated biomass and solar polygeneration systems producing electricity, freshwater, hydrogen, and ammonia. First, the system proposed by Lu et al. [102] utilized solid waste as its biomass source and coupled a gasifier, gas turbine, RC, solar collectors, MSF, PEME, and Haber-Bosh ammonia synthesis cycle. Results indicated that increasing the biomass flow rate expands the freshwater production capacity while increasing the overall costs. Moreover, the system's energy efficiency, overall costs, and network output were determined to be 37 %, 0.395 $\frac{\$}{s}$, and 18,900 kW. Second, the system investigated by Siddiqui et al. [103] deployed rice husk as feed for the gasifier producing biofuel. Furthermore, a solar tower, RO, TEG, BC, RC, ammonia synthesis reactor, PEME, and AC were integrated. A cryogenic air separation unit was also included to separate oxygen and nitrogen from air for use in the gasifier and ammonia reactor respectively. Overall energy and exergy efficiency values were determined as 20.1 % and 21.1 % while the hydrogen and ammonia production rates were calculated as 20 g/s and 79 g/s. Lastly, the savings in carbon dioxide emissions when compared to natural gas and coal-based plants were estimated to be 29, 998,632 kg/year and 88,269,768 kg/year.

Siddiqui and Dincer [104] and Khan et al. [105] both investigated solar and biomass powered polygeneration systems producing electricity, cooling, freshwater, and hydrogen. The first study included a gasifier, pressure swing adsorption unit, RC, RO, WSG, ammonia-water AC, and solar tower. Rice husk was assessed as biomass gasifier feed. The overall energy and exergy efficiencies were found to be 46.8 % and 47.8

% respectively. Meanwhile, the system proposed by Khan et al. [105] utilized MSW as biomass and included a PTC, incinerator, SEAC, ORC, PEME, and RO. It was found that the turbine inlet temperature and solar irradiation both had a positive impact on the thermodynamic performance of the system. Results also indicated that the incineration boiler accounted for 78 % of the overall system's exergy destruction.

Alirahmi et al. [106] simulated a biomass and solar powered system which included a gasifier, gas turbine, RC, ORC, solar tower, PEME, and MED-TVC producing electricity, hydrogen, freshwater, heating, and hot water. Results demonstrated that the total cost rate for the proposed system was 224.1 $\frac{\$}{h}$ while the exergy efficiency was 26.7 %. Also, it was found that increases in the biomass flow rate corresponded positively to the exergy efficiency and production rates of hydrogen and freshwater. Hashemian and Noorpoor [107] looked into another solar and biomass polygeneration system where PTC, RC, EJRC, PEME, TEG, and MED subsystems were integrated. The results included 76.12 % energy efficiency, 14.24 % exergy efficiency, 33.03 MW net power output, 16.09 $\frac{m^3}{h}$ potable water production rate, 90.87 $\frac{kg}{h}$ hydrogen production rate, and 149.86 MW cooling load. Moreover, the PTC had the highest share of exergy destruction following the consistent results of other studies. Finally, the economic analysis revealed that the overall cost of the system was 0.98 $\frac{\$}{s}$ and the levelized cost of power was 0.018 $\frac{\$}{MW}$.

Some studies opted to rely on more than two energy sources. For example, Bamisile et al. [108] proposed a solar, biomass, and wind powered polygeneration system producing electricity, hydrogen, cooling effect, hot air, and hot water, and freshwater at rates of 3.4 MW, 12.41 $\frac{L}{s}$, 279.4 kW, 17.546 $\frac{kg}{s}$, 144.18 $\frac{L}{min}$, and 10.31 $\frac{L}{min}$ respectively. The system coupled a WT, PVT, PEME, gas cycle, steam cycle, MSF, hot water chamber, hot air chamber, and biogas digester. Results revealed energy efficiency values ranging from 64.91 % to 71.06 % and exergy efficiency values from 31.8 % to 53.81 %. Another investigation involving systems with three energy sources was conducted by Bozgeyik et al. [109] investigating a solar, biomass, and geothermal powered system. The proposed system integrated PTC, RC, ORC, AC, gas turbine, MSF, geothermal plant, and PEME. Production rates were 7684 kW power, 12,474 kW heating, 358.9 kW cooling, 3.51 $\frac{kg}{h}$ hydrogen, and 6.16 $\frac{kg}{s}$ freshwater. Moreover, energy and exergy efficiencies were 65.55 % and 27.09 % respectively. The biomass combustion chamber was found to be the component with the largest exergy destruction rate.

