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Stand-Alone Solar Organic Rankine Cycle Water Pumping System and Its Economic Viability in Nepal

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Abstract: The current study presents the concept of a stand-alone solar organic Rankine cycle (ORC) water pumping system for rural Nepalese areas. Experimental results for this technology are presented based on a prototype. The economic viability of the system was assessed based on solar radiation data of different Nepalese geographic locations. The mechanical power produced by the solar ORC is coupled with a water pumping system for various applications, such as drinking and irrigation. The thermal efficiency of the system was found to be 8% with an operating temperature of 120 °C. The hot water produced by the unit has a temperature of 40 °C. Economic assessment was done for 1-kW and 5-kW solar ORC water pumping systems. These systems use different types of solar collectors: a parabolic trough collector (PTC) and an evacuated tube collector (ETC). The economic analysis showed that the costs of water are \$2.47/m^3 (highest) and \$1.86/m^3 (lowest) for the 1-kW system and a 150-m pumping head. In addition, the cost of water is reduced when the size of the system is increased and the pumping head is reduced. The minimum volumes of water pumped are 2190 m^3 and 11,100 m^3 yearly for 1 kW and 5 kW, respectively. The payback period is eight years with a profitability index of 1.6. The system is highly feasible and promising in the context of Nepal.

Keywords: solar ORC water pumping system; irrigation; economic viability; thermal efficiency; solar energy; Stand-alone system

1. Introduction

Nepal is an agricultural country with a large number of people residing in remote areas who depend on the agricultural products grown during a season. In order to irrigate or pump water for various crops, diesel-driven water pumping systems have been largely adopted rather than electrical driven systems [1–3]. Due to a lack of electricity production in remote areas, there are few electrical water pumping systems. The fossil-fuel-based systems are threatening the environment, and the country is fully dependent on neighboring countries for such fossil fuel. In this context, a new approach is presented in this study for pumping water for irrigation, hot water production, and electrical power generation in remote Nepalese areas from stand-alone organic Rankine cycle (ORC) system technology. Nepal has ample solar radiation potential that can be utilized through solar energy conversion technology. It is estimated that the average solar radiation ranges from 3.6 to 6.2 kWh/m^2/day with over 300 bright sunshine days [4,5]. The country also has 6.8 hours per day of bright sunshine with an average solar intensity of 4.7 kWh/m^2/day [6,7]. Solar energy has been widely used in stand-alone PV technology for generating electrical power and irrigation purposes in Nepal [8–11].

There are very few articles that describe the concept of a stand-alone solar ORC water pumping system. Gopal *et al.* [12] reported a solar thermal water pumping system that uses a flat plate solar collector and pentane as the working fluid. The system's efficiency ranges from 0.12% to 0.14% for a 10-m dynamic head. Wong and Sumathy [13] reviewed papers on various types of pumps and proposed different modifications for different pumping conditions and environments for irrigation purposes. However, there are few articles that discuss solar ORC technology for a reverse osmosis desalination unit [14–16].

Solar ORC technology has been utilized in various forms. A novel concept for a water pumping system uses this technology with R245fa as the working fluid. The organic working fluids should be suitable for solar applications. The refrigerant should be chosen according to the types of solar collectors, and these issues have been discussed in various papers [17–19]. In addition, this technology can produce electricity, hot water, heating, and cooling from the same unit. It could be a promising technology for use in Nepal. The hot water from the condenser can be used in rural health clinics, domestic uses, schools, and small communities.

The concepts of economic viability for different types of solar collectors are discussed. The solar collectors are a parabolic trough collector (PTC) and evacuated tube collector (ETC). The PTC is normally designed for reaching high temperatures of 60 °C–300 °C, whereas an ETC is designed for temperatures of 50 °C–200 °C [20]. This study compares the total costs of systems using these collectors. The study also examines the cost of water per cubic meter and yearly volume of water pumped for both cases. The economic viability assessment will help solar ORC developers, manufacturers, investors, and rural practitioners to examine the feasibility of investment. Since Nepal's solar intensity is different for various locations, this economic assessment also gives an idea of how solar insolation will change the total cost of water pumping.

2. Description of Experimental Setup

The block diagram in Figure 1 shows the technology for solar energy conversion to water pumping (electrical energy).

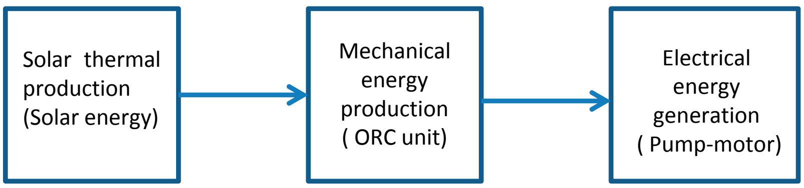

Figure 1. Block diagram for solar energy to electrical energy generation.

