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Solar Driven Organic Rankine Cycle System and Hydrogen Fuel Production with Waste Heat Recovery

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Abstract

Energy systems that rely on non-renewable sources like fossil fuels are contributing to climate change by emitting more carbon dioxide. It is crucial to shift towards renewable energy sources such as solar, wind, biomass, and geo-thermal to meet our energy needs. Organic Rankine Cycle (ORC) is a thermodynamic cycle which utilizes an organic fluid with higher molecular mass and lower vaporization temperature than water-like organic fluids such as refrigerants. ORC technology powered by solar energy and waste heat plays an essential role in reducing carbon emission impact. It is becoming one of the most promising approaches to recovering waste heat using regenerative cycles. In this work, ORC driven by solar energy was performed in CYCLE tempo. The heat from solar panels was given as an input to run the ORC power system in the primary circuit. The system involves an evaporator, steam turbines (high pressure and low pressure), a condenser, a feed pump, a waste heat source and R134a as the working fluid for the primary ORC. In the secondary circuit, R245fa was used to produce additional power. Hence, the total power produced by the integration of these two circuits was 5.114 MW and a share of total electricity was utilized for hydrogen production by reversible fuel cells (i) Solid Oxide Electrolysis Fuel Cell (SOEFC) and (ii) Proton Exchange Membrane Fuel Cell (PEMFC). They also compared the results of these fuel cells. The net power of 3.114 MW was available to meet local energy demands as well.

Keywords: *Hydrogen, Organic Rankine Cycle, Solar Energy, Waste Heat, Working Fluid*

1.0 Introduction

Renewable energy sources, such as solar, wind, and biomass, are known for their green credentials, as they have minimal environmental impacts and help reduce carbon emissions. These technologies play a key role in meeting energy demands sustainably. Solar energy, for example, is harnessed by the environment in various ways, through the absorption and transformation of heat and light from the sun. Both biomass and wind energy can be seen as direct results of solar energy. Renewable energy technologies show a promising approach to mitigate climate change by reducing greenhouse gas emissions as a better replacement for conventional energy sources[1].

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As the population increases, energy demand is also increasing drastically. Thereby to meet the energy demand an increasing consumption of fossil fuels is noticed. Even though, the present energy demands alarming about the energy crisis. This promotes an interest towards renewable alternatives to match the world's growing energy needs. The excessive burning of conventional fossil fuels has caused increasing in global warming temperature to 1.1°C by releasing carbon dioxide. The objective of the Kyoto Protocol agreement is to regulate greenhouse gas emissions with overall pollution prevention targets. Renewable energy resources will play a predominant role in the world's future. Renewables are replenishable energy sources which can be renewed, e.g. solar energy, wind energy, biomass energy, geothermal energy, etc.[2]. By using locally available renewable energy sources, energy requirements can be met and provide energy supply with minimal or almost zero emission. By global protocols, Renewable technologies help in economy of the country by reducing exports of fossil fuels. And installation of renewable energy systems creates employment for the local people and also ensures a sustainable development of the remote regions[3]. Among all, solar energy is an essential source of renewable energy since it is the cleanest and abundantly available across the world. Solar energy received from the sun can be converted into solar thermal or solar power. Various technologies are available in the current market to harness solar energy for different purposes including generating electricity and water heating. ORC power system was studied to recover low-grade heat by admission of service steam into the steam boiler in the exhaust gas passage for the ORC unit on large ships. The working fluid was pressurized working fluid from the pump was fed to the recuperator, further, it was preheated, evaporated and superheated in the exhaust gas boiler channel. This superheated fluid was sent to the steam turbine where it was expanded thereby additional power was produced[4]. Organic Rankine Cycle (ORC) is a proven technology that can transform low to medium-grade heat into useful work[5]. Exhaust from a diesel engine was also considered as a low-grade heat energy and it was utilized to convert to power in ORC power system[6]. A significant amount of research has been carried out in the area of ORC power systems. Most of them were from China, the USA, and European countries. The works focussed more on the selection of working fluids, performance analysis and optimization of ORC power systems[7]. Industrial processes and thermal devices have become one of the major sources of waste heat, and continue to grow as well. In this regard, waste heat recovery ORC systems shortly get great attention[8]. Lecompte *et al.,*[9] performed various cycle configurations which modified the basic ORC for waste heat recovery applications. Quoilin *et al.,*[10] presented different ORC applications such as Biomass ORC systems, Geothermal ORC systems and Solar ORC systems, the authors showed the development of ORC for the future and benefits over steam Rankine cycle. Tocci *et al.,*[11] presented a techno-economic review of the ORC technology, conclusions were made that financial support by the governments is essential for the advancement in the ORC technology for the power output range 1kW to 100kW to make up the current market gap.

