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A COMPREHENSIVE REVIEW OF GREEN HYDROGEN PRODUCTION FROM SOLAR ENERGY USING THERMODYNAMICS CYCLES.

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Abstract. *Adopting renewable energy sources to the detriment of non-renewable energy matrices is a change in progress worldwide. This movement is in concordance with the mutual necessity to reduce the emission of greenhouse gases and decelerate the impacts of global warming. Green hydrogen has been pointed out as a sustainable energy alternative since it is a product from renewable energy sources and its production process is carbon-free. This work proposes a comprehensive review of the main methods to produce green hydrogen derived from solar thermal energy. The presented review mentions thermodynamic cycles concepts and the more quoted models regarding sustainability according to the literature. The qualitative analysis foresees parameters like the working fluid, energetic efficiency, the project's production level, and performance. Considering the information presented, the organic Rankine cycle (ORC) is the most suitable cycle to elaborate a viable large-scale project, owing to the possibility of functioning with lower temperatures in the heat source. Brayton and Rankine cycles are indicated for intermediate and higher temperatures. This detailed revision of the proposed productive methods powered by solar thermal energy expects to guide future projects to describe a more insightful and profound proposition for an ideal plant.*
Keywords: *green hydrogen, thermodynamics cycles, Rankine cycle, Brayton Cycle, solar energy.*

1. INTRODUCTION

The discussion on renewable energy sources is becoming increasingly relevant, owing to the risks of the world's dependence on nonrenewable sources. For instance, oil, gas, and coal cannot be naturally reposed at the same consumption rate (Mohtasham, 2015). The indicated restriction directly affects the growing difficulty of long-term extraction of these resources. As a result, the extraction requests constant technological advances until they are exhausted by the market's demand (Toft & Duero, 2011). Furthermore, fossil sources present carbon dioxide gas as a by-product, contributing to the greenhouse effect aggravation. In this context, efforts should be continuously directed toward favoring the productive viability of carbon-free renewable sources (Olabi and Abdelkareem, 2022).

A promising carbon-free energy source alternative is hydrogen (H_2). The H_2 has a potential energy of combustion almost three times bigger than gasoline's. Besides that, its only combustion by-product is water (Siyal et al., 2015). However, for H_2 to be an efficient and sustainable solution, a carbon-free production chain is needed, with the greatest possible use of renewable resources from the beginning at the primary source to their availability (Dawood et al., 2020). In this way, H_2 generation systems become essential components for solutions to the impacts of global warming. For a sustainable future, hydrogen must be affordable, reliable, safe, clean, and efficient (Acar and Dincer, 2019).

Hydrogen produced from renewable clean energy is called green hydrogen (Feder, 2021). Many models of green hydrogen production have been presented in recent years. Reuß et al. (2019) propose an analysis of three models of solar hydrogen production. They differ in the constitution and integration of photovoltaic components and electrolysis subsystems, modeling the integrated behavior of the system by diversifying assemblies and operating conditions to optimize parameters The study shows that weather conditions directly influence photovoltaic production, which presents the possibility of improvement in input power stabilization over time.

Another energy source for hydrogen production would be waste heat from chemical reactions. Zhang et al. (2020) bring a conceptual framework for electrochemical processes controlled by pyroelectric materials, that is, that convert thermal energy into the polarization of electric charges. Nami et al. (2017) evaluate the thermodynamic efficiency of a model powered by a molten carbonate fuel cell. In a recent publication, Zhang et al. (2022) assesses three methods of

producing hydrogen with solar energy. The first is based on photothermal energy coupled with a PEM electrolysis system. The second replaces photothermal power with photovoltaic, and the third with a thermochemical mechanism of water breakdown using solar photothermal technology of S-I cycle coupling. Among the publications observed, it is worth mentioning the work of Gupta et al. (2022), in which they present a broad review of the application of the Organic Rankine cycle (ORC) in poly-generations. Overall, the ORC is a potential candidate cycle for assemblies with solar thermal sources, mainly because it operates at low temperatures.

Despite existing review articles that evaluate models of hydrogen production and works that comprehensively review solar-driven multigeneration systems, there is a lack of reviews on proposed solar-driven power generation cycles ideal to feed the production of green hydrogen. Therefore, the main objective of this work is to qualitatively evaluate the published methodologies to produce green hydrogen from thermodynamic cycles (photothermal solar energy). Specifically, it is intended to present the most prominent proposed models, mention the advantages and disadvantages of each cycle, and direct future investigations.