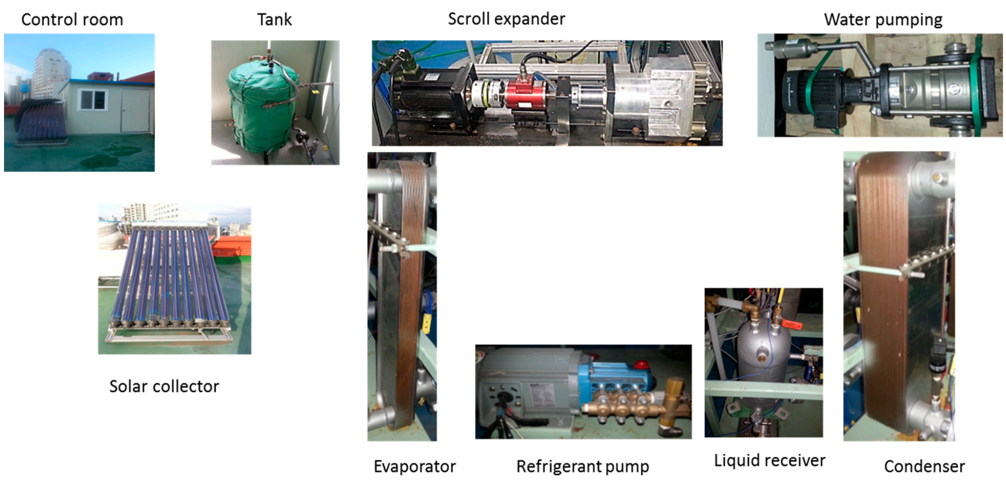

Figure 2. Components for the solar ORC water pumping system.

To observe the performance of the solar ORC system, the components were purchased and assembled. Figure 2 shows the different components for the experiment. Table 1 shows the characteristics features for different components used in experiment. The system's working principle is described briefly. Hot water obtained from the solar collector is passed into the heat exchanger (braze type). The working fluid (R245fa) is pumped into the evaporator where the fluid changes phase and enters the expander. This expansion device produces mechanical work and is coupled with a generator or water pumping device. The fluid is then cooled by the cooling water and goes back from the condenser to the receiver in liquid form. In this way, the cycle runs in a closed loop which is shown in Figure 3.

Table 1. Characteristics of different components in solar ORC water-pumping system.

Characteristics of solar collectors			
Collector	Evacuated tubular		
Type	Heat pipe		
Manufacturer	Apack Inc.		
No. of tubes	10		
Heat capacity (kCal/m^2.day)	3342.47		
Gross area (m^2)	2.55		
Collector efficiency (%)	72.95		
Filled with water (kg)	62.8		
Characteristics of evaporator			
Evaporator (Model: CB60-14H-F, Alfa Laval)	Unit	Hot side	Cold side
Fluid Name	-	Water	R245fa
Temperature In	°C	115	52
Temperature Out	°C	105	109
Flow rate	kg/s	0.45	0.08
Operating Pressure	bar	5	15
Characteristics of condenser			
Condenser (Model: CB76-50E, Alfa Laval)	Unit	Hot side	Cold side
Fluid Name	-	R245fa	Water
Temperature In	°C	77	22
Temperature Out	°C	50	25
Flow rate	kg/s	0.08	0.13
Operating Pressure	bar	4	5
Characteristics of scroll expander			
Model	E15022A-SH		
Type	Scroll		
Manufacturer	Airsquared		
Maximum operating temperature (°C)	175		
Maximum operating pressure(bar)	13.8		
Volume ratio	3.5		
Maximum speed(rpm)	3600		
Characteristics of working fluid feed pump			
Model	2SF22ES		
Type	Plunger		
Manufacturer	CAT PUMPS		
Maximum operating pressure(bar)	140		
Flow rate (l/m)	8.3		
Characteristics of Heat transfer fluid(HTF) pump			
Model	A979641P11515		
Type	CRN1-2 F-FGJ-G-F-HQQE		
Manufacturer	GRUNDFOS		
Maximum operating pressure(bar)	25		
Maximum operating temperature (°C)	180		

The operating pressure of the expander is around 13 bar. The refrigerant is cooled when cold water at a temperature of 25 °C is passed into the condenser. The condenser was designed to produce hot water at 45 °C as a byproduct. The shaft power obtained when connected with the water pumping system was measured and could be used to pump water from rivers and springs in Nepal.

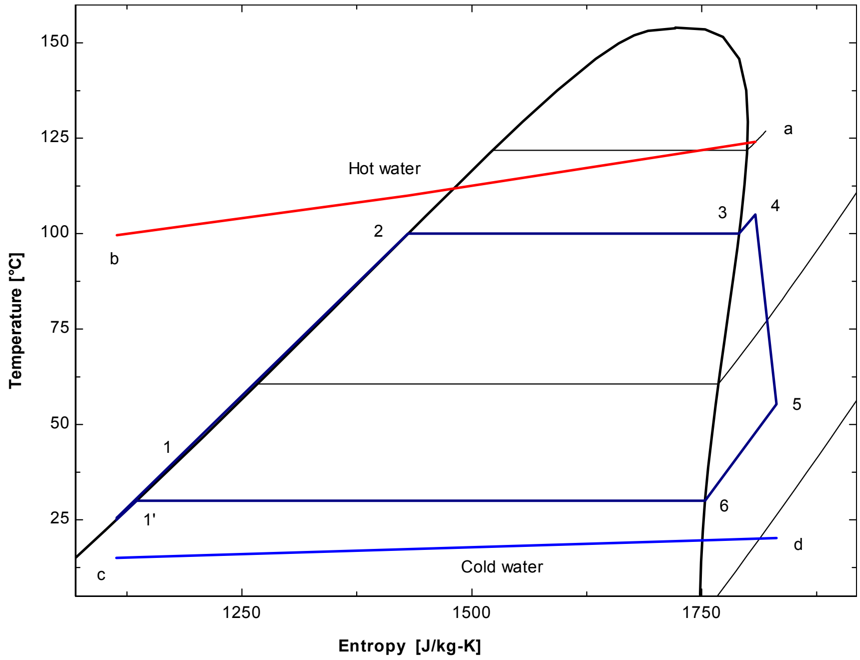

Figure 3. T-s diagram for the organic Rankine cycle system.