1.1 Climate Change Scenario

Tremendous use of fossil fuels causes the release of hazardous gasses like Sulphur oxides, Nitrous oxides and Greenhouse Gas (GHG) emissions. In specific, a significant amount of carbon dioxide gas emission takes place with other energy sources. Hence, shifting to renewable or clean energy is the inevitable option for sustainable energy development in the future[12]. Climate change has become a major aspect of human life in the 21st century. Otherwise, it leads to various health issues, for example as a result of increased frequency and intensity of heat waves due to the emission of greenhouse gases, increased floods and droughts, changes in seasonal patterns, and effects on the risk of disasters and malnutrition. The most important environmental problem with the methods adopted to produce energy is rapid climate change. The enhancement in the concentration of greenhouse gases in the conventional energy systems in the atmosphere leads to a rapid increase in the surface temperature of Earth[13].

2.0 Organic Rankine Cycle and its Types

The fluid makes it possible to recover heat from lower temperature sources through the Rankine cycle, including solar ponds, geothermal heat, biomass combustion, and industrial waste heat. The low-temperature heat is transformed into work that is beneficial and has the potential to produce energy[14,15].

From Figure 1(a), an ORC involves majorly four components: an evaporator, an expander, a condenser, and a pump. Saturated liquid from the condenser (1) is pressurized in the pump (2). An organic fluid picks up the heat in the evaporator (3) where it gets vaporized. Further, it enters the steam turbine/expander (4) and produces power using a generator coupled to it. And the cycle repeats. The efficiency of the ORC system can be enhanced by increasing the quality of steam, and a heat exchanger can be added to the basic ORC to limit the heat given to the evaporator. Common configurations in the ORC system are being recuperative type, regenerative type, and reheated type cycle systems as depicted with T-S diagrams in Figures 1(b) and (c), respectively. Both the regenerative and the reheated cycles intend to reduce the heat supply to the evaporator. In a reheated cycle an additional device called a recuperator is added where the pressurized working fluid from the pump gets preheated to reduce the supply of heat to the evaporator. Whereas in

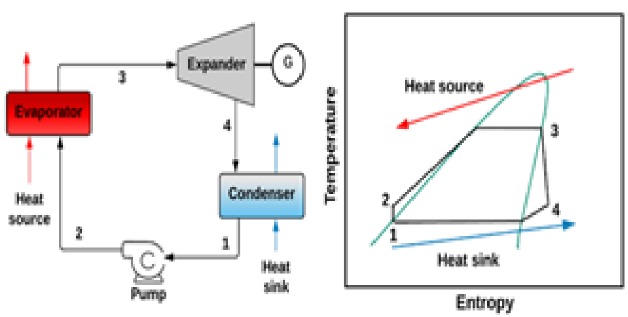


Figure 2a. Basic organic Rankine cycle.

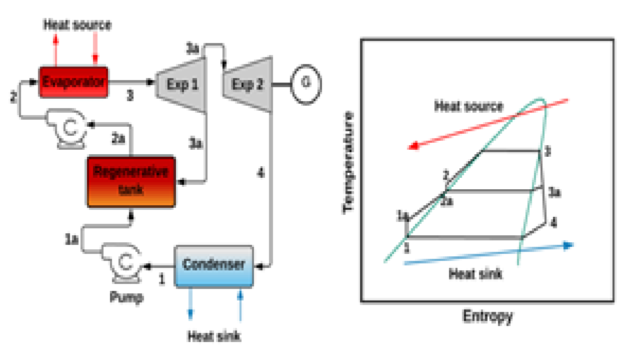


Figure 2b. Recuperative organic Rankine cycle.