Firstly, a revision on thermodynamics cycles is presented. This section highlights the most important cycle, Carnot cycle, and the most relevant cycles to this work, Rankine cycle, Brayton cycle, and others. Thereafter, previously proposed solar-driven power generation systems are reviewed, and future research directions of thermodynamic cycles to produce green hydrogen are summarized.

2 THERMODYNAMICS CYCLES

The generation of power or refrigeration is commonly a product of systems or devices, such as engines, coolers, air conditioners, and heat pumps, that operate according to thermodynamic cycles. In real devices, these cycles in operation are complex, on account of several complicator effects, like losses associated with the working fluid flow. As a result, to facilitate the study of these cycles, idealizations are adopted. A thermodynamic cycle consists of linked sequences of thermodynamic processes that involve the transfer of heat and work into and out of the system, while varying pressure, temperature, and other state variables (Cengel & Boles, 2008).

The thermodynamic cycle assumes the use of thermal energy from a heat reservoir to provide work. According to the second law of thermodynamics, if there is only one heat source, it is impossible to build a heat engine that takes heat from the source and converts all of it into work (Bejan, 2006). However, to build a complete thermodynamic cycle, at least two heat reservoirs must be implemented. In this way, it is shown how it is possible to construct a reversible cycle, known as the Carnot cycle. The Carnot cycle is defined as an ideal reversible closed thermodynamic cycle. Four successive operations are involved: isothermal expansion, adiabatic expansion, isothermal compression, and adiabatic compression (Feidt, 2020).

Carnot advanced the study of the second law by forming a principle (also called Carnot's rule) that specifies limits on the maximum efficiency any heat engine can obtain. In short, this principle states that the efficiency of a thermodynamic cycle depends solely on the difference between the hot (T_h) and cold (T_c) temperature reservoirs. No engine can be more efficient than a reversible engine (Calingaert, 1952). The efficiency (η) in the cycle is given by (Atkins et al., 2018):

$$\eta = 1 - \frac{T_c}{T_h} \qquad (1)$$

2.1 Rankine Cycle

The Rankine cycle has become the go-to process in vapor power plants. In contrast to the Carnot cycle, this method of power generation provides more value to the outcome of the process. The Simple Rankine Cycle (SRC) is an ideal model for a steam potency plant. It combines constant-pressure heat transfer processes with reversible adiabatic compression and expansion processes. The working fluids most used in this cycle are water and organic liquids (Geyer & Stine, 2001). The main components of a system that operates this cycle are a boiler, where the working fluid temperature and pressure increase, and the fluid turns into vapor, a turbine, where the thermal energy is converted into usable energy, a condenser, where the working fluid is cooled and condenses, and a pump, where the working fluid is pressurized (Moran et al., 2010) (Reddy et al., 2010). Figure 1 shows the Rankine T-S diagram. The efficiency of the cycle is given by (Çengel & Boles, 2008):

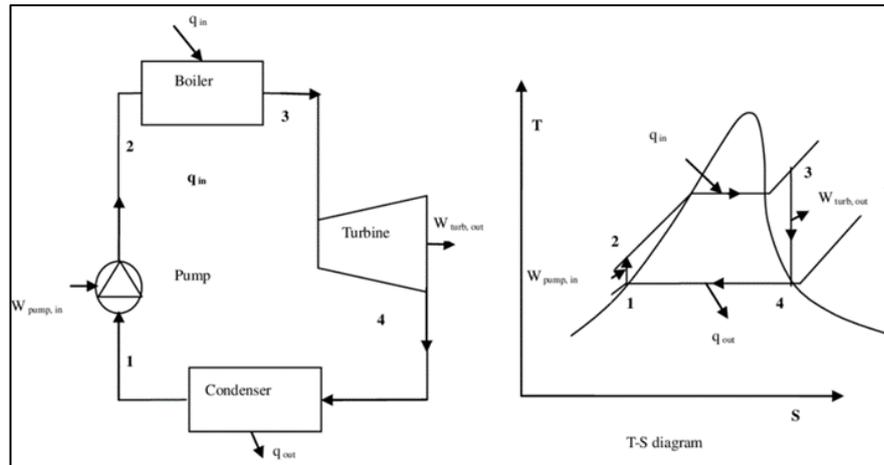$$\eta = \frac{W_{turb}}{Q_{\dot{m}}} \qquad (2)$$

Figure 1: Ideal Rankine cycle. (Miller, 2017)

There are some variations on the basic cycles to increase efficiency under certain conditions. The organic Rankine cycle (ORC), for example, uses an organic fluid to improve performance at low temperatures. The modeling of an organic Rankine cycle starts from the choice of fluid from its isentropic saturation curve (Cengel and Boles, 2008). Regardless of the fluid used, the cycle can still suffer a loss of efficiency due to irreversibility. Among the current proposals for reducing irreversibility, there is the supercritical Rankine cycle. This cycle operates similarly to any Rankine cycle, with the difference that the steam (or organic vapor in ORC) is generated at supercritical pressures. In this condition, there is no phase separation (Bugge et al., 2006).