The useful heat gain rate for the collector is given by the following Expression:

$$Q_u = F_R \times A_c\,[S - U_L \times (T_i - T_a)] \tag{1}$$

where F_R, U_L, A_c, T_i, and T_a are the collector heat-removal factor, total loss coefficient, thermal-absorption area of the collector, water inlet temperature, and ambient temperature, respectively.

The heat energy required for heating working fluid for the ORC system can be expressed by the following equation:

$$\text{Evaporator},\ Q_{eva} = m_f(h_1 - h_4) \tag{2}$$

The expansion device for the work done can be calculated using the following expression:

$$\text{Expander},\ W_{\text{exp}} = m_f(\text{h}_5 - \text{h}_4) \tag{3}$$

The heat rejected to the environment can be expressed by:

$$\text{Condenser},\ Q_{con} = m_f(\text{h}_5 - \text{h}_{1'}) \tag{4}$$

The pumping of the working fluid to the heat exchanger can be expressed as:

$$W_p = \frac{m_f v_{1'}(P_{1'} - P_1)}{\eta_P} \tag{5}$$

where h, v, m, and P represent the enthalpy, volumetric flow, working fluid mass flow rate, and pressure at different states, respectively. The efficiency of the working fluid feed pump is denoted by $\eta_{p.}$ The net electrical output power is:

$$W_{net} = W_{\exp} - W_p \tag{6}$$

The Solar ORC cycle efficiency is:

$$\eta_{ORC} = \frac{W_{net}}{Q_u} \tag{7}$$

The thermal efficiency of the solar ORC system is calculated as follows [21]:

$$Thermal\ efficiciency = \frac{Power\ output}{Solar\ heat\ input} \tag{8}$$

The power required for pumping water from the river can be determined by [22]:

$$P = \rho g Q H \tag{9}$$

where ρ is the density of water (kg/m^3), g is gravitational acceleration (m/s^2), H is the total dynamic head (m), and Q is the volumetric flow rate of water (m^3/s). If the density and gravitational acceleration are kept constant and assuming that there is no significant variation, the product QH is directly proportional to the power requirement for pumping water. Hence, QH is considered as the rate of pumping capacity. Equation (10) can now be expressed for determining the rate of pumping capacity QH in m^3/s for available power.

$$QH = \frac{P}{\rho g} \tag{10}$$

The volumetric flow rate of required water that can be pumped from a river can be calculated using the total head. Therefore, the expression for estimating the total pumping capacity for a certain period of time can be written as:

$$QH \times t = \frac{P \times t}{\rho g} \tag{11}$$

The size of the required pump can be estimated by the following expression:

$$P = \frac{\rho g Q H}{\eta_p} \tag{12}$$

where η_p is the pump efficiency for pumping water.

3. Results and Discussion

In Figure 4, the shaft power ranges from 0.8 kW to 1.4 kW when the system's operating pressure changes from 10 bar to 13 bar. When the rotational speed of the expander increases, the mechanical power output is also increased. In this experiment, the speed ranges from 2400 rpm to 3600 rpm in order to run the system according to the design conditions. When the system operates at 13 bar and 3600 rpm, the maximum power is obtained.

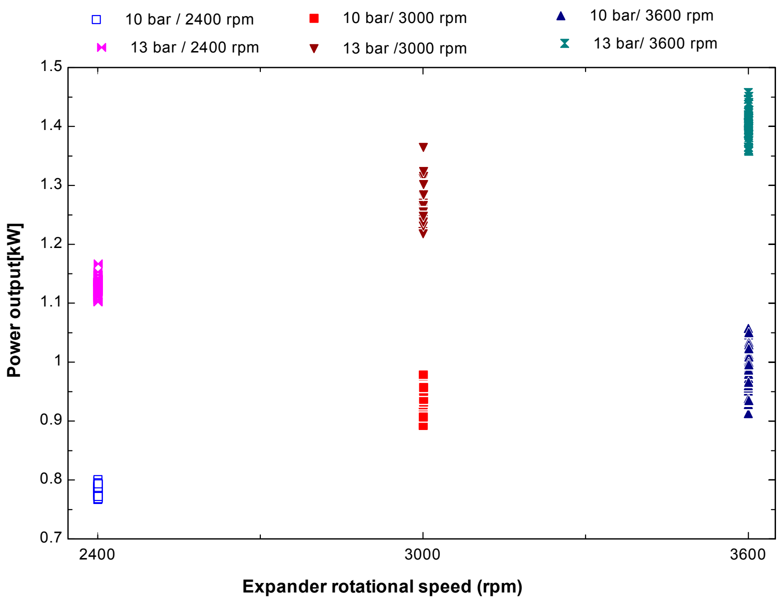

Figure 4. Mechanical power output as a function of rotational speed of the expander.

The efficiency of the system depends on the heat input from the solar collector. The efficiency of a water-cycle in this temperature range would be even lower and the main advantage of the ORC is the thermo-physical characteristics of the organic compound. In addition, the heat source temperature is only 120 °C for this experiment. If the heat source temperature is increased, the efficiency could be increased. The aim of the present study is to utilize the ORC system with a low-temperature heat source such as a solar collector with an ETC. The PTC could increase the system's efficiency significantly. Figure 5 shows the experimental results of the thermal efficiency as a function of rotational speed of the expander. The system's thermal efficiency reached a maximum of 8.1% when the expander was operated at 13 bar and 3000 rpm. At 10 bar and 2400 rpm, the maximum thermal efficiency is 7.1%. The deviations for one pressure and one rotational speed are large because there is change in pressure ratio in the system. The ORC system was operated in off-design conditions there by changing the pressure and working fluid mass flow rate.