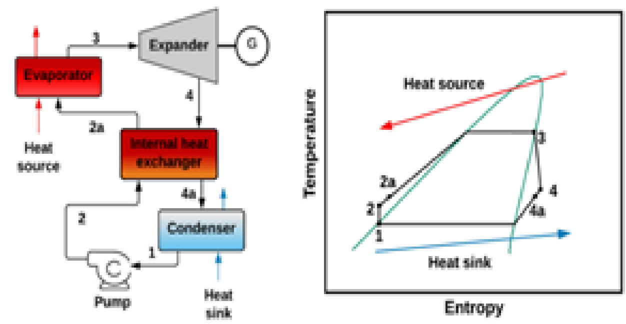


Figure 2c. Regenerative organic Rankine cycle.

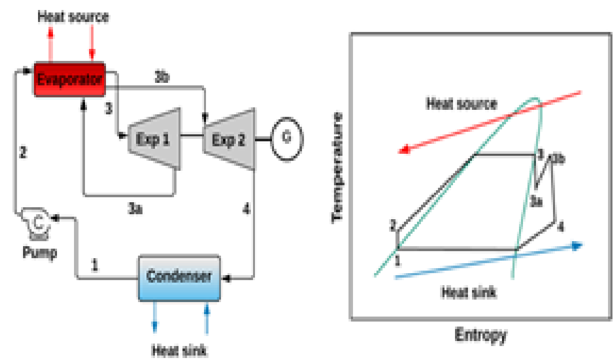


Figure 2d. Reheated organic Rankine cycle.

the regenerative ORC, working fluid from the first low-pressure expander is made to pass through a regenerative heat exchanger which is mixed with condensate coming from the condenser and gets preheated.

In reheated ORC, without using an additional heat exchanger, the exit of Exp 1 (Expander 1) is made to flow through the evaporator again, and then the superheated working fluid gets reheated and made to flow through the Exp 2 (Expander 2) as depicted in Figure 1(d), In this configuration, the cycle efficiency can be improved in terms of significant amount of power production by the addition of more heat to the evaporator[16].

3.0 Selection of working fluids

In the present scenario, there is a huge scope in the development of ORC systems. By employing various organic working fluids under different operating conditions and configurations innumerable researchers have modelled and simulated ORC power systems. These technologies showed greater efficiency at below 120°C

Table 1. Properties of the working fluids R134a and R245fa[17]

Properties	R134a	R245fa
Evaporation temperature (K)	247.23	288.4
Critical pressure (MPa)	4.06	3.65
Molecular mass	102.03	134.05
Saturated pressure at 293K (MPa)	0.5717	0.1227
ODP (Ozone Depletion Potential)	0	0
GWP (Global Warming Potential)	1300	950

with *R123, R1233zd(E), R134a, R600, R290, R1234yf, and R245fa,* and at higher temperature ranges, benzene, methanol, toluene, and cyclohexane are considered. Given the economic aspect, *R1234yf* and cyclohexane were treated as best, whereas from the environmental point of view *R600, R601, R123,* and *R134a* fluids performed better at lesser range temperatures, and at higher temperatures, toluene showed better performance. Working fluids *R134a* and *R245fa* were chosen for lower temperatures ranging up to 120°C as they showed better energy conversion efficiency[6]. The thermal efficiency of the modified ORC could be increased by 14% with a working temperature of 160°C using *R600a, R245fa* and *R290* as working fluids compared to the basic ORC10.