2.2 Brayton Cycle

A Brayton-type cycle consists of three components: a compressor, a mixing chamber, and an expander. Modern Brayton engines are almost always a turbine type. Compressed air reaches the chamber where it is mixed with fuel, then ignited in an expander in which work is generated and heat released to the surroundings. This sequence forms two isentropic processes (compression and expansion) and two isobaric (heat and work) (Cengel and Boles, 2008) (Bugge et al., 2006) (Ranasinghe et al., 2019). Figure 2 shows the Brayton T-S diagram. The efficiency of the cycle is given by:

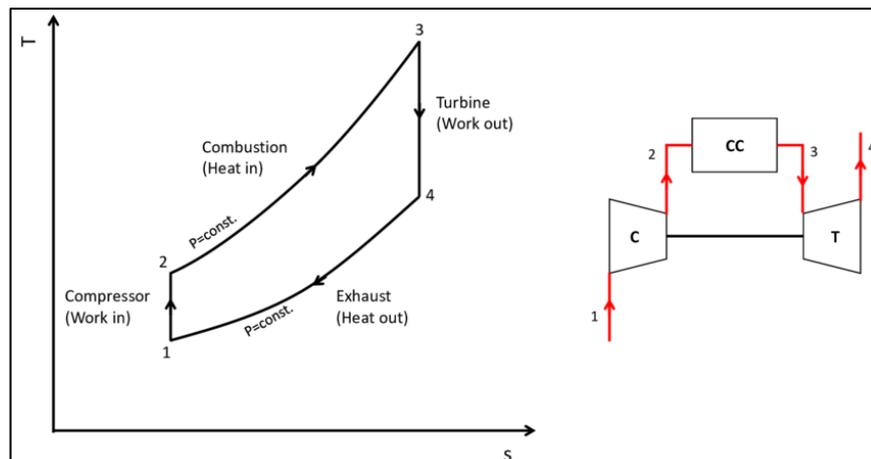$$\eta = 1 - \frac{1}{r_p^{(k-1)/k}} \qquad (3)$$

Figure 2: Ideal Brayton cycle. (Ranasinghe et al., 2019)

2.3 Other Cycles

Another possibility to improve the efficiency of a cycle is using mixtures. Kalina cycle uses a solution of fluids with different boiling points for its working fluid. Since the solution boils over a range of temperatures, more of the heat can be extracted from the source in comparison with a pure working fluid (Nabat et al., 2022).

What happens in real projects are cycles combined for the best use of the plant. Thermal solar power technology deployment in the short and medium term should be focused on combined cycles (CC) consisting of a topping Brayton cycle and a bottoming Rankine cycle, which in solar power leads to Integrated Solar Combined Cycle (ISCC) concepts (Rovense et al., 2022). Another modeling of combined cycles will also be verified for green hydrogen production.

3   THERMAL SOLAR ENERGY APPLICATIONS

Applying solar thermal energy to produce green hydrogen consists of building a power plant based on the expansion and compression of a working fluid. This working fluid receives heat from an HTF heat exchanger fluid, which, in turn, has its temperature raised by the energy of the Sun. Regardless of the model, the combination between the thermodynamic cycle of the HTF and that of the working fluid is necessary (Chen et al., 2010). The HTF must have the property of easily absorbing and releasing heat, while the working fluid must be able to perform work under pressure in the turbine and generate power (Marchã et al., 2014). One of the critical factors of the combined cycle is condensation or cooling, so that the working fluid resumes contact with the HTF, reheating and completing the cycle (Zhang et al., 2020)

Recent publications have shown several possibilities for modeling power generation cycles, mostly in a simulation environment. Brayton, Rankine, and ORC combined cycles have been noted with more relevance over the past five years (Lykas et al., 2022). In this session, a sample of those publications in which solar energy is applied to power thermodynamic cycles is presented. It is important to note the main characteristics of each project, such as location, cycle type, efficiency parameters, and generated power. When there is information on economic viability, this will also be highlighted.

