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Article

Experimental and Thermoeconomic Analysis of Small-Scale Solar Organic Rankine Cycle (SORC) System

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Abstract: A small-scale solar organic Rankine cycle (ORC) is a promising renewable energy-driven power generation technology that can be used in the rural areas of developing countries. A prototype was developed and tested for its performance characteristics under a range of solar source temperatures. The solar ORC system power output was calculated based on the thermal and solar collector efficiency. The maximum solar power output was observed in April. The solar ORC unit power output ranged from 0.4 kW to 1.38 kW during the year. The highest power output was obtained when the expander inlet pressure was 13 bar and the solar source temperature was 120 °C. The area of the collector for the investigation was calculated based on the meteorological conditions of Busan City (South Korea). In the second part, economic and thermoeconomic analyses were carried out to determine the cost of energy per kWh from the solar ORC. The selling price of electricity generation was found to be \$0.68/kWh and \$0.39/kWh for the prototype and low cost solar ORC, respectively. The sensitivity analysis was carried out in order to find the influencing economic parameters for the change in NPV. Finally, the sustainability index was calculated to assess the sustainable development of the solar ORC system.

Keywords: SORC; ORC; solar energy; exergy; thermoeconomic; sustainable development; economic analysis; sensitivity analysis

1. Introduction

Power obtained from solar energy in developing countries plays an important role in changing the living standards of people residing in remote areas. Developing countries have abundant solar energy resources and the capacity to produce and manufacture comparatively cheap solar power systems that can be harnessed. Through the proper utilization of this solar energy, the isolated rural areas of developing countries can be electrified. One of the promising technologies for powering rural areas is the solar organic Rankine (SORC) cycle system. The SORC is similar to the conventional steam Rankine cycle system but it uses renewable energy as the heat source (solar energy) and pure or mixed organic compounds as the working fluid. A small-scale SORC can be used to electrify the homes in rural communities and run small businesses. Large-scale SORC have already been commercialized, but small-scale systems are still in the development phase. The small-scale system is applied in rural areas where electricity grid connections/extensions are not economically feasible due to difficult geographic terrain. An off-grid SORC provides a sustainable and cost-effective alternative to un-eco-friendly and expensive diesel generators for electricity generation. In addition, this small-scale technology helps to replace kerosene based lamps and traditional biomass, in which 2.7 billion people around the globe depend on it for their energy requirements [1]. An off-grid power supply can provide power for domestic uses, such as lighting, running televisions, radios, refrigerators, communications, and water pumping. Moreover, it can be used for public uses, including electrification in rural schools and health clinics. In particular, the SORC is a reliable technology for exploiting low and medium range temperature heat sources obtained from different types of collectors, such as flat plate**,** evacuated tube collector and parabolic type of collectors. Because the ORC system uses organic compounds as a working fluid, a poor choice of working fluid influences the solar plant performance, which could adversely affect the economics. Therefore, the working fluid properties should also be considered when designing a solar ORC system.

Several authors [2–7] reported R245fa to be a good candidate for a solar ORC system. This working fluid has good thermo-physical characteristics when subjected to a various range of heat source temperatures. In addition, it causes low ozone depletion, has low global warming potential, and is non-toxic and non-flammable when it is used in a solar ORC system. Several studies have discussed the SORC technology for electricity generation but few have been conducted for the purposes of rural electrification. Quoilin *et al*. [8] designed the solar ORC unit to be installed in rural clinics of Lesotho with a net target power output of 3 kW. They used a collector trough, one- or two-stage expansion device (modified commercial HVAC compressor), plate type heat exchangers, and air-cooled condenser, and reported an overall efficiency of 8%.

Mathew *et al*. [9] examined the technical and economic feasibility of the small-scale solar ORC systems comparing with photovoltaics hybridized with LPG/propane and diesel generator small plant for electricity generation in the rural areas of Africa. They showed that net cost for rural health clinic systems has a specific levelized electricity cost of 0.26–0.31 USD/kWh. Similarly, Wolpert *et al*. [10] carried out theoretical analysis of the CHP system for electricity generation using evacuated heat pipe solar collectors and reported an efficiency of 15% using the refrigerant R134a at a sink temperature of 10 °C. Similarly, Nguyen *et al*. [11] constructed and tested a small-scale solar ORC prototype that used *n-pentane* and delivered 1.5 kW of electricity with a thermal efficiency of 4.3%. Kane *et al*. [12] design a mini-hybrid solar power plant integrating solar collectors, ORC cycles and bio-diesel engine to confirm the operational characteristics of this hybrid system to meet the electricity, cooling and pumping needs for rural areas. Baral *et al*. [13] tested a small-scale ORC unit with a commercial scroll expander and found that the unit has the capacity to produce 1.4 kW of electric power when the heat source was 120 °C. In a similar manner, Delgado and Lourdes [14] conducted a parametric study of the influence of the configuration of the solar ORC system for various working fluids in a desalination process to determine the minimum aperture area required to produce mechanical power output under different operating conditions. The result showed that compound parabolic collector (CPC) and flat plate collector (FPC) require 25–26 m^2 and 22–23 m^2, respectively, to produce 1 kW power. In a different study, Gang *et al*. [15] reported an overall electrical efficiency of 8.6% using a compound parabolic trough with a solar irradiation of 750 W/m^2. Delgado [16] studied the small-scale solar ORC system that can be used to pump water and found that they were installed mostly in Asian countries.

The main objective of this study was to determine if a small scale SORC system is a good option for electricity generation in rural areas. The findings of the present study are expected to help rural practitioners, solar ORC developers and investors to consider a small-scale solar ORC system as economically feasible for producing electricity for rural houses, health posts, schools, and even run small businesses in the un-electrified areas of developing countries. The first part of this study is on the experimental analysis of the SORC system and the second part is the thermoeconomic analysis. The experimental section includes the SORC system efficiencies, power output during months of the year, area of the solar collector required for electricity generation. The thermoeconomic analysis section contains the cost of energy per kWh through energy analysis, payback period and sensitivity analysis.

2. Methodology

For the analysis of small-scale solar ORC system, an electric heater was used to produce hot water in the temperature range of 90–120 °C. It is assumed that a vacuum tubular heat pipe solar collector can produce the same range of temperatures. In order to determine the size of collector, the required heat input value was calculated based on the experiment performed in small-scale ORC unit. Since the solar insolation plays an important role in solar ORC system, the mean weather condition of Busan, South Korea has been taken for analysis [17]. This weather condition was thus used for calculation of solar collector area. In addition, the ORC unit's thermal efficiency, mechanical power output and expander efficiency have been calculated for further analysis regarding solar power output during different months of the year. The experimental investigation assessed the performance of the ORC unit when the system was designed to work at 90 °C, 100 °C, 110 °C, and 120 °C.

3. Investigated SORC Technology Design

Figure 1 shows the basic simple operation of solar ORC system. The SORC process can be described briefly as follows. Solar radiation is incident to an evacuated tubular type solar collector. Cold water is passed through it and the heated water is stored in a storage tank. The hot water from the tank is pumped through the pump and passed into the plate type heat exchanger (evaporator). The organic working fluid, refrigerant R245fa, vaporizes when passed into the evaporator, which drives the magnetically coupled scroll expander to produce mechanical power. The working fluid changes its phase from a vapor to liquid state when the cooling water from the tap is passed into the condenser. Lastly in its liquid form, the working fluid runs into the refrigerant tank to complete its cycle. The mechanical power produced by the ORC unit is then coupled to an electrical generator for electricity generation. The efficiency of the SORC is relatively low because it is operated at low range of temperatures obtained from the collectors. Hot water (90–120 °C) can be obtained from the solar collector installed in the test facility.