4.0 Regenerative Fuel Cells or Reverse Fuel Cells

Reversible Fuel Cells (RFCs) also called "regenerative fuel cells," are reversible electrochemical devices that can perform both fuel cell mode production of electricity generation as well as electrolysis mode for hydrogen/chemicals production. Nevertheless, a particular device might not be constructed so that it can be operated backwards and is often designed for running in a single mode. Except they are specifically meant to perform in dual modes, such as high-pressure electrolyzers, regenerative fuel cells, solid-oxide electrolyzer cells, and unitized regenerative fuel cells, standard fuel cells run backwards and often do not produce highly efficient systems[18]. Production of hydrogen from water using excess electricity generated using some renewable energy sources because the process emits no carbon dioxide. The current trend has shown an increased interest in using hydrogen as a fuel for buses, trucks and even ships. The major factor is its transportation from the point of source to the point of application and storage as well. To overcome this, the researchers

Table 2. Resources needed to generate 1 Kg of hydrogen

Type	Electrolysis	
Conversion pathway	Proton Exchange Membrane (PEM)	Solid Oxide Electrolysis Cell (SOEC)
Input	Electricity	Electricity
Electricity (kWh/ kg H_2)	54.6	34.14
Water (kg/ kg H_2)	18.04	9.1

found regenerative-type solid-oxide fuel cells which can operate in dual mode[19]. Optimising the consumption of energy produced locally has become the top priority to minimize the strain on transmission and distribution networks. Reversible Solid Oxide Fuel Cell technology ensures power supply matches demand. Unitized Reversible Fuel Cells (URFCs) display a sustainable solution for having to perform as an electrolyzer and a fuel cell mode and thus avoid the cost addition of installation of two separate units which do the same[20].

5.0 Methodology (Figure 2)

Identification of a geographical location [Pavagada, (77.315°N, 14.14°E and elevation 621m) Karnataka, India]. Using polysun software, the daily maximum temperature of the collector was recorded. The collected solar thermal energy was given as an input source to the primary Organic Rankine Cycle power system in Cycle tempo software, Also using a reheater, the fluid is reheated and made to flow into a low-pressure turbine, and thereby additional electricity is produced. Part of the total electricity produced was then used for regenerative fuel cells to produce hydrogen by electrolysis using water.

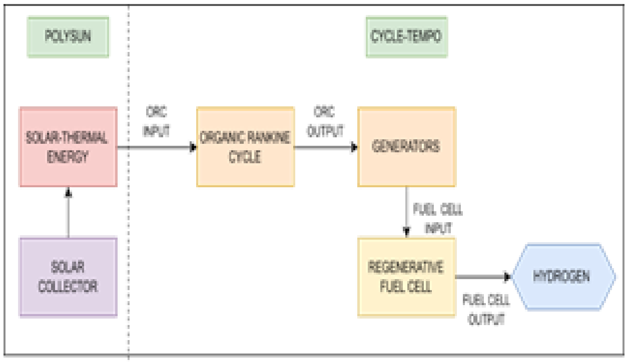


Figure 2. Methodology.

6.0 Results and Discussions

The input parameters for each component given are tabulated in Table 3.

Table 3. Input parameters to various components

Apparatus	Parameter	Quantity
Boiler	PIN	26 bar
	TOUT	80°C
	DELE	200 kW
Turbine 1	PIN	26 bar
Heat Exchanger 1	PIN1	24 bar
	TIN1	24°C
	PIN2	3 bar
Waste Heat Source	POUT	3 bar
	TOUT	120°C
Stack	PIN	3 bar
	TIN	30°C
Turbine 2	PIN	6.5 bar
	TIN	48°C
Heat Exchanger 2	PIN1	2.5 bar
	TIN1	12°C
	PIN2	4 bar
Pump 2	PIN	2.5 bar
	TIN	-4°C
R245fa Source	POUT	4 bar
	TOUT	10°C
Pump 1	PIN	4 bar
	TIN	50°C
Turbine 3	PIN	4.6 bar
	TIN	60°C
CONDENSER 2	EEQCOD	2
	PIN1	4 bar
	TIN1	10.5°C
	PIN2	1.013 bar
	POUT2	1.013 bar
	TIN2	15°C
	TOUT2	8°C