3.4. Solar, wind, and nuclear multigeneration systems

Although less commonly encountered, some systems investigated the utilization of wind and/or nuclear energy sources with solar. Two examples of wind energy utilization by Bamisile et al. [108] and Bozgeyik et al. [109] were already discussed in the previous section. Another such study was done by Esmaeilion et al. [110] utilizing wind and solar energy to produce electricity, cooling, freshwater, hydrogen, and sodium hypochlorite. This study was unique in its investigation of the use of a salinity gradient solar pond. Also, FPC, SEAC, TEG, WT, RO, and a brine electrolysis unit were integrated within the system. Production capacities were found to be 2391 kW cooling load, 583.9 kW electricity, 1.48 $\frac{m3}{s}$ hydrogen, 0.01445 $\frac{m3}{s}$ freshwater, and 0.001416 $\frac{kg}{s}$ sodium hypochlorite with energy and exergy efficiency values of 27.3 % and 19 %. Similarly, Bolt et al. [111] proposed a system fueled by solar and wind energies. However, their proposed system also utilized waste heat from steel production in the form of its flue gas. Subsystems included PEME, WT, RC, PTC, MED, mono-ethanolamine AC, and methane reactor. The mono-ethanolamine AC unit separated carbon dioxide from the flue gas through the Sabatier chemical reaction for utilization in methane production minimizing emissions. Carbon dioxide was captured at a rate of around 0.0567 $\frac{kg}{s}$ and led to methane production at an approximate rate of 0.0207 $\frac{kg}{s}$. Furthermore, energy and exergy efficiencies of 43.14 % and 22.67 % were reported. Lastly, other products of the polygeneration system included electricity, heating, hydrogen, and freshwater produced at rates of 3.28 MW, 207.2 kW, 0.0575 $\frac{kg}{s}$, and 1 $\frac{kg}{s}$ respectively.

Nuclear energy was utilized in two studies of solar multigeneration systems producing hydrogen and water. The first was Temiz and Dincer [112] which investigated an offshore solar, wind, and nuclear powered system coupling a wind farm, floating PV plant, nuclear reactor, steam turbine, AC, MED, and anion exchange membrane electrolyzer. The system was designed to cover the power, water, heating, cooling, and hydrogen needs for a community of 275,000 people. Hydrogen was considered as fuel for transportation requirements. Time dependent modelling of the system produced the results presented in Fig. 15 for the variation of exergy efficiency over an entire year. Finally, average overall energy and exergy efficiencies were calculated as 63.36 % and 52.42 % respectively for production of 1551.4 GWh power, 820.3 GWh cooling, 2324.8 GWh heating, 39,575,634 $\frac{ton}{year}$ freshwater, and 28,713 $\frac{ton}{year}$ hydrogen. Similarly, Temiz and Dincer [113] presented a solar and nuclear powered system. It produced electricity, freshwater, and hydrogen by integrating a bifacial PV, pebble bed nuclear reactor, RC, MED, and SOE. The results found exergy and energy efficiencies of the overall system at 19.84 % and 22.7 %. In addition, the bifacial PV was shown to increase hydrogen production from 0.03 $\frac{kg}{s}$ to 0.5 $\frac{kg}{s}$.

3.5. Renewable multigeneration systems with hydrogen storage or consumption

Production of hydrogen in all the multigeneration systems mentioned above was done for the purpose of meeting demand for hydrogen fuel by end users. However, some investigations opted for the use of produced hydrogen within the system itself. It was most commonly used as an energy storage system; however, other uses have been observed such as serving as the feedstock for methanol production. In such systems, hydrogen was either exclusively or partially consumed within the system boundaries instead of transported out of them. One such investigation was performed by Rokni [114] which deployed a reversible solid oxide cell (RSOC) to covert power to hydrogen and vice versa. In addition, a direct contact MD was utilized for freshwater production. Dish-Stirling units were used to directly convert solar energy to electrical power meeting demand during high solar availability periods. Moreover, some of the power produced by these units was used to fuel the solid oxide cell for hydrogen production. At times of low solar energy, the cell operation was reversed to produce power using the stored hydrogen making up for solar energy loss. The hot water output of the PTC was used as an input to the electrolyzer for water splitting and as a heat source to the MD system producing freshwater. The system was simulated to meet 500 kW of demand, and the results demonstrated variation in the levels of accumulated hydrogen and produced freshwater during different seasons. For example, summer was shown to be the season with highest hydrogen production and storage due to excess solar energy while the opposite was true for winter. Moreover, it was shown that a 70 stack and 200 cell RSOE, one hundred and seventy-five 25 kW Dish Stirling units, and 7 × 200 m PTC were needed to meet the stated demand. With an efficiency of 19.3 %, production rates of electricity, hydrogen, and freshwater were reported as 500 kW, 3281 $\frac{\text{standardized } m^3}{day}$, and 8466 $\frac{L}{day}$.