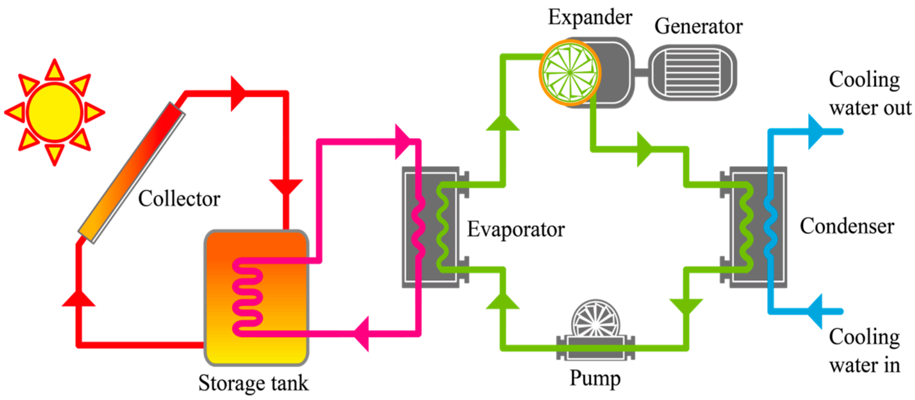

Figure 1. Schematic diagram of a small-scale solar ORC system.

Figure 2 shows the experimental setup for the solar ORC system. The design points and parameters were obtained from a series of test experiments at different heat source temperatures conducted in the test facility. The solar ORC system was designed to work at various solar source temperatures based on the maximum temperature of hot water produced from the flat and vacuum type collectors. The solar source temperatures were obtained from the flat plate collectors and vacuum type collectors. In addition, the SORC system was designed for 12 months of the year. Table 1 lists the meteorological conditions for the design of the ORC system.

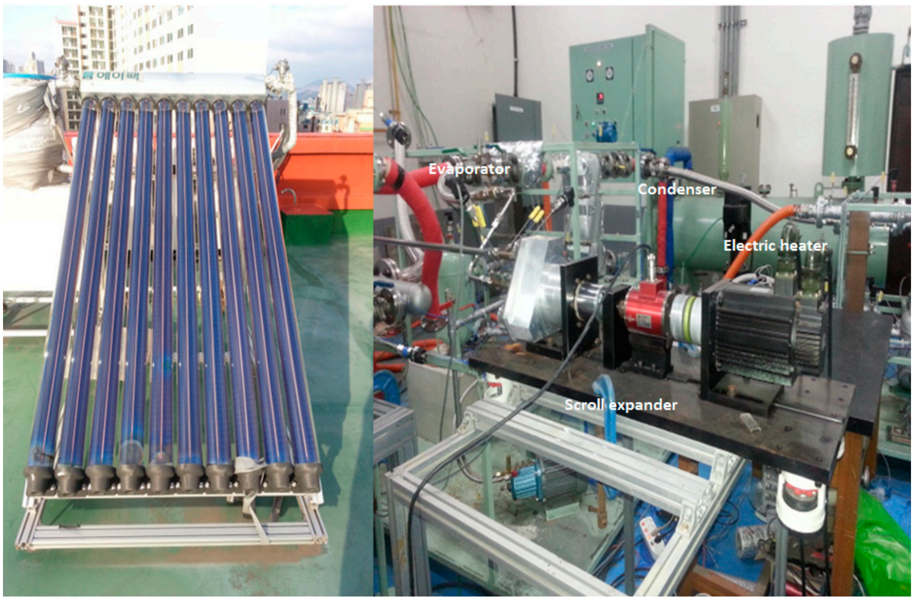

Figure 2. Experimental setup for the solar ORC system investigation.

Table 1. Meteorological data for Busan, South Korea (Latitude: 35.17° N, Longitude: 129.07° E).

Month	Solar Insolation ($kWh/m^2/day$)	Daylight Hours	Ambient Temperature (°C)
January	2.9	10	5.7
February	3.55	10.9	10.8
March	4.22	11.9	16.1
April	5.26	13	20.3
May	5.57	14	23.5
June	5.05	14.5	26.1
July	4.4	14.2	27.1
August	4.3	13.4	27.2
September	3.72	12.4	24.4
October	3.56	11.3	19.7
November	2.83	10.3	14.3
December	2.64	9.86	8.6

4. Thermodynamic Fundamentals

The described SORC system was analyzed from the code developed using the Engineering Equation Solver (EES). The following assumptions were made for the analyses of the overall performance, system and sub-systems:

- All the thermodynamic processes and systems are in a steady state.
- The working fluid feed and expansion devices are adiabatic devices.
- The simple ORC system has negligible pressure losses in the heat exchanger and piping system so it is neglected.
- The reference state (dead state) temperature and pressure are 25 °C and 1 bar, respectively, for the system's performance calculations.

The energy balance is applied to each of the system components based on the first law of thermodynamics. The general energy balance equation in steady state for any components can be written as follows:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

$$\dot{Q} - \dot{W} + \sum \dot{m}_{in}\, h_{in} - \sum \dot{m}_{out}\, h_{out} = 0 \tag{2}$$

where subscripts in and out represent the inlet and outlet, respectively; $\dot{m}$ and h represents the mass flow rate and specific enthalpy of the streams of the system working fluid, respectively, and $\dot{Q}$ and $\dot{W}$ represent the heat transfer crossing the component boundaries, respectively.

The limitation of the energy assessment can be overcome using the method of exergy analysis. This analysis deals with the conversion of energy along with the second law of thermodynamics. Because energy and mass are neither consumed nor generated, exergy is consumed during the thermodynamic process due to the irreversibility of transformation and this exergy consumption is proportional to entropy generation. In this paper, exergy analysis was carried to determine the maximum energy that can be extracted from the system. This helps to reduce the existing inefficiencies caused by different heat sources. In addition, it is the maximum theoretical useful work that can be obtained when the system interacts to equilibrium with the surrounding environment. The exergy balance in the system components at the steady state can be determined using the following general equation:

$$\dot{E}_{d,k} = \dot{E}_{X_Q} - \dot{E}_{X_W} + \sum \dot{m}_{in} ex_{in} - \sum \dot{m}_{out} ex_{out} \tag{3}$$

where $\dot{E}_{d,k}$ denotes the exergy destruction rate occurring on device *k*, and $\dot{E}_{X_Q}$ and $\dot{E}_{X_W}$ denote the exergy rate due to work and heat transfer, respectively. The exergy rates following in and out in the system is denoted by ($\dot{m}.ex$). The exergy transfer due to heat and work can be expressed as

$$\dot{E}_Q = \sum (1 - \frac{T_0}{T}) \dot{Q} \tag{4}$$

where T_0 is the reference state temperature (dead state) that describes the state at which the system is in equilibrium with the environment and T is the boundary temperature at which heat transfer occurs.

The useful collected energy rate from the vacuum tubular single collector is defined as

$$\dot{Q}_u = \dot{m}_c (C_p T_o - C_{pi} T_i) \tag{5}$$

where C_p is the specific heat capacity, $\dot{m}_c$ is the mass flow rate in the collector and T_o and T_i are the outlet and inlet temperature of solar collector, respectively.

The area of the solar collector was calculated using the collector energy balance equation as follows:

$$\dot{m}_c .(h_o - h_i) = G_b .\eta_c .A_c \tag{6}$$

where η_c, A_c and G_b are the collector efficiency, area of collector and global radiation on the surface, respectively.

The net solar ORC efficiency of the system is given by the following equation:

$$\eta_{SORC} = \eta_c \times \eta_{ORC} \tag{7}$$

where η_{ORC} is the thermal efficiency of the ORC system.