Assareh et al. (2022) proposed a system composed of a Brayton cycle, powered by CSP (concentrated solar power) and a PEM (proton exchange membrane) electrolyzer, which is powered by SRC (steam Rankine cycle) combined with an ORC (organic Rankine cycles), the two cycles are implemented to make the most of the thermal energy produced in the process. The study brings as a novelty the application of the CSP as the combustion chamber for the gas turbine (Brayton Cycle). Software (Engineering Equations Solver) was used to model and analyze the proposed system (from a thermodynamic and economic point of view). After assessing the impact of several parameters, the NSGA-II (algorithm) was used to optimize the results. And the optimal operating condition was selected by TOPSIS (algorithm), according to Pareto frontier (multi-objective optimization). In this article, aspects such as the variation of ambient temperature and solar irradiation in the performance of the system were also considered. Figure 3 shows the simulated thermal scheme.
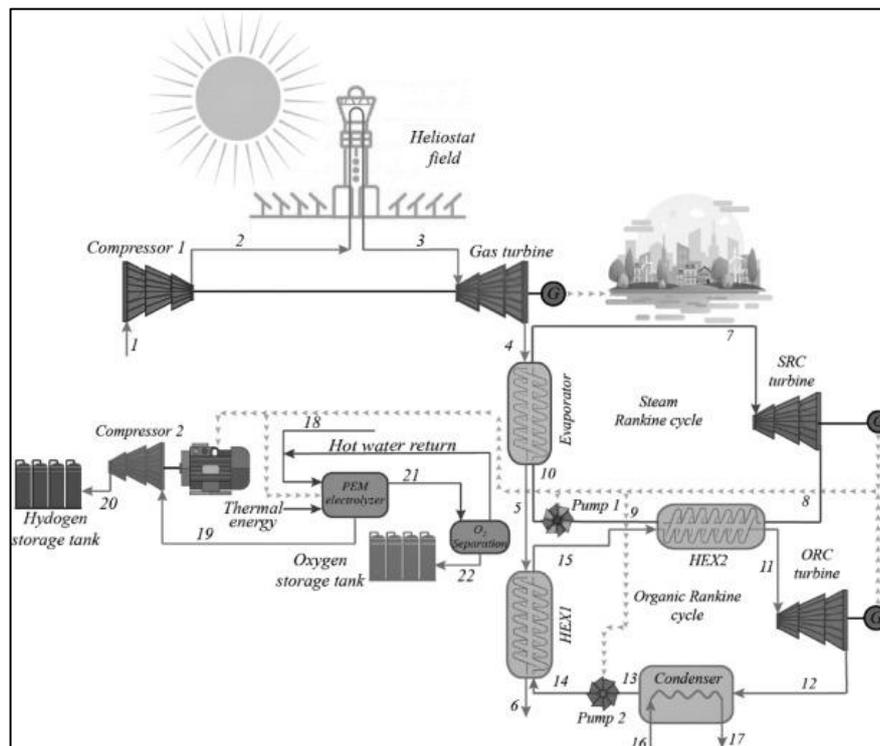

Figure 3: Combined Brayton-Rankine-ORC cycle. (Assareh et al., 2022)

In the presented modeling, the optimal operating point had an exergy efficiency of 22.2% and the cost rate was 272.6 $/h. The system has an indeterminate Payback and is very expensive and complex.

Sigue et al. (2023) proposed to build a unique simulation, design, and optimize the CSP-ORC (concentrated solar power - organic Rankine cycles) plant. So, they use open-source tools, and implemented the DWSIM simulator, with the Python programming language, the SAM CSP model. The proposed system consists of a CSP field coupled with an ORC. This system was specially designed for a rural village in Africa. The adopted ORC is regenerative and includes a regenerator that transfers heat from the superheated working fluid. Cyclopentane is the fluid that increases efficiency and reduces energy costs. The critical temperature and pressure of the fluid are 238.5°C and 45.2 bar. For an operation of 15h/day, which corresponds to an irradiation of 450 W/m2, the optimal design parameters are a temperature change of

the heat transfer fluid of 75ºC, the solar multiple of 1.4, and 4h of storage capacity. The annual thermal power generated by this field is about 3812 MWt, while the annual electrical power is 694 MWe. The annual efficiency of the system (18.21%) is lower than the projected plant efficiency (19.20%).

Puig-Samper et al. (2022) modeled a CSP plant coupled to the SOE (solid oxide electrolyzer) and presents an investigation of the possible environmental implications. The proposed plant is composed of three different sections: CPS, electrolysis, and hydrogen conditioning. The CSP section consists of a field with photothermal collectors, a storage system (TES), a gas boiler for maintenance, and a Rankine cycle with regeneration and superheating. The plant uses synthetic oil (Therminol VP-1) as the heat transfer fluid. In the storage tanks, a binary mixture of molten salts (60% NaNO3 + 40% KNO3) is used. The working fluid is superheated steam. The conversion efficiency of solar energy to electricity obtained was 15.54%. The results of the annual simulations show that the specific electricity and heat demand were 35.11 kWh/kg H2 and 10.42 kWh/kg H2, respectively.