Another polygeneration system with hydrogen energy storage (HES) was presented by El-Emam and Dincer [115] and coupled PTC, ORC, AC, hydrogen fuel cell, PEME, regenerative ORC, and RO units. Products included hot water and cooling in addition to electricity, freshwater, and hydrogen. The parametric analysis performed revealed that increasing the turbine inlet temperature had a positive effect on both energy and exergy efficiencies up to a certain point after which the trend inverted. Moreover, the multi objective optimization considering costs and thermodynamic performance resulted in a pareto front the two extremes of

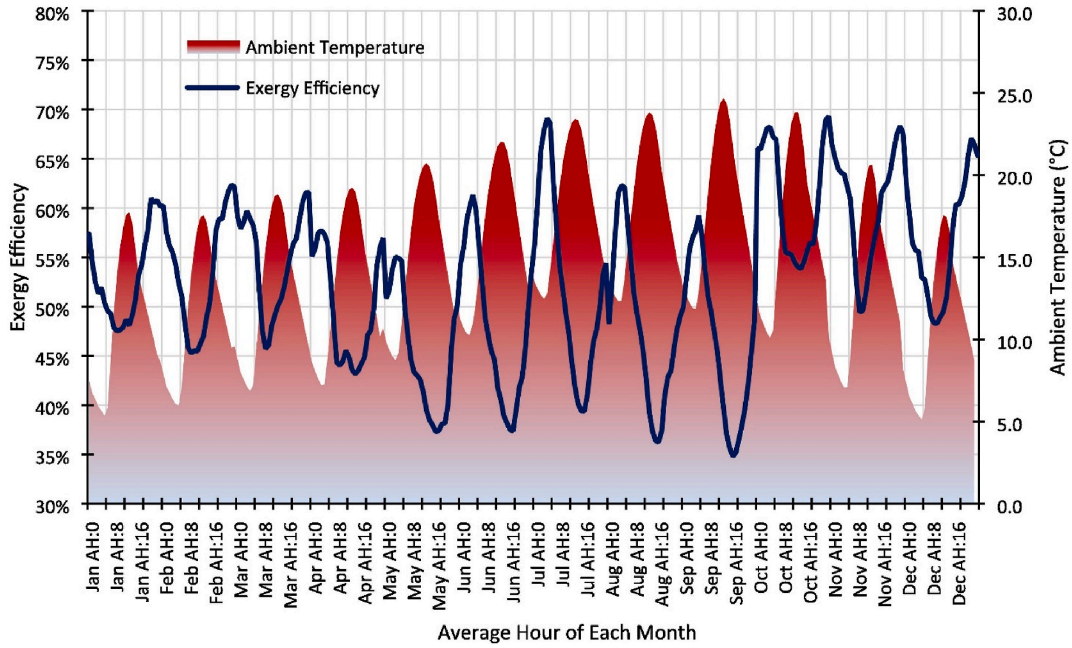

Fig. 15. Results of exergy analysis for solar, wind, and nuclear powered polygeneration system over a typical year [112].

which corresponded to 39 % exergy efficiency at a cost of 309.56 $\frac{\$}{h}$ or 21.7 % at a cost rate of 241.7 $\frac{\$}{h}$. Similarly, Islam et al. [116] proposed a solar polygeneration system which integrated PV, RO, PEME, hydrogen blended homogenous charge compression ignition (HCCI) engine, and lithium bromide AC. Providing power, the HCCI engine was fueled by a mixture of ethanol, hydrogen, and water. The polygeneration system produced hydrogen, electricity, heating, cooling, hot water, and freshwater. The inclusion of a Pelton turbine to recover energy from the RO unit was investigated and found to recover 24.3 % of the unit's power input. Moreover, the inclusion of the cooling system was reported to lead to a 16 % increase in overall energy efficiency as shown in Fig. 16.