The exergy from the sun (exergy input), which is also a function of the sun's outer surface temperature ($T_s = 5800\,K$) is given by the following equation:

$$E_{sun} = A_c .G_b \left(1 + \frac{1}{3} \left(\frac{T_0}{T_s} \right)^4 - \frac{4}{3} \left(\frac{T_0}{T_s} \right) \right) \tag{8}$$

The net electrical exergy efficiency is a defined as follows:

$$\eta_{ex,el} = \frac{\dot{W}_{net}}{Ex_{in}} \tag{9}$$

The irreversibility ratio of a component *k* is defined as

$$Y^*_{d,k} = \frac{E_{d,k}}{E_{D,total}} \tag{10}$$

The improvement potential in the exergy destruction of a component *k* is defined as

$$IP_k = (1 - \eta_{ex,el}) E_{d,k} \tag{11}$$

5. Results and Discussion: Solar ORC System Performance

In designing a solar ORC system, the main parameter to examine is the heat input required to produce the power output at different heat source temperatures. From the experimental results, the heat input and solar collector area needed to produce solar ORC power output was determined, as shown in Table 2. For solar sources of 90 °C, 100 °C, 110 °C, and 120 °C, the heat required was 11.05 kW, 12.3 kW, 12.6 kW, and 17 kW, respectively. This experimental data showed that a 7.1 bar, 9.9 bar, 10.2 bar, and 13 bar evaporator inlet pressure is needed to produce a power of 0.63 kW, 0.77 kW, 0.87 kW, and 1.38 kW, respectively, at corresponding different solar source temperatures. The ORC unit was operated at 3600 RPM, which is the maximum rotational speed of the expander. The maximum inlet pressure of the scroll expander is limited, *i.e.*, maximum operating pressure is 13.5 bar. The commercial expander is designed for utilization of a low temperature heat source. The corresponding expander inlet temperatures were 79.9 °C, 90.49 °C, 99.41 °C, and 113 °C, respectively. The experimental analysis shows that the scroll expander has a maximum isentropic efficiency of 70% when the unit working is with a heat source temperature of 120 °C and inlet pressure of 13 bar.

Table 2. Experimental results for the organic Rankine cycle (ORC) working at different heat source temperatures.

ORC unit parameters	Source Temperature (°C)				Solar Collector	
Source Temperature	90	100	110	120	Collector	Evacuated tubular
Evaporator Pressure (bar)	7.1	9.9	10.2	13	Type	Heat Pipe
Expander Inlet (°C)	79.9	90.49	99.41	113	No. of tubes	10
Condenser Pressure (bar)	1.3	1.7	1.7	2.1	Heat capacity (kCal/m^2 day)	3342.47
Heat Supplied (kW)	11.05	12.3	12.6	17	Gross area (m^2)	2.55
Heat Released (kW)	9.8	11.6	12.1	15.68	Aperture area (m^2)	1.87
Expander power output (kW)	0.63	0.77	0.87	1.38	Copper, titanium-coated	Co ($\alpha \leq 95\%$, $\varepsilon \geq 5\%$)
Expander Efficiency (%)	64	66	67	70.2	Dimension (L × W × H) (mm)	2185 × 1165 × 162
Pump efficiency (%)	70	70	70	70	Collector Efficiency (%)	72.95
Cycle efficiency (%)	5.7	6.6	0.69	8.1	Filled with water (kg)	62.8

The pump isentropic efficiency was assumed to be around same as the expander. In the experiment, the refrigerant, R245fa, was superheated. This superheat temperature of the working fluid increases the solar ORC efficiency slightly. The efficiency of the solar ORC system was calculated based on the thermal efficiency and collector efficiency obtained from the scale-small prototype unit. Figure 3 shows the variation of the collector heat input and solar ORC efficiency when the degree of superheat changes.

The maximum solar ORC efficiency was 4.14%, 4.42%, 5.18%, and 5.66% when the degree of the superheat temperature are 7.9 °C, 8.8 °C, 9.09 °C, and 11.69 °C, respectively.

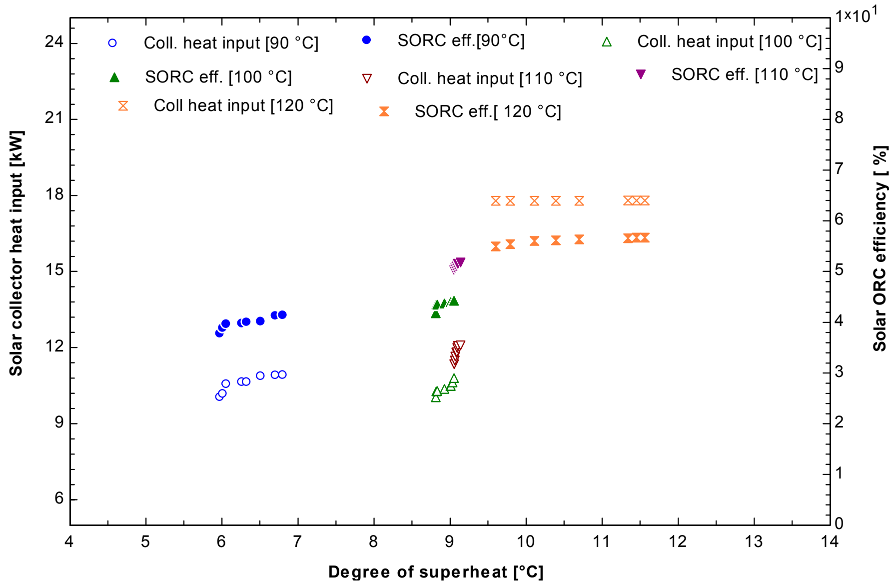

Figure 3. Variation of the solar collector heat input and solar ORC efficiency as a function of the degree of superheat temperature for different solar source temperatures.

Different temperatures and pressures in the ORC system will cause the scroll expander to be operated at off-design conditions. The power output in the commercial expander can be controlled by changing the rotational speed of expander and can be illustrated from the Figure 4. When the temperature and pressure change, the ORC system is operated at low RPM. From the experimental results, it is seen that power output decreases from 0.98 kW to 0.63 kW when the rotational speed of the expander changes from 3600 RPM to 2400 RPM. Thermal efficiency decreases from 7.5% to 6.3% during the change in rotational speed of the expander.

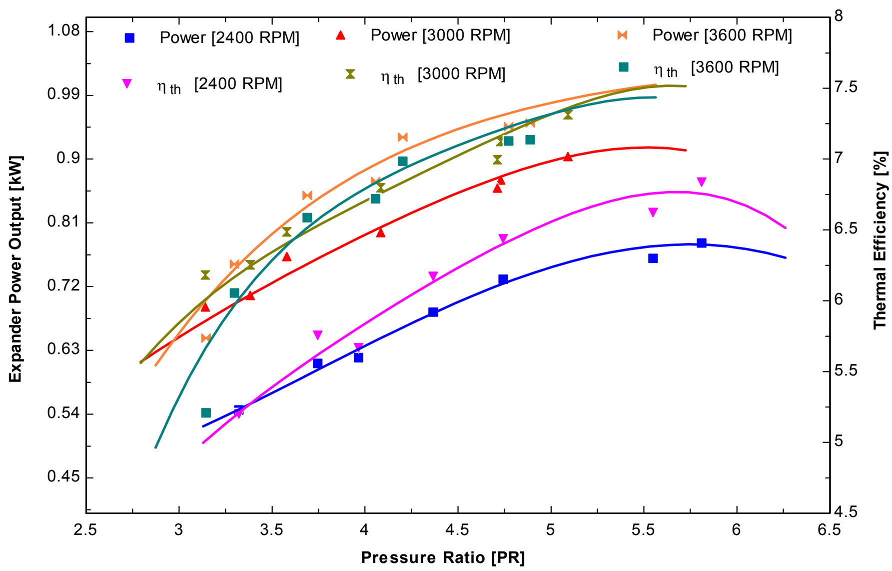

Figure 4. Variation of expander power output and thermal efficiency as a function of pressure ratio (off-design condition).