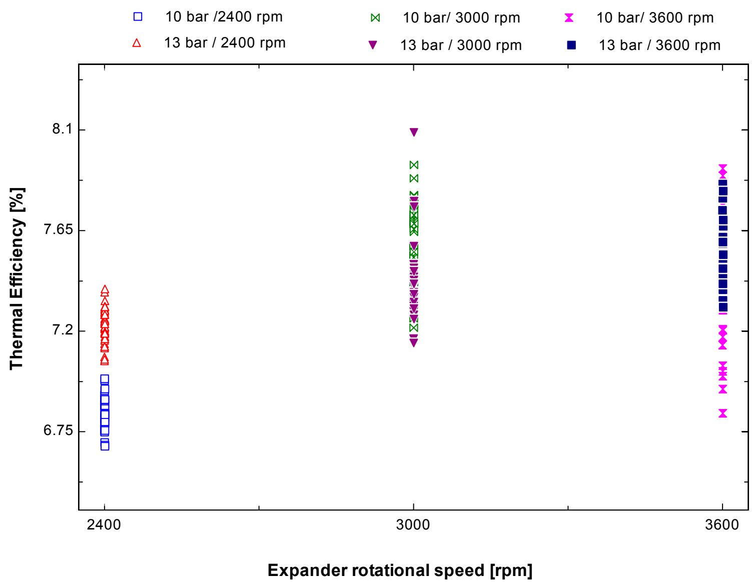

Figure 5. Thermal efficiency of the system as a function of expander rotational speed.

The thermal efficiency is maximum when the rotational speed of the expander is 3000 rpm at 120 °C. The efficiency is dropped when the speed increases because the scroll expander is designed to work efficiently when the temperature is at the maximum point (175 °C) and 3600 rpm. This is the standard value from the manufacturer. In the present study, the maximum temperature is 120 °C, so the expander cannot reached its maximum designed point. One of the important features of this ORC technology is the production of hot water from the same unit. The hot water is produced at the outlet of the condenser. The condenser should be designed to have a large heat transfer area. The hot water production, electrical power output, and its application in a water pumping system are the goals of the study. The water pumping system is only described as a potential application, and the produced mechanical power can be directly coupled with such a pumping system for solar ORC water pumping. A maximum of 320 liters of hot water can be produced in an hour by this unit with a temperature of 45 °C.

The uncertainties in measurement were also calculated based on the instruments used and their uncertainty ranges. Table 2 shows the uncertainty ranges for various instruments used in the experiment.

Table 2. Uncertainty range for various instruments.

Parameters	Instrument	Uncertainty range
Temperature	K type thermocouples	±1.1 °C
Pressure	Transducers	±0.044% full scale
Mass flow	Flow meter	±0.4 (L/min) full scale

The uncertainties in the measurement of the expander and thermal efficiency are ±0.042 kW and ±0.13%, respectively.

Figures 6 and 7 show the expander power output and thermal efficiency as a function of pressure ratio with the uncertainty measurement values at the operating pressure of 13 bar. The pressure ratio plays an important role in the ORC system for determining the system's performance. The higher the pressure ratio, the greater the power and efficiency are.

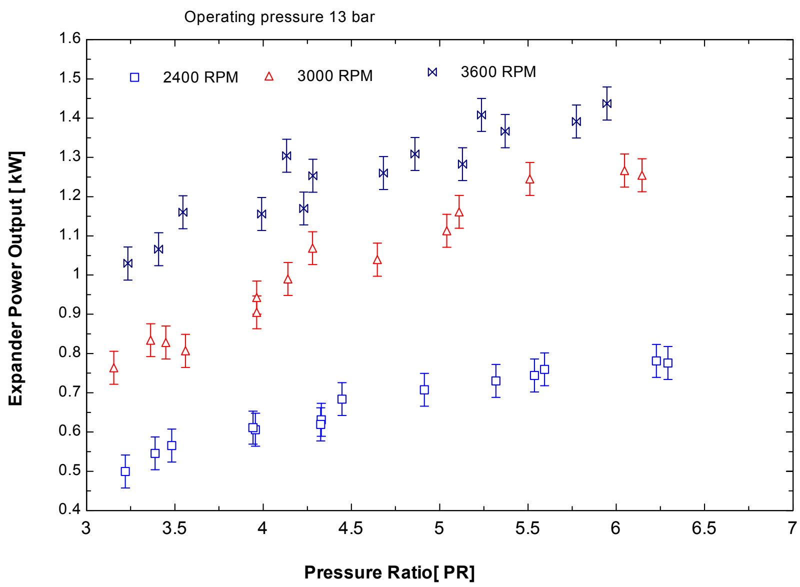

Figure 6. Power output with error analysis (13 bar) as a function of pressure ratio.