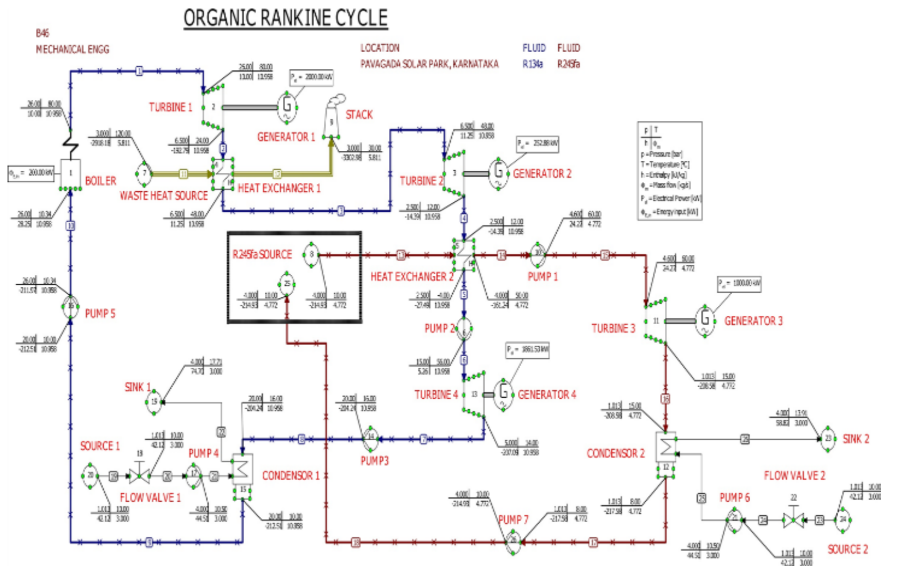
Turbine 4	PIN	15 bar
	TIN	56°C
Pump 3	PIN	5 bar
	TIN	14°C
CONDENSER 1	EEQCOD	2
	PIN1	4 bar
	TIN1	10.5°C
	PIN2	20 bar
	POUT2	20 bar
	TIN2	16°C
	TOUT2	10°C
Pump 5	ETHAI	0.9
Pump 4	POUT	4 bar
Valve 1	DELP	0
	PIPE	20
	FLOW	3 kg/s
Sink 1	PIN	4 bar
Source 1	POUT	1.013 bar
	TOUT	10°C
Pump 6	POUT	4 bar
Valve 2	DELP	0
	PIPE	24
	FLOW	3 kg/s
Sink 2	PIN	4 bar
Source 2	POUT	1.013 bar
R245fa Source	PIN	4 bar
	TIN	10°C
Pump 7	PIN	1.013 bar
	TIN	8°C
Generator 1	ETAGEN	0.9
Generator 2	ETAGEN	0.9
Generator 3	ETAGEN	0.9
Generator 4	ETAGEN	0.8
Medium Pipe 1	Library	freeStanMix
	Fluid	R134a
Medium Pipe 11	Type	GASMIX standard Fluegas
Medium Pipe 13	Library	freeStanMix
	Fluid	R245fa
Medium Pipe 23	Type	WATERSTM
Medium Pipe 19	Type	WATERSTM

From Figure 3(a), the organic fluid R134a gets heated up and vaporized to high pressure, and high-temperature steam is sent to the high-pressure steam turbine/ expander. This is the first power generation stage in the system. The turbine uses the pressure energy and converts it into mechanical energy. The shaft of the turbine is connected to a generator as shown in the configuration diagram.

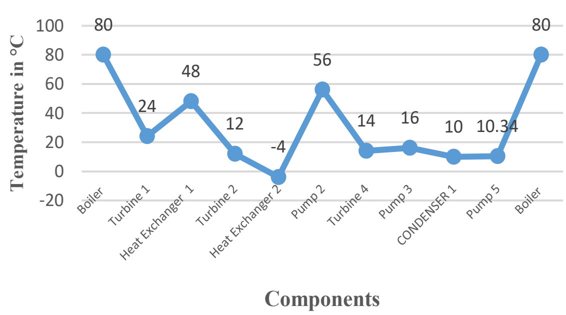
Once used in the high-pressure turbine, the working fluid, which is R134a, now with lower pressure and temperature gets sent to the reheater which is connected to a waste heat source. The reheater heats the working fluid to a suitable temperature and directs it towards the low-pressure steam turbine/expander to produce additional power. This completes the primary circuit. The low-pressure and low-temperature fluid, after exiting the low-pressure turbine, flows into a counter-flow heat exchanger, which is connected to another circuit with R245fa as the organic fluid in use. Here, heat exchange takes place between both the fluids and the fluids flow into a third and fourth generator respectively, thus producing more power.