The variation of the solar irradiation on the solar ORC system plays an important role in producing power output. Figure 5 shows the solar collector area needed to produce a power output at different source temperatures during different months of the year. The maximum area of the collector needed depends on the solar irradiation during the month. In this case, it was 23 m^2 in December and 15 m^2 in April for a 90 °C solar source. Similarly, 37 m^2 and 25 m^2 collector areas were needed to achieve a 120 °C solar source temperature in December and April, respectively. The utilization of solar energy is subjected to change according to the seasons, weather and location. Therefore, the efficiency of the collector changes with the varying solar irradiation. The working conditions of a solar ORC system are instantaneous. Therefore, to analyze the monthly performance of a SORC system, it is essential to consider the efficiency of the collector. According to the manufacturer's catalog, the prototype collector efficiency could be up to 70%. In this framework, the monthly solar ORC power output was calculated. Figure 6 shows the monthly solar ORC power output for different temperatures according to the meteorological conditions of Busan City (South Korea).

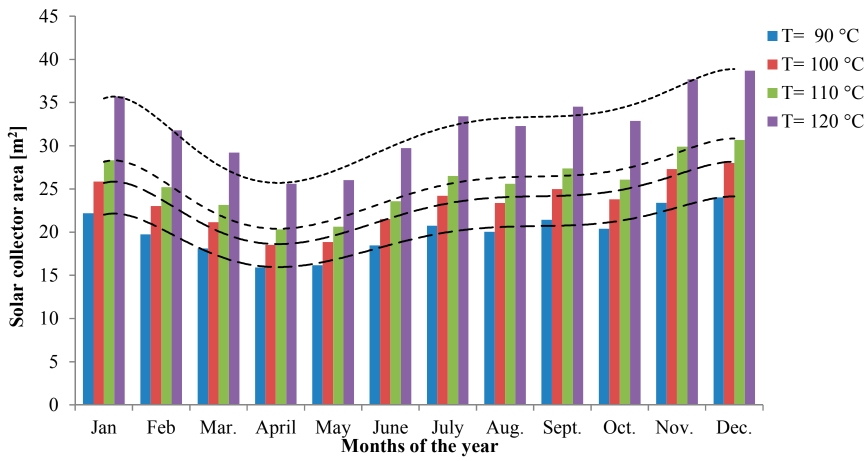

Figure 5. Variation of the solar collector area at different months of the year for different solar source temperatures.

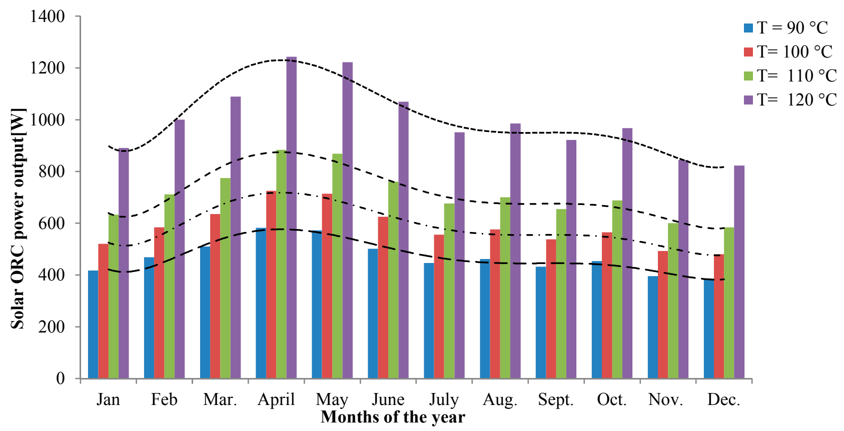

Figure 6. Variation of the solar power output at different months of the year for different solar source temperatures.

The maximum solar power output can be obtained when there is high solar irradiance. In April and May, the maximum power was obtained (1.2 kW and 1.19 kW, respectively), whereas in December, the output power obtained was 0.9 kW for a solar source temperature of 120 °C. The lowest power obtained from the solar ORC system during December was 0.4 kW, 0.53 kW and 0.61 kW for T = 90 °C, T = 100 °C and T = 110 °C, respectively. The solar irradiance varied from 2.68 kWh/m^2/day to 5.57 kWh/m^2/day during the year in Busan.

In order to see if the solar ORC system can be operated at different loads at different times of the year, an electricity demand load in the particular location should be known. For this, a case study conducted by Beck and Cecilia [18] in Dhading district, Nepal has been taken as a reference for estimating electricity demand in the Rayal village, which has 70 households. The electricity demand of Rayal was estimated based on observations of the daily life in the village. It was observed that electricity demand of 8.6 kWh/day was needed to fulfill the basic human needs (lighting). For this, four LED lamps (5 W each) and one wall socket for recharging cellphones (5 W) per household was needed. The time for electricity demand was from 6–8 a.m. and 7–11 p.m. Based on the case study, electricity demand per month has been estimated in order to observe the performance change in different months of the year when optimal solar ORC configuration is suggested. The monthly electricity demand is estimated to be 224.25 kWh. Figure 7 shows that the electricity demand can be met easily by the solar ORC system of collector area 37 m^2 (December) but there is an excess production of energy in the month of April if it is design to operate through the year. Another design configuration selected is the collector area 25 m^2 (April). Here, the electricity demand is only met during the summer season so designing the solar ORC based on April is also not favorable. The most suitable solar ORC configuration is to design the system based on the collector area needed in August (32.3 m^2). In this case, the electricity demand is met almost throughout the year, but the energy is excessive during the summer season. This excessive energy can be utilized in production of hot water for domestic purposes. The maximum power output obtained is 394 kWh during the month of April if the collector area is designed based on the month of December.

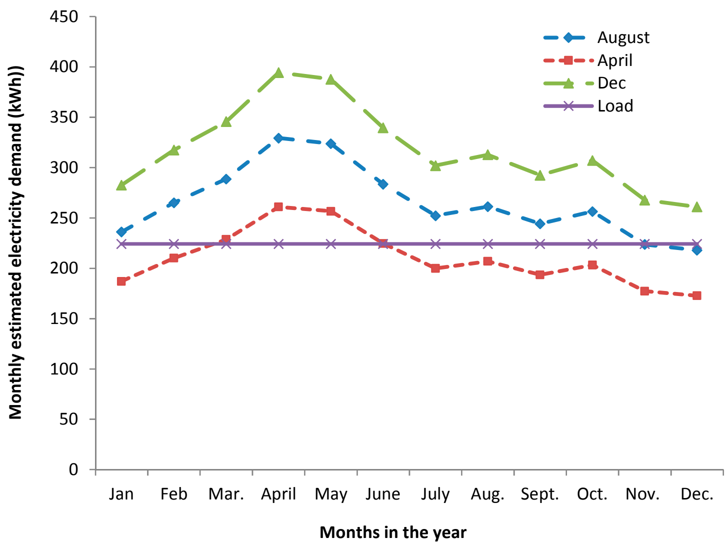

Figure 7. Variation of performance of solar ORC system power output during the year.

Detailed exergy analysis was conducted for different solar source temperatures through an exergetic assessment of the solar ORC system components. The main parameters for consideration of the exergetic assessment included the exergy destruction rate, exergetic improvement potential and relative irreversibility. Table 3 lists the calculated parameters. The parameters were estimated under the following baseline conditions: solar insolation, G_b = 800 W/m^2 and power output (0.65 kW, 0.75 kW, 0.88 kW, and 1.38 kW) for 90 °C, 100 °C, 110 °C, and 120 °C, respectively. As shown in Table 3, the main source of exergy destruction is the solar collector, which are 14 kW, 15.3 kW, 16.9 kW, and 21.3 kW for 90 °C, 100 °C, 110 °C, and 120 °C, respectively. The key reasons for this large exergy destruction in the solar collectors were incomplete absorption of the incident radiation coming from the sun, heat dispersed to the environment, and the large temperature difference between the sun, the absorber plate and fluid.