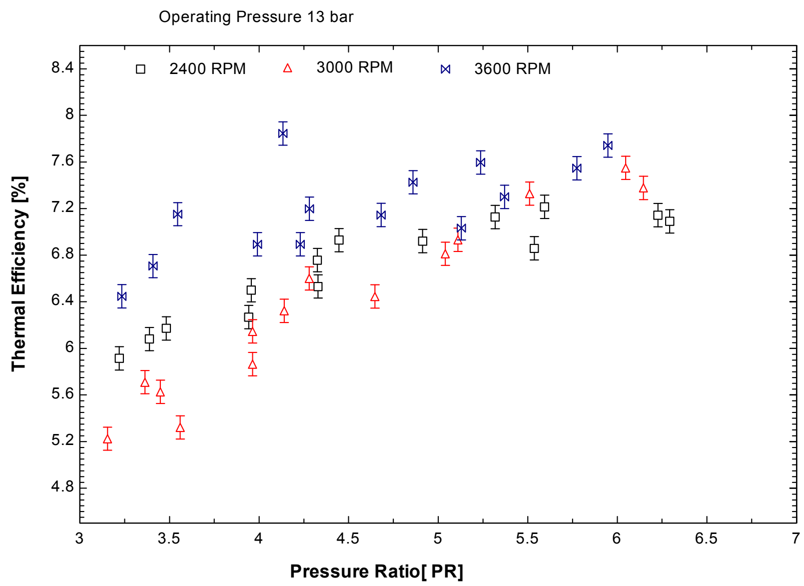

Figure 7. Thermal efficiency with error analysis (13 bar) as a function of pressure ratio.

4. Economic Viability of Solar ORC Water Pumping System

Solar ORC water pumping systems are designed to pump water and irrigate areas where there is no main electricity supply. This system consists of a solar collector, ORC unit, battery storage system, motor, and pump. A solar energy power system has large fluctuations. These can be overcome by the battery storage system for smooth running of the plant. Batteries also work when the solar intensity is low during the winter season and on cloudy and rainy days. However, the battery-less systems are cheaper and simpler. Since the primary goal of the study is to develop a stand-alone solar ORC water pumping system, a battery system is included. The battery helps to start the ORC system during in the first hours of operation. The working fluid feed pump, hot water circulation pump, and other control systems should be operated by the battery system in order to start the ORC system.

Nepal has many rivers and springs in the hilly areas, and running water can be pumped by this technology. The country also has plain land where drip irrigation can also be feasible. This study therefore analyzed the cost of water production in different regions of the country. The solar radiation also varies according to the geographic locations, which have different sunshine hours per day and numbers of sunny days during the year. The solar radiation at different locations was measured in a previous study [7]. These data were taken as a reference for the economic viability of the water pumping system. The investigated locations have the following average solar radiation: Biratnagar, 652.5 W/m^2 day; Jumla, 920.5 W/m^2 day, and Simikot, 810 W/m^2 day. The sunshine per day typically ranges from 5.5 to 6.5 hours, while the sunshine days vary from 300 to 310 days per year.

The total cost of the solar ORC system has been estimated by summation of cost of each component of the experimental prototype. The cost of a 5-kW solar ORC system has been projected based on the cost of a 1-kW plant. The cost of the motor pump has been estimated using the manufacturer's catalog price [23]. PTC and ETC collectors have been considered for the economic analysis. The operation and maintenance costs are assumed to be 2% based on the literature [24,25]. Table 3 shows the total cost of the stand-alone solar ORC water pumping system for different sizes and types of solar collectors in various locations of the country. The total cost is estimated for a dynamic head of 150 m. It is reasonable to assume this head because Nepal's rural irrigated farmland has different heads. The pumped water can be utilized for various purposes, such as drinking and irrigation. This would help rural farmers and people with income generation through crop productivity. In this way, rural living standards can be improved. The cost of solar ORC system is high. One reason is due the un-matured technology in small scale and is not commercialized so far. The R&D in small scale solar ORC system is still ongoing. Another reason is that this solar ORC system is feasible for medium and large scale. The payback period is high when the size of the plant is smaller. Thus, this technology is costly compared to other rural electrification technology.

Table 3. Total cost of the solar ORC water pumping systems.

Component Cost item	Biratnagar		Jumla		Simikot	
	1 kW	5 kW	1 kW	5 kW	1 kW	5 kW
Solar collector arrays with installation cost($)	13,577	66,897	13,057	64,292	13,316	65,582
ORC unit with power block ($)	10,615	52,301	10,208	50,265	10,410	51,273
Labor cost ($)	494	2433	475	2338	484	2385
Battery Storage System($)	2130	10650	2130	10650	2130	10650
Water Pumping system($)	900	2700	900	2700	900	2700
Total cost , PTC ($)	27,715	378,240	74,250	364,035	75,660	371,070
O&M cost, PTC ($)	554	7565	1485	7281	1513	7421
Total cost, ETC($)	26,085	126,840	25,600	124,470	25,850	125,645
O&M cost, ETC ($)	522	2537	512	2489	517	2513

The area of the solar collector plays an important role in determining the total cost of the system. Therefore, it is necessary to find the optimum area of the collector needed for a specific power output. Solar collectors have different collecting efficiency [19,20]. In this study, the solar collector efficiency ranges from 40 to 70%. The lower the collecting efficiency, the higher the area of the collector is, and the cost of the system increases. The area of the solar collector is calculated by the following Expression:

$$A = \frac{Q}{I \times \eta_o} \tag{13}$$

where A is the area needed for the designed power output, Q is the amount of heat gained to operate the ORC system in the design conditions, I is the solar insolation, and η_o is the solar collector efficiency. Figures 8 and 9 illustrate the total cost of the systems and the area of the solar collector that uses different types of solar collectors in different locations of the country for 1-kW power output.