Deymi-Dashtebayaz et al. [117] studied a trigeneration system producing heating, electricity, and freshwater using PEME, ICE, MED, PVT, and PTC. Excess power was converted to hydrogen by the PEME and back to power by the ICE. It was found that the PVT system provided 70 % of the power and 48.1 % of the heating demand. Meanwhile, the PTC system accounted for 87.4 % of the heating load of the MED unit and HES. 351,857.4 kg of water was produced annually, 18.3 % of which went to building residents while the rest was used by the HES. Lastly, the energy and exergy efficiencies for the overall system were found to be 20 % and 7 %. Also, Mahmood et al. [118] proposed a polygeneration system which coupled PTC, ORC, MSF, PEME, hydrogen-oxygen combustor, AC, and a greenhouse. Aimed at food production, the system provided cooling and freshwater for the greenhouse. The assessment determined production capacities for power, freshwater, cooling, oxygen, and hydrogen of approximately 2.70 MW, 72.2 $\frac{m^3}{day}$, 796 kW, 6420 $\frac{kg}{day}$, and 802.3 $\frac{kg}{day}$ respectively. Furthermore, energy and exergy values were determined as 41 % and 28.4 % with PTC area of 80,000 m^2.

Karavaz et al. [119] proposed a polygeneration system producing electricity, heating, cooling, hydrogen, and freshwater. The system was powered by wind and solar energy and coupled a PV, WT, battery bank, PEME, RO, and PEMEFC. The optimum system was found to include a PV array with installed power of 21.24 kWp and a battery bank of capacity 800 Ah at 48V. Moreover, the optimal system was shown to have minimum reliance on the fuel cell, instead utilizing it as a backup power producer. In another investigation, utilization of both geothermal and solar energies for a multigeneration system was done by Shahverdian et al. [120]. The proposed system utilized KC, PEME, MED, PEMFC, FPC, and HES units. The optimization analysis performed aimed to maximize overall efficiency, increase water production rate, and minimize both payback period and levelized cost of electricity (LCOE). A PEMFC was utilized for converting hydrogen to electrical power during time periods where production did not meet demand. Results demonstrated that the optimum system had an efficiency of 6.23 %, water production rate of 182.09 $\frac{m^3}{day}$, 5.29 years payback period, and 0.238 $\frac{\$}{kWh}$ LCOE.

Another such investigation was performed by Sezer and Koç [121] which analyzed a solar, wind, and osmotic renewable energy powered system. Osmotic power was extracted from the rejected desalination brine by pressure retarded osmosis which also mitigates the environmental impact of brine disposal. Other system components integrated were PVT, WT, PEME, PEMFC, MSF, and vapor compression refrigeration cycle. The system produced hydrogen, freshwater, electricity, and refrigeration at rates of 559 $\frac{kg}{h}$, 403.2 $\frac{l}{s}$, 51.5 MW, and 40.2 MW respectively. Moreover, the system required a heliostat area of 0.4 km^2 while the PV subsystem had a conversion efficiency of 29.7 % as presented in Fig. 17. Finally, the overall energy and exergy efficiencies of the proposed system were 73.3 % and 30.6 % respectively when the PEMFC was not included. When it was included, the values reduced to 71.7 % and 29.2 %.

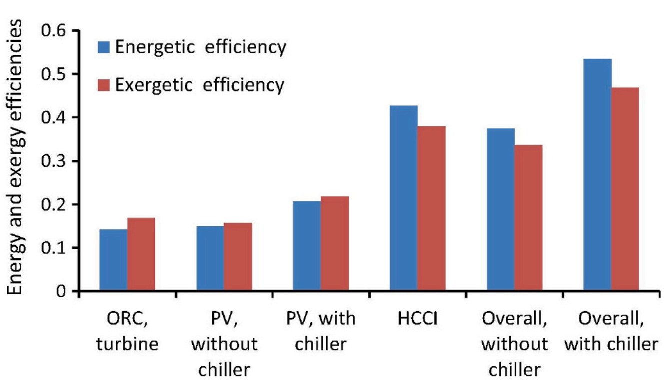

Fig. 16. Results of energy and exergy analysis carried out for solar polygeneration system utilizing hydrogen storage [116].