Petrollese et al. (2020) worked on the description of the CSP plant and performance analysis. This installation is experimental, it is in the district of Ottana, Italy. The installation integrates the CSP-ORC plant, which generates a power of 630 kW and has a storage system (TESS), with a CPV plant with a power of 400 kW equipped with a molten salt battery system. The organic Rankine cycle is regenerative, and the working fluid used is hexamethyldisiloxane (C6H18OSi2). The ORC unit was designed to produce an electrical power of 629 kW with an efficiency of 20.3% for nominal conditions, but the cycle often works outside these conditions. In addition, the article considers possible losses and risks over variations in weather conditions.

Hai et al. (2022) built a system for producing hydrogen from solar energy. This system is composed of a field of heliostats that feed a closed supercritical Brayton cycle combined with an organic Rankine cycle and an absorption cooler, the power produced by these cycles feeds a PEME (Proton exchange membrane Electrolyzer). The hot source reaches temperatures of up to 1000ºC, the air is used as HTF (heat transfer fluid), and the working fluid of the Brayton cycle is helium. To recover the heat that would be rejected in the Brayton cycle, an ORC is implemented. The ORC cannot recover all the heat, so an AC (Absorption Chiller) is coupled to the system. The EES software was used to perform the thermodynamic modeling. In addition, a multi-objective optimization was performed with the aid of a code developed in MATLAB software. The exergy efficiency (solar for H2) obtained for the combined CBC-ORC-AC system was 23.63% and the levelized cost of hydrogen production was 7.01$/kg H2. Figure 4 shows the simulated thermal scheme.
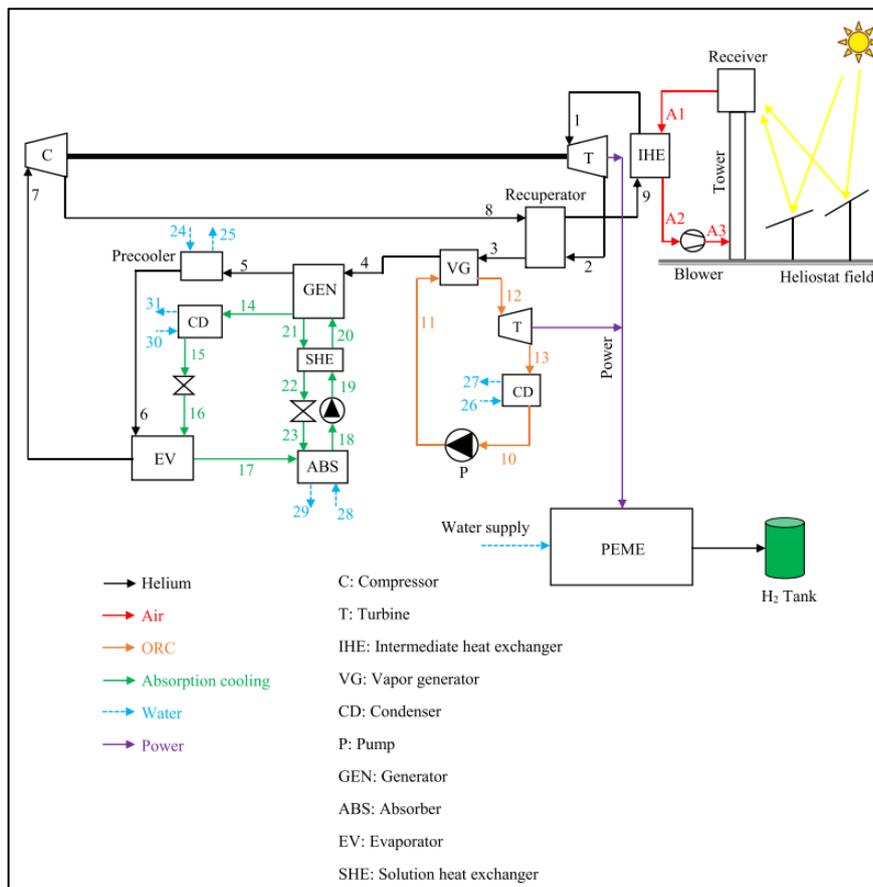

Figure 4: Combined Brayton-ORC cycle. (Hai et al., 2022)