After the exit from the final turbines, the organic fluids pass through a condenser which cools the fluids down. They are then pumped back to their respective reservoirs with the help of electric pumps and the cycle repeats. Thus, almost the entire available heat energy input is used with the help of these multiple stages of turbines and reheaters.

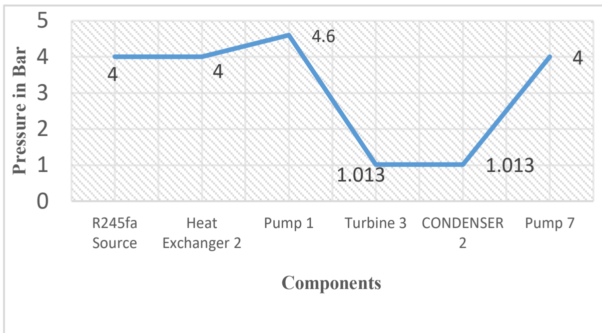
A part of power is used for theoretical analysis of the production of hydrogen in reversible fuel cells. The



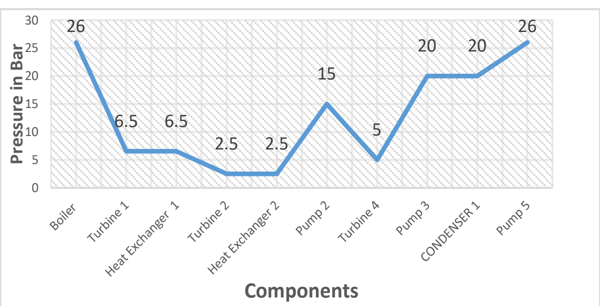
(a)



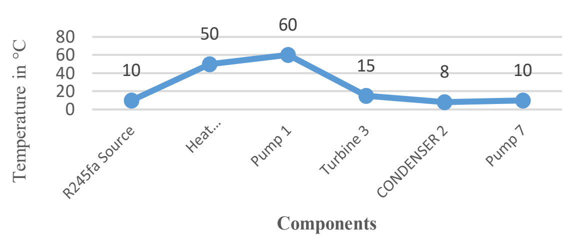
(b)



(c)



(d)



(e)

Figure 3. **(a)** Integrated Proposed ORC power system, **(b)** Temperature variation of R134a in each component, **(c)** Pressure variation of R134a in each component, **(d)** Temperature variation of R245fa in each component, **(e)** Pressure variation of R245fa in each component.

fuel cell used is of Solid Oxide type, where the fuel cell can be reversed. Meaning the fuel cell can be used to either produce electricity with Hydrogen as the input or can be used to produce Hydrogen and Oxygen with water and electricity being the input. Figures 3 b and c represent the temperature and pressure variation of R134a working fluid in each component involved in the ORC power system. Figures 3 (d) and (e) represent the temperature and pressure variation of R245fa working fluid in each component involved in the ORC power system.

7.1 Formulae

The first law of thermodynamics applied for an open system; Steady Flow Energy Equation (SFEE)

$$(Q_{in} - Q_{out}) + (W_{in} - W_{out}) = m[(h_{out} - h_{in}) + \left(\frac{V_{out}^2 - V_{in}^2}{2}\right) + g(Z_2 - Z_1)] \quad [I]$$

where,

Q_{in}→Heat Input (kJ/Kg), Q_{out}→Heat output (kJ/Kg), W_{in}→Work supplied (kJ/Kg), W_{out}→Work done, h_{out}→Enthalpy out (kJ/Kg), h_{in}→Enthalpy in (kJ/Kg), V_{out}→Exit velocity (m/s), V_{in}→Inlet Velocity (m/s), Z_1 and Z_2→Datum (m).