Table 3. Detailed exergy parameters for the small-scale solar ORC system.

Components	**Solar Source T = 90 °C**			**Solar Source T = 100 °C**			**Solar Source T = 110 °C**			**Solar Source T = 120 °C**		
	E_d (kW)	Y_D*	IP (kW)	E_d (kW)	Y_D*	IP (kW)	E_d (kW)	Y_D*	IP (kW)	E_d (kW)	Y_D*	IP (kW)
Solar collector	14.00	0.95	13.30	15.30	0.95	14.54	16.90	0.95	15.89	21.30	0.94	19.81
Evaporator	0.42	0.03	0.40	0.50	0.03	0.48	0.57	0.03	0.54	0.76	0.03	0.71
Scroll Expander	0.19	0.01	0.18	0.24	0.01	0.23	0.27	0.02	0.25	0.36	0.02	0.33
Condenser	0.09	0.01	0.09	0.11	0.01	0.10	0.13	0.01	0.12	0.17	0.01	0.16
Pump	0.01	0.00	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.01	0.00	0.01
Total	14.71	1.00	13.97	16.16	1.00	15.35	17.88	1.00	16.81	22.60	1.00	21.02

Similarly, other sources of exergy destruction are the evaporator followed by the scroll expander, condenser and pump. The exergy destruction in the evaporator is due mainly to the following reasons: heat transfer between the hot water and working fluid are not uniform, pressure losses due to fluid friction, and dissipation of energy to the environment. The trends are the same for all different heat source temperatures. The exergy destruction in the system components can be improved by careful design of the system components from an exergetic point of view. As observed from Table 3, the largest proportion of exergy destruction is the solar collector, so it requires careful design to improve its performance. For a solar ORC system that uses the working fluid R245fa, the total exergy destroyed were 14.71 kW, 16.16 kW, 17.88, and 22.60 kW, respectively, whereas the improvement potential were 13.97 kW, 15.35 kW, 16.81 kW, and 21.02 kW for 90 °C, 100 °C, 110 °C, and 120 °C, respectively. This means that approximately 94% of the destroyed exergy can be avoided with careful design of the solar collector. An improvement in designing a higher optical efficiency of the collector should be taken into consideration while other improvements include minimizing the heat losses from the collector receiver. Further improvements can be obtained by careful design of the evaporator that requires a larger heat exchange surface area. Another important exergetic parameter that identifies the ratio of the exergy destroyed to the total exergy destroyed in a system is the relative irreversibility. As shown in Table 3, 94%–95% is the destroyed exergy in the solar collectors and 3% is in the evaporator.

6. Economic and Thermoeconomic Analysis

In this study, the topic of the attribution of a financial value to the thermal energy recovered by the solar ORC system is addressed according to the thermoeconomic approach. Economic analysis of the solar ORC system was carried out by taking into account the purchased components and equipment costs, operation and maintenance (O&M) costs, and the energy input cost. Thermoeconomic analysis is a combination of energy and economic analysis, which provides crucial information that cannot be obtained through conventional and simple thermodynamic analysis.

6.1. Estimation of Investment Cost

The thermoeconomic analysis was carried out to determine the cost of electricity production with 120 °C solar source temperature. In addition, the payback period and internal rate of return (IRR) of small-scale solar ORC system were calculated. The main expensive components in the solar ORC system are the solar collectors and scroll expander. Table 4 lists the cost of different components for estimating the cost of electricity production according to the prototype cost when the solar source temperature is 120 °C, which can produce 1.38 kW of power and annual energy production available equals to 3022.2 kWh. Table 5 shows the annual expense of the small-scale solar ORC system. The cost is associated with operation (1%), maintenance (1%) and insurance cost (0.65%) of the cost of electromechanical components [19]. Since this system is simple in construction, robust and has few moving parts, the O&M cost is lower. Figure 8 shows the cost shared by every subsystem when installing SORC system. It is concluded that the majority of shared percentage is for thermal energy production system followed by ORC unit and power block. If the costs of these components are reduced, it may be feasible to be adopted in the rural areas of developing countries for electricity generation without huge subsidies. The prototype cost of solar ORC system is high compared to other rural electrification technology. It is seen that solar collectors and expander plays an important role in reducing the investment cost of the system. This study also presents economic analysis for the possibility of developing the low cost solar ORC system where the solar collector costs \$80/m^2 according the reference article [20].

Table 4. Prototype cost of small-scale solar ORC system.

Parameters	Cost ($)	% of the total cost	Economic life (years)
Thermal energy production unit			
Installation of solar collectors	3100	9.89	-
Solar collectors (15 collectors @ $900)	13500	43.06	20
Collectors pump	450	1.44	20
ORC Unit			
R245fa/water Evaporator	450	1.44	20
R245fa/Water Condenser	1650	5.26	20
Scroll Expander	3950	12.60	20
R245fa Pump	750	2.39	10
Fluid (R245fa)	150	0.48	-
Refrigerant tank and piping	250	0.80	20
Labor cost	200	0.64	-

Table 4. *Cont.*

Parameters	Cost ($)	% of the total cost	Economic life (years)
Power Block			
Generator	550	1.75	20
Control systems	300	0.96	20
Others			
Water tank	150	0.48	20
Measuring devices	200	0.64	15
Miscellaneous	150	0.48	-
Total Investment cost	25800	100.00	-

Table 5. Annual costs for small-scale solar ORC system (prototype).

Parameters	Cost ($)
Operational cost	247.5
Maintenance cost	247.5
Insurance (Electromechanical equipment)	117.15
Total annual cost	612.15

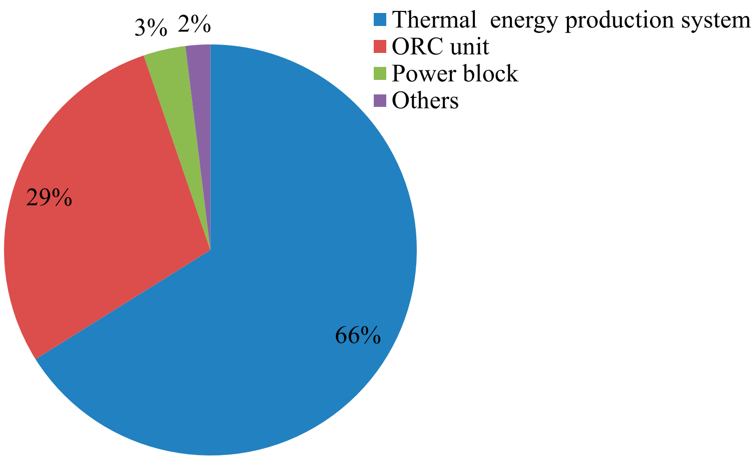

Figure 8. Cost significance of subsystem in the SORC system.

6.2. Economic Analysis of the SORC System

For the economic analysis of the proposed system, it is assumed that the installation of the system is completed within the period of one year. The economic lifetime of the system is assumed to be 20 years but not all the components' life cycle is this long; for example, that of working fluid feed pump and measuring devices. In addition, after 20 years, which is considered to be the life cycle of the system, the system has no salvage value and is not considered in the present study. An interest rate of 5% was used for the analysis. Based on the above assumptions, the annual cash flow rate can be calculated along with present values and annual equivalent cost. The estimation of annual equivalent cost is crucial to find the cost of energy per kWh. The general expression can be written as follows:

$$AEC = \sum_{C=1N} \frac{IC_C \times (i)}{1-(1+i)^{-n}} \tag{12}$$

where IC_C represents investment cost of each components which has economic life *(n)* and *i* denotes the interest rate.