Yu et al. created a design of an ORC powered by solar energy. For the system to be able to generate electricity 24 hours a day and operate under nominal design conditions, maintaining high efficiency, the storage system (TES) was implemented. The chosen model was the two tanks, a hot and a cold tank, previously proposed in the literature. The integrated system consists of a parabolic collector (PTC), a storage system (TES), and an ORC for power generation. This work tested different fluids. It was concluded that the cycle with regeneration for all fluids tested obtained better efficiency. The thermal efficiency of the ORC improved to 24.3%, compared to the 22.2% efficiency reported in the other paper. System efficiency improved from 14.9% to 17.4% for basic ORC. For ORC with regeneration, thermal efficiency improved from 30.4% to 36.3% and system efficiency improved from 17.9% to 24.8% (Yu et al., 2021).

Moradi Nafchi et al. (2018) analyzed a model using the EES software. The calculations were designed for the city of Yazd, Iran. The plant in this model is fed by a field of heliostats, which concentrate solar radiation on a solar tower, where superheated steam is generated (withstands temperatures up to 2200 K). This superheated steam is the working fluid of a Rankine Cycle, in which part of the thermal energy is stored in a storage system (TES) and the other portion is used to produce electrical energy. The working fluid is not specified and in the heat exchangers for the storage tanks, molten salt ($NaNO3-KNO3$) and HTF are used. It is assumed that 30% of the electrical energy generated in this cycle is used to produce hydrogen and the rest is transferred to the electrical grid. Electrolysis takes place in a PEM (proton exchange membrane) electrifier. One of the highlights of the work is that electrolysis is carried out at high temperatures (170°C), so the thermochemical energy for the process of breaking down water molecules is lower. As a result, electricity consumption is lower and the H2 production cost is lower. The energy and H2 generation efficiency of the integrated systems is, respectively, 20.1% and 41.25%.

Su et al. (2023) developed a cascade Brayton cycle with He-CO2 for improved concentrated solar energy and proposed some optimizations. The entire system was created in the MATLAB mathematical model software, it was verified if the model worked, then analyses predicting the performance of the system were made and finally, the thermodynamic and exergoeconomic benefits of the system were evaluated. The optimized system is powered by heliostats and a receiver, it includes a storage system and three cycles in parallel: the first is the improved Brayton cycle in cascade (He-CO2 working fluid) which works at high temperatures, the second which works at medium temperatures is also a Brayton cycle (working fluid He-CO2) and the third is a Rankine cycle (working fluid C6H6-C2H6O) which works at low temperatures. The results obtained through the multi-objective optimization showed that the most appropriate exergoeconomic condition generated 697.75 kW of power, had an investment rate of 33.09 $/h, and had an energy efficiency of 26.75%. The temperature of the hot spring is 1380°C.

Javed and Tiwari (2023) compare three configurations of an ORC, basic, recuperative, and regenerative. And for each configuration different working fluids are considered, toluene, nonane, decane, and n-dodecane. The system is powered by a PTC (Parabolic Trough Collector). The simulation was performed using the Aspen Plus software. With a continuous flow for the organic fluid, 5.3 kg/s, it was possible to compare the different working fluids. The configuration that presented the best results was the regenerative ORC cycle that used toluene. This cycle generated a power of 1106.92 kW with an ORC efficiency of 49.51%, an annual cost of US$3085.66k, and an operating cost of US$211.65/hour.

Morais et al. (2020) propose a system that is composed of a PTC field, a biomass burner, an intermediate heat transfer system, an ORC, and an absorption cooling system. Energy, exergetic and economic analyzes are carried out. The study intends to use solar energy as the primary source to feed the system and secondarily biomass. The work compares the performance of different working fluids and evaluates how different parameters affect the system. From a thermodynamic point of view, the best working fluids for this system would be pentane, decane, or nonane, but considering economic feasibility, the best working fluid would be cyclohexane. The system produces 1000 kW of electricity and 35 kg/s of cold water (approximately 300 kW). Among the equipment used, those responsible for generating more irreversibility are the solar field, the biomass burner, and the absorption system. From an economic point of view, there must be availability of solar energy, on the other hand, according to thermodynamic analysis, the less solar energy used, the greater the exergy efficiency.

Arslan and Kilic (2021) studied an organic Rankine cycle fed by a parabolic collector located in an area with little solar radiation (between 241 and 398 W/m2). The selected area was the province of Bilecik, Türkiye. The system also has a storage system (TES). The HTF (heat transfer fluid) used was Therminol-VP1, in the storage system a molten salt with a low melting temperature was used. For the power generation cycle, some working fluids were considered: R152a, R-600a, R601a, R718, cyclopentane, cyclohexane, and toluene. The system was optimized with a code in Excel and an economic analysis was also made with the Net Present Value (NPV) method. Under optimal conditions, the working fluid that obtained the best NPV results was R718 with energy and exergy efficiencies, respectively, equal to 10.19% and 10.94%. The system generates 19.47 MW. According to the economic analysis, the system is in an area of low solar radiation and is not a good investment.