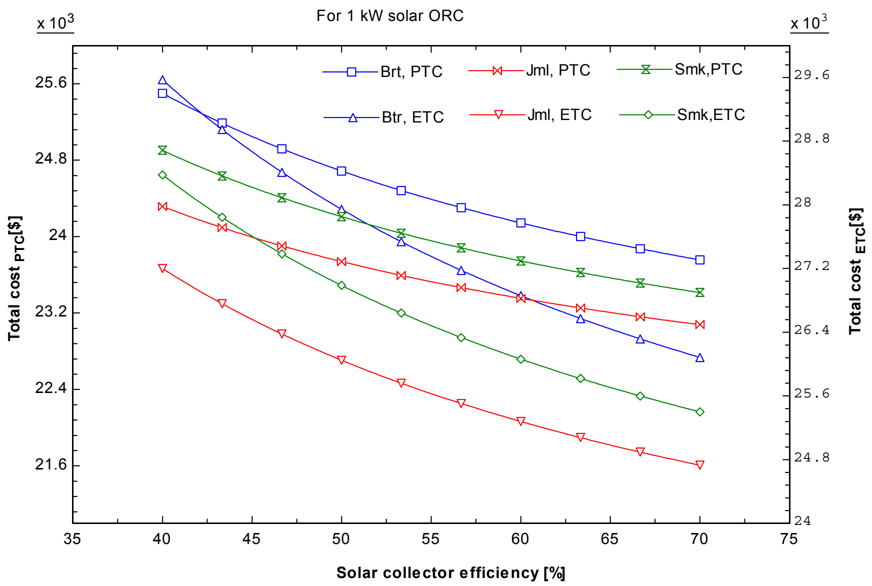

Figure 8. Variation of total costs of the solar ORC water pumping systems (1 kW) with respect to solar collector efficiency.

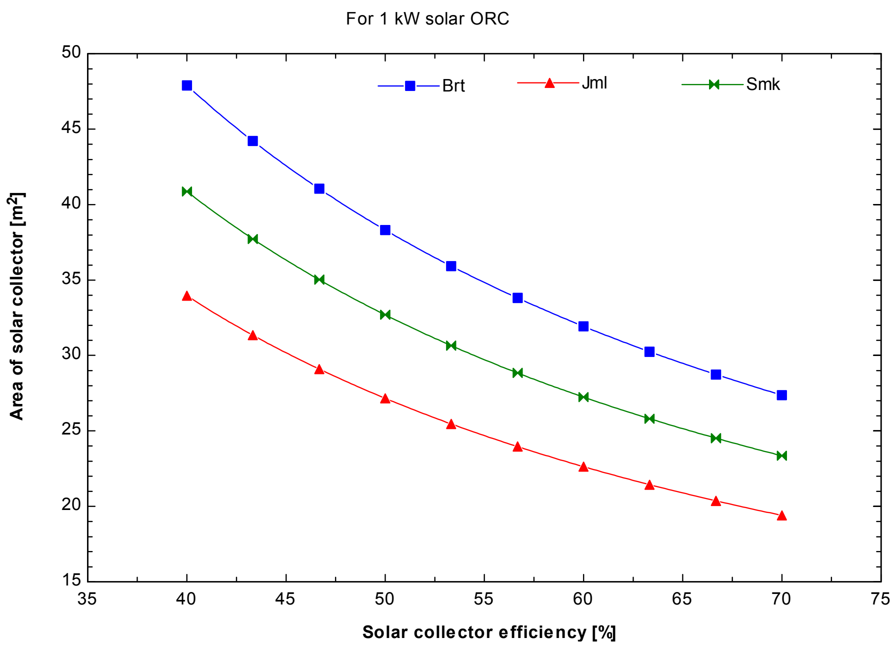

Figure 9. Variation of area of the solar collector with respect to solar collector efficiency (1 kW).

These results indicate that when the solar collector efficiency is 70%, the total costs of the systems using the PTC are $2602, $24,728, and $25,399 whereas the costs of the system with the ETC are $23,756, $23,079, and $23,415 for Biratnagar (Brt), Jumla (Jum), and Simikot (Smk), respectively. In both cases, the areas of the solar collectors are 27.8 m^2, 19.4 m^2 and 23.35 m^2, respectively.

For 5-kW power output, Figure 10 shows the variation of total cost of the systems when the efficiency of the solar collector changes. The total costs of the system using the PTC are $137,917, $128,435, and $133,135, whereas those with the ETC are $121,634, $116,893, and $119,243 for Biratnagar, Jumla, and Simikot, respectively.

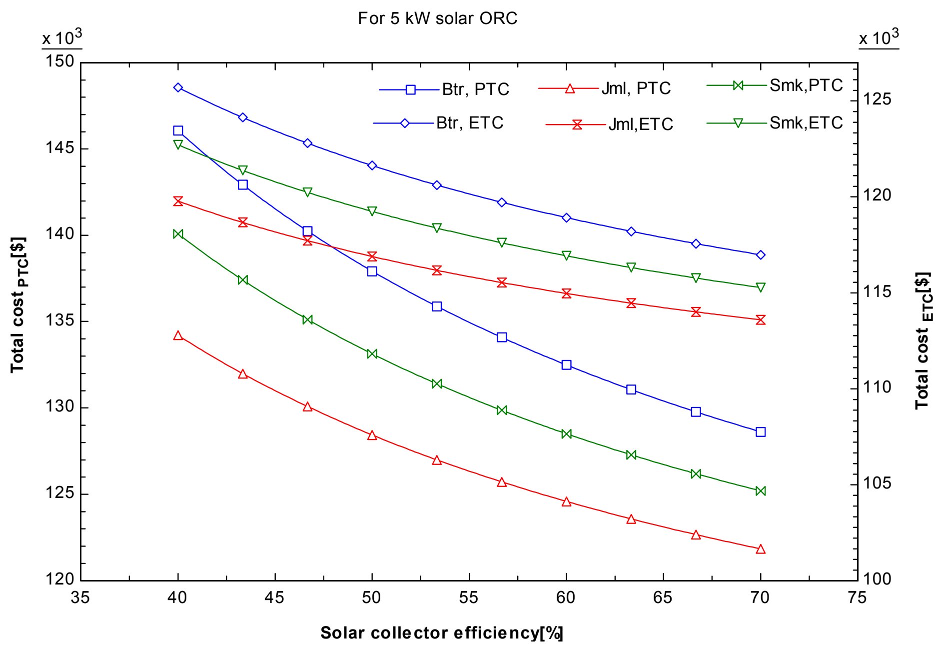

Figure 10. Variation of total costs of the solar ORC water pumping systems (5 kW) with respect to solar collector efficiency

The required areas of the solar collector are 191.6 m^2, 135.8 m^2, and 164.0 m^2 for the respective locations. These estimations were based on the solar collector efficiency of 50%. The variation of the collector area with respect to the solar collector efficiency for 5-kW systems is shown in Figure 11.