The present value coefficient, which correlates a future cash flow with present value, is given by:

$$CF_{t=0} = \frac{CF_{t=n}}{(1+i)^n} \tag{13}$$

where $CF_{t=0}$ is the present value of the future cash flow *(t)*.

The present value of the total cash flows during the economic life cycle of an investment is the net present value (NPV) and is given by:

$$NPV = B_{t=0} - C_{t=0} = \sum_{j=0}^{n} \frac{B_{t=j}}{(1+i)^j} - \sum_{j=0}^{n} \frac{C_{t=j}}{(1+i)^j} \tag{14}$$

where, $B_{t=j}$ is the benefit of the investment in each year and $C_{t=j}$ is the cost of the investment in each year, which includes the installation cost in the beginning of its operation.

Benefit-Cost (BC) ratio is an alternative way of expressing the investment criteria and is an index of the ratio of the present value of the benefit cash flows to the present value of the cost cash flows and is given by the following expression:

$$BC = \frac{B_{t=0}}{C_{t=0}} = \frac{\sum_{j=0}^{n} \frac{B_{t=j}}{(1+i)^n}}{\sum_{j=0}^{n} \frac{C_{t=0}}{(1+i)^n}} \tag{15}$$

The payback (PB) period is the number of years needed for the net present value (NPV) to reach a zero value and is obtained by solving Equation (14) with NPV = \$0, so it is now written as

$$\sum_{j=0}^{PB} \frac{B_{t=j}}{(1+i)^j} = \sum_{j=0}^{PB} \frac{C_{t=j}}{(1+i)^j} \tag{16}$$

The internal rate of return (IRR) is the critical interest rate where the NPV = \$0 and it is always greater than interest rate used for the investment to be economically feasible. IRR can be calculated from the given expression:

$$\sum_{j=0}^{n} \frac{B_{t=j}}{(1+IRR)^j} = \sum_{j=0}^{n} \frac{C_{t=j}}{(1+IRR)^j} \tag{17}$$

Equations (12)–(17) can be found in references [19,21]. For the efficient investment, the benefit to cost ratio (BC) should be larger than 1. The small-scale solar ORC system (prototype) and low cost solar ORC have BC ratios 1.02 and 1.01, respectively, which revealed that the investment is sustainable. From the economic point of view, the SORC system's investment will be profitable after 19 years of installation and operation. This payback period is high and it approaches nearly the life cycle of the system. The main goal of this study is to install the SORC system in rural areas of developing countries for electricity production so it can be treated as a social benefit investment. The investment criteria (IRR) in this study has the value 5.01% in each case, and is greater than 5%, so it is also a favorable investment.

The cost of energy per kWh produced from the system can be calculated from annual equivalent cost divided by annual mechanical energy produced and is equal to 0.68 $/kWh (prototype) and 0.29 $/kWh (low cost solar ORC). Figures 9 and 10 illustrated annual present value cash flows and net present value (NPV) for prototype and low cost SORC system. From the Figure 10, it is seen that the sum of the annual cash flows becomes positive at the end of 19 years of operation, which is the payback period. In the 10th and 15th year of the SORC operation, the gradient of the slope changes due to replacement of components (pump and measuring devices), so the cost of the system is increased.

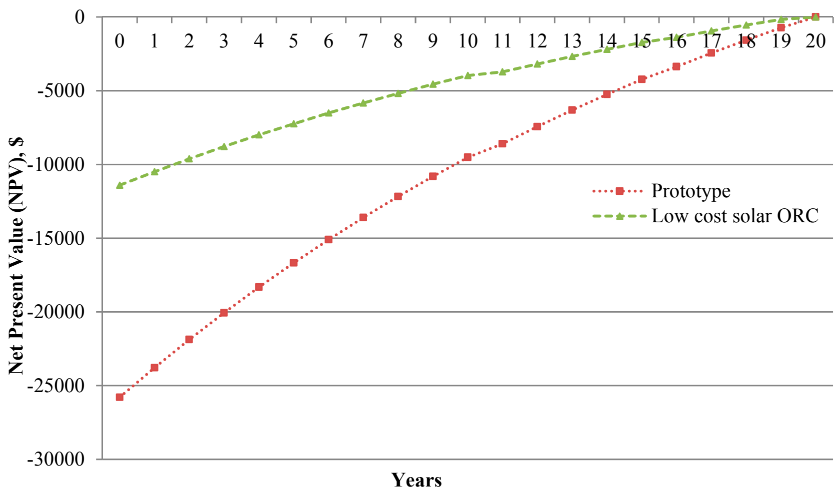

Figure 9. Net present values during the life cycle of the system (prototype and low cost solar ORC).

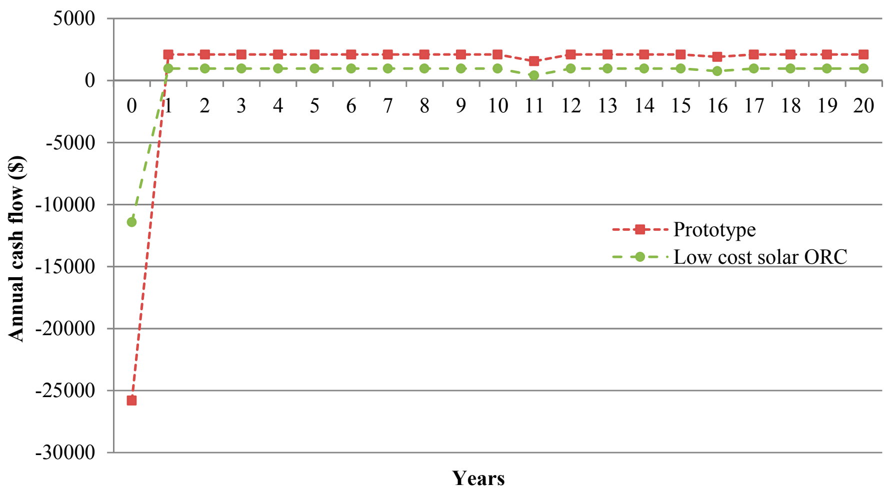

Figure 10. Annual cash flows during the life cycle of the system (prototype and low cost solar ORC).

6.3. Sensitivity Analysis

One way to glean a sense of all possible outcomes of an investment is to perform a sensitivity analysis, where different values of a certain key variables are tested to see how sensitive investments are to possible change in assumptions. It is the method of evaluating the riskiness of an investment. In the present study, in calculating cash flows, some parameters have more influence on the final result (NPV) than others. The data for different financial scenarios that has been examined for comparison with the standard scenario are presented in Table 6. Table 7 (prototype) and Table 8 (low cost solar ORC) show the results of various scenarios for sensitivity analysis.

Table 6. Scenarios for examination.

Scenario	Economic parameters
1	Standard Scenario
2	20% increase in investment cost (IC)
3	20% decrease in investment cost (IC)
4	20% increase in annual benefit (AB)
5	20% decrease in annual benefit (AB)
6	20% increase in annual cost (AC)
7	20% decrease in annual cost (AC)
8	20% increase in interest rate (IR)
9	20% decrease in interest rate (IR)

Table 7. Results of all scenarios regarding the NPV (prototype).

Scenario	Investment cost ($)	Annual benefit ($)	Annual cost ($)	Interest rate (%)	NPV ($)
1	25800	2107.85	612.15	5	0
2	30960	2107.85	612.15	5	−5042
3	20640	2107.85	612.15	5	5216
4	25800	2651.85	612.15	5	6834.71
5	25800	1686.28	612.15	5	−6724.17
6	25800	2107.85	734.58	5	−1553.11
7	25800	2107.85	489.72	5	1663.66
8	25800	2107.85	612.15	6	−1991.59
9	25800	2107.85	612.15	4	2382.31

Table 8. Results of all scenarios regarding the NPV (low cost solar ORC).