A similar investigation was investigated by Temiz and Dincer [122]

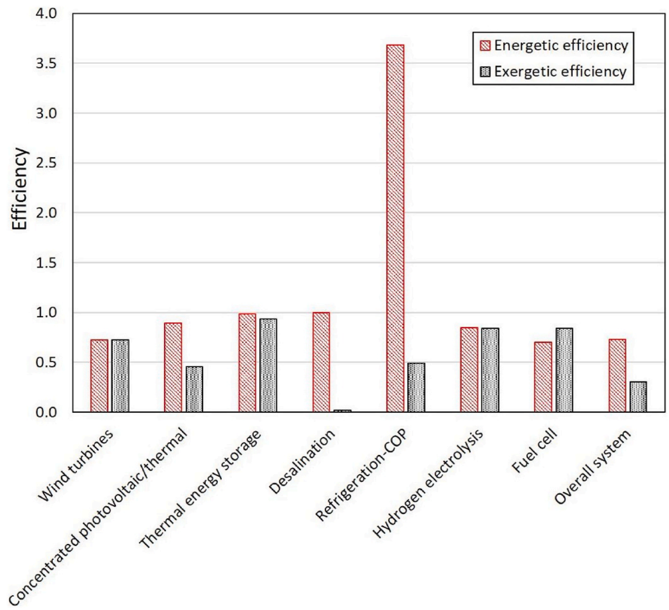

Fig. 17. Energetic and exergetic efficiency results for all components of a renewable polygeneration system [121].

which investigated a geothermal and solar powered polygeneration system integrating a bifacial PV, PEMFC, PEME, and MED to produce hydrogen, heating, freshwater, and electricity. Hydrogen was provided to the target community for fuel as well as utilized for the HES. Results demonstrated the system's ability to meet annual demand for thermal load of 485 MWh and annual power demand of 1642 MWh at energy and exergy efficiency values of 16.3 % and 14.9 % respectively. Moreover, the system annually produced 7938 kg of hydrogen and freshwater at a rate of 14,551 $\frac{kg}{day}$. Finally, the levelized cost of energy was reported as 0.058 $\frac{\$}{kWh}$.

A solar, biomass, and muddy sea water chemical energy powered polygeneration system was analyzed by Rabeti et al. [123] to produce electricity, freshwater, carbon dioxide, hydrogen, heat, and methanol as shown in Fig. 18. It deployed a BC, ORC, double pressure steam cycle, KC, PEME, and PTC. In addition, muddy sea water was fed to a microbial fuel cell producing power while MED-TVC and RO units were utilized for desalination. A carbon capture unit was included and flue gas exiting the power cycle was stripped of carbon dioxide which, in addition to hydrogen produced by the PEME, constituted the methanol production process feedstock. Three different biomass sources were considered and assessed including MSW, MPW, and DPW. MSW was found to be the biomass source with the lowest costs while DPW was the one with the lowest environmental impact. Moreover, results indicated that the gasification process was the largest contributor to exergy destruction. The optimum system had energy and exergy efficiencies of 29.25 % and 23.59 %. Furthermore, it had the capacity to generate 63.88 $\frac{kg}{s}$ of freshwater, 1820.78 $\frac{kg}{h}$ of methanol, and 62.86 MW of electricity by consuming 13.93 $\frac{kg}{s}$ of waste.

Multiple investigations proposed solar, and wind powered systems. First, Nikitin et al. [124] analyzed one integrating FPC, WT, AC, RO, ICE, and PEME. The system produced electricity, heating, cooling, and freshwater. Models were tested for buildings in four different cities with the maximum energy and exergy efficiencies reaching 33.51 % and 27.07 %. Moreover, Dezhdar et al. [125] looked into a system producing the same products with the addition of hot water. Multiple units including RO, heat pumps, fuel cells, WT, PVT, battery bank, and PEME were coupled. Results demonstrated that the use of both batteries and HES improved overall system performance. Moreover, life cycle costs for the system were determined to be 674,278.4 $\frac{\$}{h}$ while its power production capacity was reported as 225,694.8 kWh. Lastly, Ju et al. [126] investigated a system also powered via wind and solar with the addition of biomass. It integrated RO, MED, AWE, fuel cell, PV, WT, gas turbine, in addition to a biomass digester and gasifier. Producing freshwater, electricity, natural gas, and heating, the system was simulated for four different scenarios. The base scenario excluded the biomass conversion