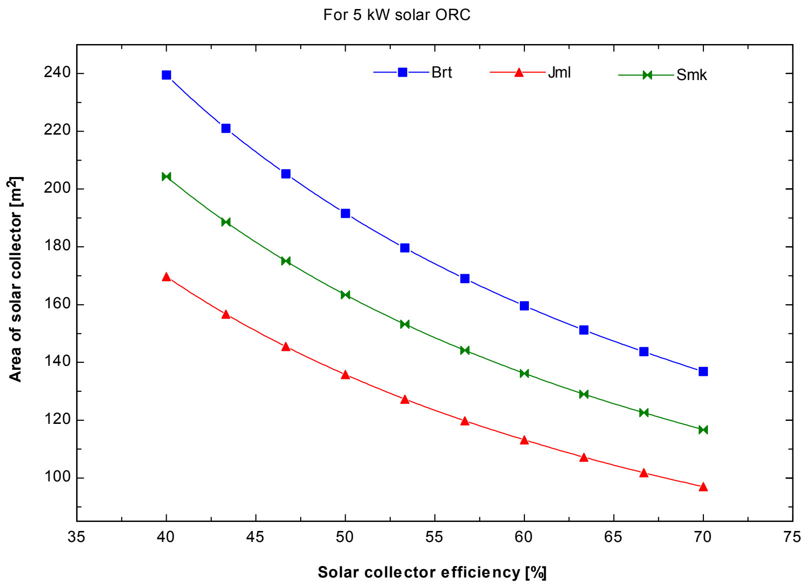

Figure 11. Variation of area of the solar collector with respect to solar collector efficiency (5 kW).

The solar insolation in Jumla is higher than in Biratnagar and Simikot, so a smaller collector is needed. The replacement costs of the components are also included in the economic analysis. The battery storage system and pumping system should be replaced at half of the total life cycle of this system, and the remaining all components are assumed to work for up to 20 years.

Theory for Economic Analysis of the Investigated System

In order to compare the total costs of pumping water in different locations of the country, the basics of economics should be understood clearly. This analysis will help solar ORC developers, manufacturers, and investors to determine the feasibility of the system. The economic parameters under investigation are the net present value (NPV), internal rate of return (IRR), profitability index (PI), and payback period (PBP). The discount rate (k) for this analysis is taken to be 8%. The interest rate is reasonable in the context of Nepal [26].

The equivalent annual cost (EAC) is the cost per year of investing in, operating, and maintaining the solar ORC water pumping system over its lifetime. It is given by the following expression [24,27]:

$$EAC = \sum_{c=1}^{n} \frac{CC_c \times k}{1 - (1+k)^n} \tag{14}$$

where CC is the capital cost, k is the interest rate, and n is the lifetime of the system.

The net present value (NPV) is the present value of all expected cash inflows of an investment minus the costs of acquiring it:

$$NPV = \sum_{j=0}^{n} \frac{P_{t=j}}{(1+k)^j} - \sum_{j=0}^{n} \frac{E_{t=j}}{(1+k)^j} \tag{15}$$

where $P_{t=j}$ is the profit of investment in each year, and $E_{t=j}$ is the expenses of investment in each year, which includes the capital cost at the beginning.

The profitability index (PI) identifies the relationship between expenses and the profit of the proposed system as a ratio:

$$PI = \frac{\sum_{j=0}^{n} \frac{P_{t=j}}{(1+k)^j}}{\sum_{j=0}^{n} \frac{E_{t=j}}{(1+k)^j}} \tag{16}$$

The internal rate of return (IRR) is the interest rate at which the net present value of all the cash flows from a proposed system or investment equal zero:

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

The payback period (PBP) is the length of time required to recover the cost of an investment and also represents the years needed for NPV to reach zero:

$$\sum_{j=0}^{PBP} \frac{P_{t=j}}{(1+k)^j} = \sum_{j=0}^{n} \frac{E_{t=j}}{(1+k)^j} \tag{18}$$

5. Results and Discussion

5.1. Estimation of Cost of Water

The cost of water from this technology is estimated to range from \$1.78/m^3 to \$2.47/ m^3 for the 1-kW power system. The maximum cost of water was observed in Biratnagar because of the low solar insolation in that region. The lowest cost of water is in Jumla at \$1.86/m^3 (PTC) and \$1.78/m^3 (ETC). The volume of pumped water ranged from 2190 m^3 to 2803.2 m^3 per year. Similarly, for the 5-kW solar ORC water pumping system, the cost of water ranged from \$1.71/m^3 to \$2.38/m^3. The volume of water pumped ranged from 11,100 m^3 to 14,208 m^3 per year. The analysis was carried out with a dynamic head of 150 m for all the cases and locations. The results of the investigated economic parameters and criteria are presented in Table 4.