7.2 Hydrogen Production using Electrolysis Method

7.2.1 Solid Oxid Electrolysis Cells (SOFC)

Electricity (kWh/Kg-H_2) =36.14
Water (Kg/Kg-H_2) =9.1

7.2.2 Amount of water required for electrolysis with 2000 kW of power

water =electricity
9.1/x=1.5058/2000
Total water required=x=12086.598 Kg

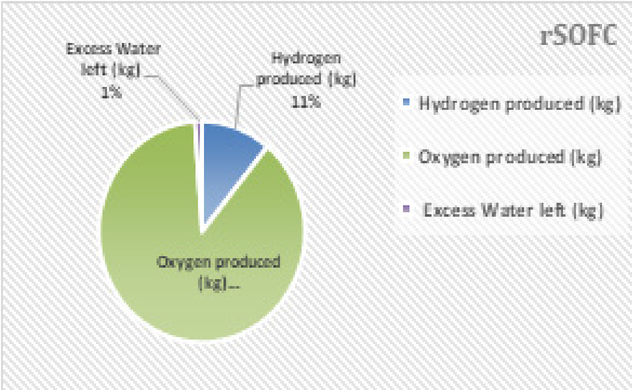
7.2.3 Total amount of hydrogen produced from 12086.598 Kg of water

water=hydrogen 9.1/12086.598=1/x
Total amount of hydrogen produced = x =1328.19 Kg

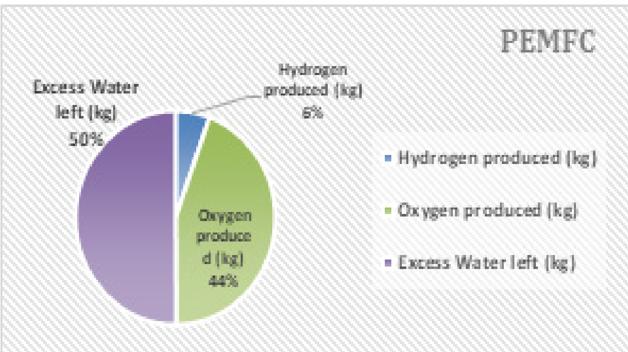
7.3 Comparison of SOEFC vs PEMFC

Table 4. Comparison of fuel cell

Particulars	SOEFC	PEMFC
Electricity (kW/kg of H_2)	1.505	2.275
Water (kg/kg of H_2)	9.1	18.04
Power Consumed (kW)	2000	2000
Water used (Kg)	12086.598	15859.340
Hydrogen produced (Kg)	1328.19	879.12
Oxygen produced (Kg)	10625.580	7032.966
Excess Water left (Kg)	132.828	7947.26



(a)



(b)

Figure 4. **(a)** Graphical representation of hydrogen production by rSOFC, **(b)** Graphical representation of hydrogen production by PEMFC.

Figures 4 (a) and (b) depict hydrogen production by rSOFC and hydrogen production by PEMFC

8.0 Conclusions

- Organic Rankine Cycle power systems have become the most reliable and promising technology for power production from low to medium-temperature heat sources. This technology allows efficient exploitation of low-grade heat energy that otherwise would be wasted.
- In this work, modelling and simulation analysis of ORC that uses heat from solar panels was given as input to run an ORC power system in the primary circuit along with the utilisation of low-grade heat/waste heat in the secondary circuit.
- The integrated power system could generate a total power of 5.114 MW.
- A share (2 MW) of total electricity was utilized for hydrogen production by reversible fuel cells (i) Reversible Solid Oxide Electrolysis Fuel Cell (rSOFC) - 1328.19 kg and (ii) Proton Exchange Membrane Fuel Cell (PEMFC) - 879.12 kg. And showed that rSOFC is more efficient than PEMFC.
- A net power of 3.114 MW was available to meet local energy demands.

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