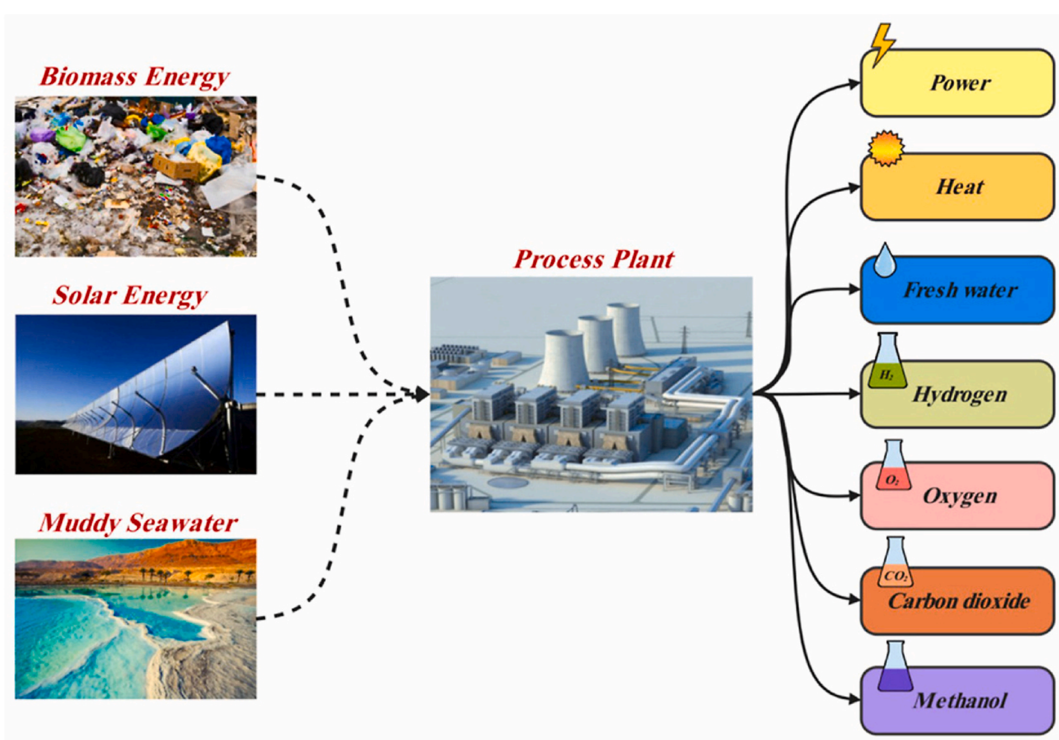

Fig. 18. Energy sources and products of a multi energy sourced renewable polygeneration process [123].

and desalination/HES systems. The second, third, and fourth cases include the desalination/HES system, the biomass conversion system, and both combined in that order. Results indicated that the second case reduced curtailment by 96.2 % and environmental impact by 72.8 % with a 6.9 % increase in fuel costs. Meanwhile, the third case reduced curtailment by 13.5 %, increased environmental impact by 9.9 %, and reduced fuel costs by 100 %. Finally, the fourth case led to 78.2 %, 61.8 %, and 77.9 % reduction in operational costs, environmental impact, and conditional value-at-risk.

Some of the analyzed solar multigeneration systems which included HES used nonrenewable fuels such as natural gas to meet their energy requirements. An example was presented and analyzed by Deymi-Dashtebayaz et al. [127]. The solar and natural gas powered multigeneration system produced electricity, freshwater, and heating utilizing an HES consisting of an electrolyzer and hydrogen engine. Both PTC and PV systems were employed for power production in addition to an MED unit for freshwater production. The inclusion of the desalination unit was analyzed by comparing the environmental and economic performance of the overall system with and without it. It was found that the inclusion of the unit increased both the economic costs and environmental impact of the overall system. Another solar and natural gas powered trigeneration system producing electricity, heating, and freshwater was analyzed by Sorgulu and Dincer [128]. Hydrogen utilization as an energy storage option was assessed and its production via a heavy element halide cycle was considered. Stored hydrogen was blended with natural gas, and a gas turbine was integrated to produce electricity from the fuel mixture. Solar tower, ORC, MED, and RO systems were utilized as well to produce the system products. Results indicated that the hydrogen production cycle achieves energy and exergy efficiencies of 9.5 % and 10.5 %. Moreover, the integrated system's overall exergy and energy efficiency were determined to be 21.28 % and 26.1 %.