Scenario	Investment cost ($)	Annual benefit ($)	Annual cost ($)	Interest rate (%)	NPV ($)
1	11410	964.19	230.81	5	0
2	13692	964.19	230.81	5	−2274.19
3	10954	964.19	230.81	5	465.80
4	11410	1203.19	230.81	5	2946.89
5	11410	725.20	230.81	5	−2922.81
6	11410	964.19	276.97	5	−507.13
7	11410	964.19	184.50	5	643.50
8	11410	964.19	230.81	6	−833.97
9	11410	964.19	230.81	4	1093.70

From the analysis, it is observed that the parameters that mostly influence the NPV are the change in the investment cost and annual benefit cost. The least influencing parameters are annual cost and interest rate. Furthermore, Tables 9 and 10 examined all different cases for evaluation of investment. The selling price of electricity (for prototype) changes from 0.81 $/kWh to 0.52 $/kWh, whereas for low cost solar ORC there is a change from 0.39 $/kWh to 0.28 $/kWh, when there is change in net present value from base case (standard scenario). The negative sign in NPV indicates that the investment is not profitable. This can be seen in scenarios 2, 5, 6, and 8. Also, a BC ratio less than 1 is not good for investment. The most efficient investment is met under scenarios 3 and 4, where the payback period is low and there is a high NPV and IRR. These favorable patterns are seen in both prototype and low cost solar ORC investments.

Table 9. Results of all scenarios regarding investment criteria (prototype).

Scenario	NPV ($)	BCR	Payback period (years)	IRR (%)	Selling price of electricity ($/kWh)
1	0	1.01	19	5.01	0.68
2	−5154.57	0.87	-	2.94	0.81
3	5165.42	1.18	15	7.82	0.54
4	6834.71	1.2	14	7.82	0.6
5	−5198.42	0.8	-	2.47	0.86
6	−1520.24	0.95	-	4.29	0.64
7	1531.17	1.05	18	6	0.72
8	−1991.6	0.93	-	5.06	0.75
9	2382.31	1.06	17	5.06	0.52

Table 10. Results of all scenarios regarding investment criteria (low cost solar ORC).

Case	NPV ($)	BCR	Payback period (years)	IRR (%)	Selling price of electricity ($/kWh)
1	0	1.01	19	5.01	0.29
2	−2274.19	0.87	-	2.93	0.38
3	465.8	1.045	18	5.5	0.25
4	2946.89	1.21	14	7.9	0.22
5	−2922.81	0.81	-	1.7	0.39
6	−507.13	0.96	-	4.46	0.28
7	643.5	1.06	17	5.66	0.32
8	−833.97	0.95	-	5.07	0.33
9	1093.7	1.08	17	5.07	0.29

The low payback period of 14 years (for prototype and low cost solar ORC) is estimated according to the tariff 0.6 $/kWh and 0.22 $/kWh, respectively, based on scenario 4. The standard scenarios have 19 years of payback period (for prototype and low cost solar ORC) with the tariff 0.68 $/kWh and 0.29 $/kWh, respectively.

Since the cost of energy per kWh is quite high compared to conventional flat PV panels, there are some benefits, which can be obtained from installing solar ORC system. They are as follows:

(1) It provides hot water as byproduct, at no extra cost.

(2) It allows using simpler, locally produced, solar collectors with minimum labor cost.

(3) It is possible to accumulate the heat for delayed use, e.g., it is possible to accumulate heat during the day for evening or night use (thermal storage tank).

(4) The heat downstream from the conversion system can be further used for heating or cooling (in an absorption chiller) purposes.

In Figures 11 and 12, the variation of NPV for all scenarios examined illustrated the importance of any single variable involved (IC, AB, AC and IR). The greatest dependence of NPV is on the investment cost and annual cost variation for both prototype and low solar ORC. The huge change in NPV is shown by change in investment cost in low cost solar ORC system. For the NPV to be positive in comparison to the standard scenario, the investment cost, interest rate and annual cost should be increased, whereas annual benefit should not be decreased even by certain percentage because the system has a long payback period almost equal to the life cycle of system. This applies for both prototype and low cost solar ORC system. If the NPV is $0, a very small change in any economic parameter makes the investment unprofitable.

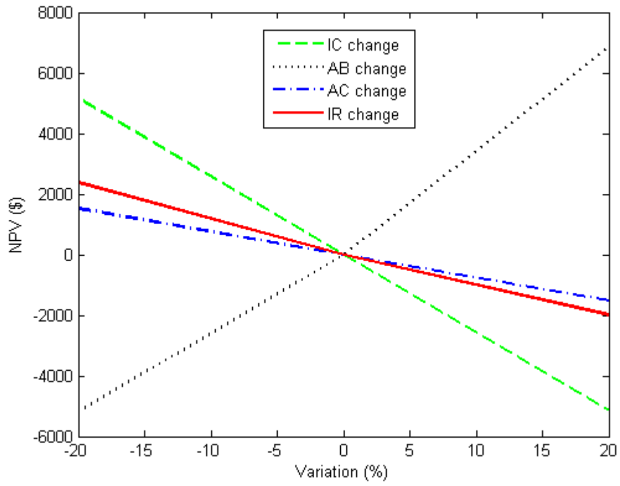

Figure 11. Variation of NPV (for prototype) as different variables change (IC, AB, AC, IR).

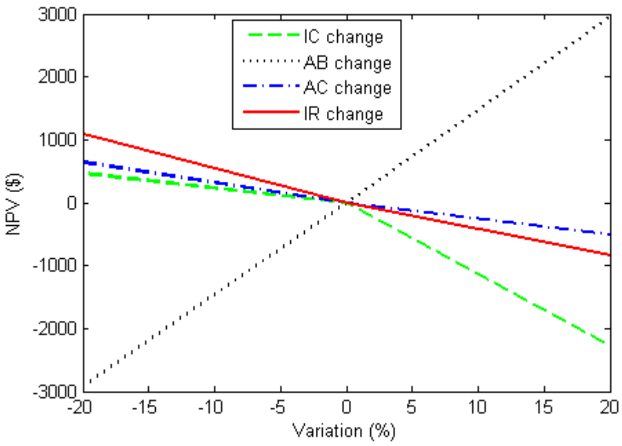

Figure 12. Variation of NPV (for low cost solar ORC) as different variables change (IC, AB, AC, IR).

6.4. Sustainable Development through Solar ORC System

Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. In this context, the ORC unit, which utilizes solar energy, helps develop sustainability and can serve to sustain the lives of millions of underprivileged people in developing countries. In addition, for the production of clean power, the solar ORC system can greatly help reduce the consumption of fossil fuels and solve the problem of greenhouse gas emissions. If a solar ORC unit is used instead in petroleum-based plants for electricity generation, the saved petroleum P_s, (L/year) and reduced CO_2 emission, R_c (Kg/year) can be estimated using Equations (18) and (19), respectively [22]:

$$P_s = 365 \times t_o \times a_1 (W_t + Q_o - W_p) \tag{18}$$

$$R_c = 365 \times t_o \times a_2 (W_t + Q_o - W_p) \tag{19}$$

where t_o is the operating time per day, and a_1 and a_2 are amount of petroleum consumed to produce 1 kWh of electric energy and the amount of CO_2 emission if 1 kWh of electric energy is produced by a petroleum-based power plant, respectively. In this study, these values were taken as 0.266 L/kWh and 0.894 kg/kWh, respectively. The normal operating time (T_n) for a solar ORC unit per day was taken to be 6 h, whereas operating time for solar ORC unit with thermal storage tanks were T_{s1} = 3 hrsand T_{s2} = 7 hrs, respectively. Figures 13 and 14 show the expected savings in petroleum and reductions in carbon emission per year for the operating time of the various types of solar ORC units at different solar heat source temperatures.