Yazdi and Khoshgoftar Manesh (2022) propose a system for generating electricity. The plant comprises a steam Rankine cycle, parabolic troughs with direct steam generation, a heat storage system, and an auxiliary boiler. The boiler is used when the storage system is unloaded, to reach the state of superheated steam at 400ºC, because at that moment the temperature of the water leaving the storage system is low. The modeling was performed by a code in the MATLAB environment. Calculations were made for the city of Qom, Iran. The system generates 50 MW. The heat storage system

in the absence of the sun generates between 6 and 50 MW for 6 hours. The total average monthly energy efficiency in different months varies between 40 and 43%.

The design proposed by Rejeb et al. (2022) is a system powered by solar energy with a poly generation of hydrogen, oxygen, electricity, and heat. The article compares hydrogen generation and electric power generation in different places, Tehran, Dubai, Paris, and London. The system components are PVT (Solar photovoltaic thermal PV/T) collectors, an ORC cycle, a PEM (proton exchange membrane) electrolyzer, and liquefied natural gas (LNG). Water is used as the heat transfer liquid (HTF) and the working fluid is propane (or R290). The LNG is used to recover the heat rejected by the ORC and from that generates power. The EES (Engineering Equations Solver) was used for a thermodynamic and economic evaluation of the system. The NSGA-II algorithm (non-dominated sorting genetic algorithm II) and the TOPSIS decision analysis method were used to estimate the optimal results for the proposed system, under these conditions the system has an exergy efficiency of 16.24%, a cost rate of 4.48$/hour and electricity production of 33.32 kW. In Tehran, Dubai, Paris, and London the critical monthly generated electricity was 9390 kWh, 8666 kWh, 7050 kWh, and 7040 kWh, respectively. In addition, the maximum monthly hydrogen production was 62 kg, 75 kg, 17 kg, and 14 kg. Figure 5 shows the simulated thermal scheme.
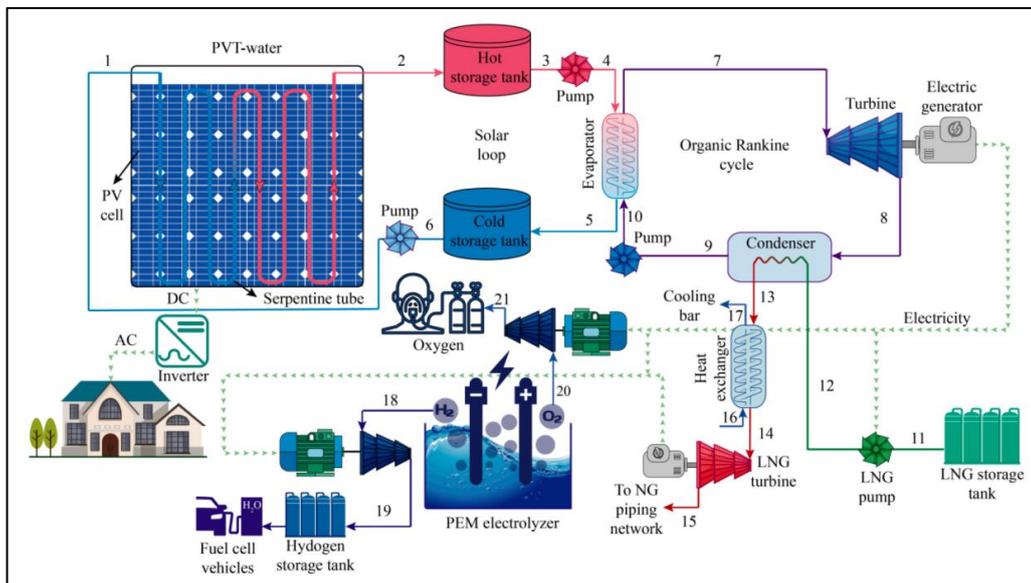

Figure 5: ORC cycle feed by a solar photovoltaic thermal source. (Rejeb et al., 2022)

Tzivanidis et al. (2016) perform an analysis of an ORC solar system to determine which combination of parameters would lead to optimal financial performance. The simulation is dynamic and is based on a numerical model developed by the authors. Thermodynamic calculations were performed using the EES (Engineering Equation Solver) software. Parabolic collectors (PTC) feed the organic Rankine cycle module with recovery, in addition, there is also a heat storage system so that the system continues to function after sunset. The fluid used for heat exchange (HTF) is Therminol–VP1. Some working fluids were considered: cyclohexane, water, n-pentane, toluene, isohexane, isopentane, MM, MDM, and MD4D. The weather data used is from the city of Athens, Greece. The maximum temperature of the selected hot source was 300°C.