Also, Bai et al. [129] proposed a solar, biomass, and methane fueled system which integrated gas turbines, SOFC, ORC, AWE, linear Frensel solar collectors, HDH, biomass combustor, and EJRC. Their results found overall energy and exergy efficiency values of 78.13 % and 47.72 %. Furthermore, it was determined that a 10 °C increase in ambient temperature leads to a 3.3 % increase in exergy efficiency. In addition, the SOFC was shown to be the largest contributor to exergy destruction. The overall system's total costs were determined to be 47.16 $\frac{\$}{h}$ corresponding to carbon emissions of 10.59 $\frac{kmol}{MWh}$. Similarly, Sorgulu and Dincer [130] investigated a solar, wind, biomass, and natural gas powered trigeneration system producing electricity, freshwater, and heat. Utilizing HES, other subsystems included a solar tower, WT, gas stoves, boiler, gas engine, biomass drying unit, biomass incineration units, and a hybrid S–Br cycle. Hydrogen produced by the system was blended with natural gas and used in the gas stove, gas engine, and combi boiler while chicken manure was fed to the biomass cycle. Energy and exergy efficiencies for the overall system were 64.43 % and 32.24 %; meanwhile, those values for the hybrid S–Br cycle were 27.85 % and 31.63 %.

Instead of natural gas, Mehrjerdi et al. [131] relied on diesel to supplement their proposed solar and wind powered trigeneration system producing electricity, freshwater, and hydrogen. Subsystems including PEME, PV, WT, hydrogen fuel cell, diesel generator, and RO were integrated. Hydrogen was used both to satisfy industrial demand and for the HES. Results demonstrated that the inclusion of HES reduced emissions by 50 % while leading to a 0.795 % increase in net present costs while its exclusion led to a 15 % increase in reliance on diesel. Liu et al. [132] proposed a cogeneration system powered by solar and wind energies producing freshwater and hydrogen. In addition, the system had the option of drawing power from the grid. Subsystems included WT, PV, RO, PEME, and PEMFC. The inclusion of a fuel cell was analyzed and found to reduce the reliance on grid power and lessen the environmental impact as well. Similarly, Baldinelli et al. [133] proposed a system which coupled an RSOE, WT, MED, PV, and diesel generator to leverage solar, wind, and diesel in a trigeneration system producing water, electricity, and hydrogen. With the aim of designing a resilient system for remote applications, the utilization of a diesel engine was considered; however, increasing the percentage of renewable energy utilization was included as an objective. Assuming the availability of sea water, modelling revealed LCOE values ranging from 0.187 to 0.192 $\frac{€}{kWh}$ with renewable energy penetration reaching 76 %.

4. Discussion

A review of the studies presented in this work shows that each system configuration employed a unique combination of components. Design factors often varied based on the specific conditions of each case study, with geographic and climatic factors playing a particularly important role. These factors affect the availability of renewable energy resources and, in turn, influence the selection of energy sources, products, and technologies within each system. This was evident in that most of the reviewed case studies were located in hot coastal cities such as Jubail, KSA; Dubai, UAE; California, USA; and Mahshahr, Iran. These locations benefit from abundant solar resources and access to seawater, making them well-suited for solar multigeneration systems producing freshwater through seawater desalination.

When evaluating performance outcomes, it is important to note that most indicators cannot be directly compared across different studies. This limitation arises from significant variation in design choices, system capacities, and operating conditions. Thermodynamic metrics such as exergy efficiency are only comparable between similar systems. For example, between different desalination plants but not between a desalination plant and a hydrogen production facility [134]. Site-specific factors, such as differences in solar irradiation, can also influence results, as highlighted by Mohammadpour et al. [54]. For example, if an identical plant design were simulated for two different locations, performance outcomes could vary considerably. Furthermore, the demand profile of the target community has a direct influence on unit sizing, which in turn affects performance; desalination output, for instance, depends on both the plant capacity and water production rate [135,136].