The annual maximum expected saving in petroleum was 1565 L at a 120 °C solar source temperature that has a storage tank with a seven-hour capacity and at the same time, the expected CO_2 emission reduction was 4966 kg. Developing countries can benefit greatly by generating revenues through the clean development mechanism (CDM) and cost rate of carbon emission trading set by the Kyoto protocol after installing solar ORC units.

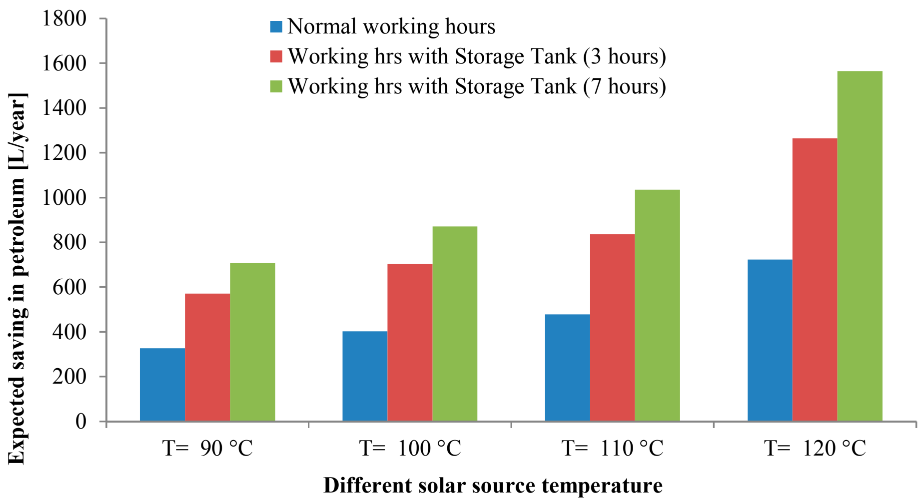

Figure 13. Comparison of expected saving in petroleum in various temperatures and operating hours.

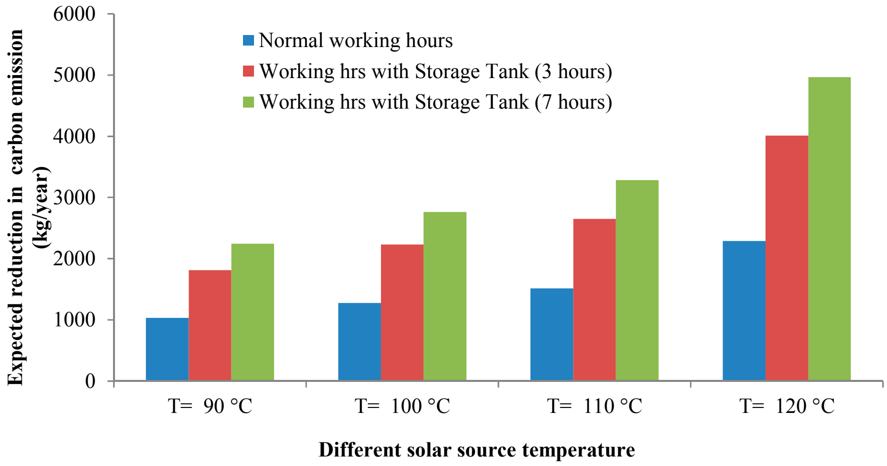

Figure 14. Comparison of the expected reduction in CO_2 emission in various temperatures and operating hours.

Another assessment for measuring the sustainable development of an exergy-based system and processes that represent the true measure of imperfections is through the sustainability index. This index indicates the possible ways for improving the design. A higher sustainability index indicates a higher sustainability of the system. The sustainability index (SI) is given by the following equation [23]:

$$SI = \frac{1}{1-\eta_{ex,ele}} \quad (20)$$

Figure 15 shows the sustainability index of the solar ORC system prototype. The solar ORC system, which works at a 90 °C solar source temperature, has a low sustainability index. Therefore, more improvement in design is needed to improve the sustainability of the solar ORC system.

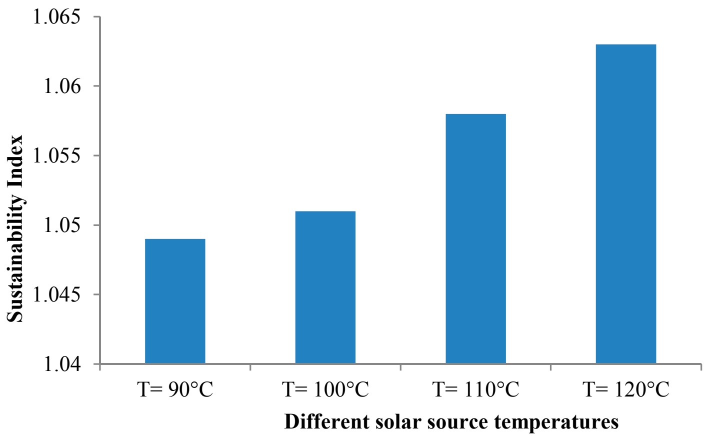

Figure 15. Sustainability index for different solar ORC source temperatures.

7. Conclusions

This paper reported the experimental results and thermoeconomic analysis of small-scale solar ORC system for electricity generation suitable for remote rural un-electrified areas in developing countries. The experiment conducted in the laboratory revealed acceptable performance characteristics that could be suitable for installation in rural areas. The maximum solar ORC efficiency was found to be approximately 6% for a 120 °C solar source temperature. To confirm the robustness of the unit, a magnetically-coupled commercial scroll expander was adopted and showed no leakage during the experiment. The seasonal variation of the solar ORC power output was also calculated. The maximum and minimum power outputs were obtained during April and December, respectively. The different solar source temperatures produce different power outputs. Therefore, the system was sized based on the weather conditions of Busan for all different months of the year. The collector area was determined based on the meteorological data of Busan City. In addition, the detailed exergy results showed the maximum exergy destruction in the solar collector followed by the evaporator, expander, condenser, and pump. The improvement potential percentage was 94%.

In the second part of the study, economics and thermoeconomic analyses were conducted to estimate the selling price of produced electricity. The selling price of electricity (for prototype) is 0.68 $/kWh, whereas for low cost solar ORC is 0.39 $/kWh. The payback period for the solar ORC system is 19 years, which is almost equal to life cycle of the system. Since the payback period is very high, this technology is only used in rural areas of developing countries, which lack electricity for lighting homes. The sensitivity analysis was carried out to observe the influence in the NPV of SORC. It is concluded that the reduction in investment and annual costs result in lowering the cost of energy per kWh. Special care should be taken in the estimation of the interest rate together with a realistic estimation of the total cost and the annual cash flow rates for economic analysis because the interest rate has strong influence on the specific cost of the developed system. The prototype cost of the system is very high, so if subsidies are not given the SORC market cannot grow exponentially. The small-scale solar ORC is currently expensive as compared to medium and large scale but if it could be successfully scaled down, the low cost solar ORC could see improved competitive with PV in short term. The mass production of the SORC components can play an important role in reducing the total investment cost of the system. The SORC system, which utilizes solar energy, helps develop sustainability and can serve to sustain the lives of millions of underprivileged people in developing countries.

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Author Contributions

All authors contributed to this work by collaboration. Suresh Baral is the first author who prepared the manuscript and analyzed the experimental results. Dokyun Kim conducted the experiment and Eunkoo Yun assisted in designing the experimental setup. The whole project was supervised by Kyung

Chun Kim. All authors contributed in preparing the manuscript and approved for the submission. All authors have read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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