Karabuga et al. (2022) experimentally evaluated the performance of a sustainable system to produce hydrogen and electricity. The components of this system are a heat exchanger, a circulation pump, the ORC cycle, a PEM electrolyzer, and a water purification unit. The plant is powered by solar thermal energy collectors. The working fluid used was NXT POE 32 (heat transfer oil). The thermodynamic analysis of this cycle was performed using the EES (Engineering Equation Solver) software. The energy and exergetic efficiency of the system are 51.82% and 16.30%, respectively. PEM generates 0.00527 kg/s of hydrogen.

4 DISCUSSIONS

The evaluated papers were related according to their main characteristics. Table 1 shows the thermodynamic cycles used and some application conditions.

Table 1: Summary of published works on thermodynamic cycles powered by solar energy applied in the production of green hydrogen.

ORDER	LOCAL	MAIN CYCLE TYPE	WORKING FLUID	NET EFFICIENCY	COST EVALUATION?	REFERENCE
1	-	Brayton-Rankine-ORC	Steam	22.2%	Yes	Assareh et. al, 2022
2	Africa	ORC	Cyclopentane	19.20%	No	Sigue et. al, 2023
3	-	Rankine	Steam	15.54%	Yes	Puig-Samper et. al, 2022
4	Italy	ORC	C6H18OSi2	20.30%	No	Petrollese. al*, 2020
5	-	Brayton-Rankine-ORC	Helium-Steam	23.63%	Yes	Hai et. al, 2022
6		ORC		17.40%,24.80% ,36.30%	No	Yu et. al, 2021
7	Iran	Rankine	Steam	20.10%	No	Moradi et. al, 2018
8	-	Brayton-ORC	He-CO2, C6H6-C2H6O	26.75%	Yes	Su et. al, 2023
9	-	ORC	Toluene	49.51%	Yes	Javed et. al, 2023
10	Brazil	ORC	various	-	Yes	Morais et. al, 2020
11	Turkey	ORC	R718	10.19%	Yes	Arslan et. al, 2021
12	Iran	Rankine	Steam	43%	No	Yazdi et. al, 2022
13	Various	ORC	Propane	16.24%	Yes	Rejeb et. al, 2022
14	Greece	ORC	various	-	No	Tzivanidis et. al, 2016
15	-	ORC	NXT	51.82%	No	Karabuga et. al*, 2022

*: Real Plant instead of simulated.

Through the sampling carried out, a diversity of Rankine, Brayton, and ORC cycles can be noticed in the developed plants. All apply combined cycles; however, ORC is predominant in solar energy-based projects. Among the ORCs, the most used fluids are hydrocarbons (cyclopentane, propane, and toluene). Four projects had efficiencies of less than 20%, while another five had efficiencies greater than 25%. R718 fluid did not perform well. Among the most efficient are the steam cycle and the remainder of organic fluids. Most of the works are simulated plants, given the smaller number of publications referring to real installations available. Approximately half of the works presented a cost analysis, either of energy or the produced hydrogen.

From the analyzed works, it is a trend that ORC cycles are indicated for temperatures up to 400ºC, while combinations of Brayton and Rankine (steam) are for higher working temperatures. Only models that work with a solar tower seem to achieve this condition. No correlation between the working fluid and the estimated efficiency was observed, supporting the hypothesis that various types of fluids can be equally efficient. It depends on the modeling and temperature conditions, turbine pressure, heat regeneration, and power dimensioning.

5 CONCLUSIONS

This work provided a comprehensive review of the most recent projects focused on the production of green hydrogen from solar thermal energy. Solar energy research for the production of green hydrogen has intensified in recent years in different parts of the world. From the published results it is possible to state that the most suitable cycle for the production of green hydrogen based on solar energy is the ORC, where the organic fluid generates power by absorbing heat from a heated exchanger fluid before penetrating the turbine. Except for the solar tower, solar thermal energy operates efficiently with different working fluids reaching temperatures up to 400°C. Regenerative ORCs range efficiencies from 19 to 50%. It is worth mentioning that some publications show high efficiency values for simple Rankine cycles at higher temperatures. In this sense, ORC cycles are also interesting due to the different working fluids that could be used for solar power plant applications.

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