Several general observations on technology selection also emerged. PTCs were the most widely used solar thermal technology in the reviewed systems, despite solar towers demonstrating superior performance in direct comparative studies. The preference for PTCs likely stems from their simpler operation and fewer technical complications in multigeneration [137,138]. RO and PEME were the most frequently integrated technologies for water and hydrogen production, likely due to their high compatibility with solar systems through direct use of electrical energy. MED was also a common desalination method; however, while RO was integrated with both thermal solar technologies and PV, MED was exclusively paired with thermal solar collectors. This reflects the adaptability of RO, as its electrical energy requirement can be met regardless of whether the system's primary solar technology is thermal or photovoltaic, provided that electricity generation occurs at some stage of the process.

5. Conclusion

In conclusion, multigeneration systems have received attention due to their potential in increasing the efficiency of essential processes such as power generation and desalination. To assess the potential of multigeneration systems, investigations of solar powered multigeneration systems producing water and hydrogen were reviewed in this paper. The analysis was extended to systems relying on other energy sources in addition to solar such as geothermal, biomass, wind, and nuclear among others. The focus on simultaneous freshwater and hydrogen production via renewable energy was due to multiple reasons. First, water desalination faces challenges such as large energy requirements and environmental impact. In this vein, multigeneration systems are assessed to find if they can potentially minimize these issues. On the other hand, hydrogen fuel offers many advantages when compared with other energy vectors in addition to its potential as a store of energy. However, hydrogen production requires large amounts of energy and water. Therefore, multigeneration systems which produce water, hydrogen, and power from renewable resources link and synergize these two important production cycles potentially improving the overall efficiency and environmental profile.

In most studies, energy and exergy analysis were carried out by determining their relative indicators to assess the thermodynamic performance of any proposed system design. Economic and environmental analysis were also carried out; however, less frequently. Parametric analysis typically follows analyzing the impact of different environmental and design factors on the target indicators. Furthermore, both single and multi-objective optimization analysis were carried out in many cases determining the optimum system design and size based on fixed factors such as demand or availability of renewable energy. Lastly, analysis of the effect of different design choices, such as the inclusion of a specific component or subsystem, on overall performance was undertaken in some studies. For example, comparing different choices for power cycle fluids or biomass sources or assessing the impact of the inclusion of an HES.

Energy and exergy were usually indicated by their respective efficiency percentages while the overall emissions rate was the most common environmental indicator. Emissions savings when compared with standalone single generation systems or fossil fuel powered systems were also reported in some studies. Moreover, various exergy and energy based environmental indices were also used to assess the environmental impact. Lastly, costs were reported in three different ways, the first being LCOE. Since LCOE is independent of system size, the values were comparable across different studies. Most LCOE values ranged between 16 and 20 $\frac{\$}{GJ}$ with two outliers at 66.112 and 8.005 $\frac{\$}{GJ}$. Levelized costs of all system products were also reported in some studies; however, the number of studies reporting them was minimal and the values varied greatly. All other indicators were dependent on the specific system investigated and since the products differed from one study to the next, their values were incomparable. Lastly, some investigations opted to report the overall costs of their respective systems per unit of time. This indicator was not comparable across studies due to its dependance on the size of the system which also explained the large variation in the reported values.

6. Recommendations for future studies

Future research on solar multigeneration systems should aim to establish standardized environmental, sustainability, and economic indicators to enable more consistent and meaningful comparisons between studies. There is also a need for detailed component-level viability assessments, which would provide a clearer understanding of the technical and economic feasibility of key subsystems under different operating conditions. This can be achieved by analyzing the system with and without a specific component to make a conclusion about its viability. Furthermore, this type of analysis could be expanded to target investigations into the inclusion or exclusion of certain renewable energy sources within the studied system. Expanding the scope of analysis to include a wider range of renewable and non-renewable energy sources, as well as hybrid configurations, could uncover new performance synergies and operational strategies.

CRediT authorship contribution statement

Mahmoud Ibnouf: Writing – original draft, Methodology. **Mohammad Alkhedher:** Writing – review & editing, Supervision, Project administration, Methodology. **Hadil Abu Khalifeh:** Writing – review & editing, Supervision, Project administration, Methodology. **Mohamad Ramadan:** Writing – review & editing, Supervision, Project administration, Methodology.

Declaration of competing interest

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

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