Table 4. Results of the investment criteria.

Economic parameters	Biratnagar				Jumla				Simikot			
	PTC		ETC		PTC		ETC		PTC		ETC	
	1 kW	5 kW	1 kW	5 kW	1 kW	5 kW	1 kW	5 kW	1 kW	5 kW	1 kW	5 kW
NPV($)	19,952.1	97,890.74	18,676.91	91,281.92	19,164.71	93,877.97	18,362.67	89,627.27	19,468.94	95,319.14	18,443.4	90,001.5
IRR (%)	8.08	8.13	8.04	8.07	8.03	8.09	8.05	8.08	8.02	8.07	8.01	8.04
PI	1.6	1.61	1.59	1.6	1.59	1.6	1.59	1.6	1.59	1.6	1.59	1.59
PBP(yrs)	8	8	8	8	8	8	8	8	8	8	8	8
Cost of water (\$/m^3)	2.47	2.38	2.32	2.23	1.86	1.79	1.78	1.71	2.13	2.05	2.02	1.94

The results showed that the internal rate of return ranged from 8.01% to 8.13%, meaning the investment is highly feasible. Another economic parameter for investment criteria is the profitability index, which must always be greater than 1 for the investment to return a profit. For the investigated system, the profitability index ranged from 1.59 to 1.61, which indicates feasibility for water pumping in Nepal. The payback period for this technology is eightyears. The cost of water decreases when the higher volume of water is pumped. This can be achieved when the total dynamic head of the pumping system is reduced. Figure 12 shows the variation of the cost of water when the pumping head changes.

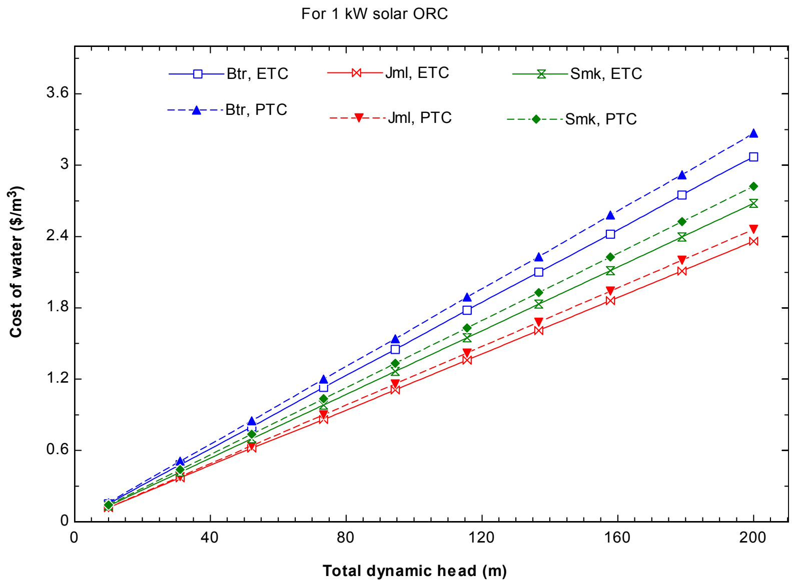

Figure 12. Variation of cost of water as a function of total dynamic head (1 kW).

The cost of water varies from \$0.12/m^3 to \$3.27/m^3 when the head changes from 10 m to 200 m for the 1-kW pumping system. The volume of the pumped water varies from 42,275 m^3 to 1651 m^3 per year. This variation in the volume of water pumped is shown in Figure 13. The cheapest cost of water production is in Jumla due to the high volume of water pumped, followed by Simikotand Biratnagar.

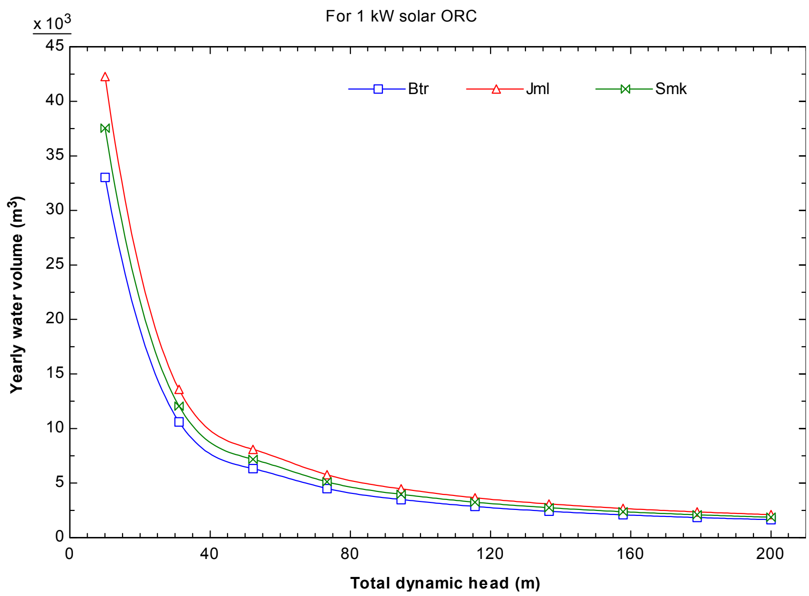

Figure 13. Yearly variation of water volume as a function of total dynamic head (1 kW).

Similarly, for the 5-kW pumping system, the costs of water are \$0.15/m^3 (ETC) and \$0.16/m^3 (PTC) when the head is 10 m, but for the head of 200 m, the cost increases to \$2.99/m^3 (ETC) and \$3.18/m^3 (PTC) for Biratnagar. This cost variation as a function of head is illustrated in Figure 14.

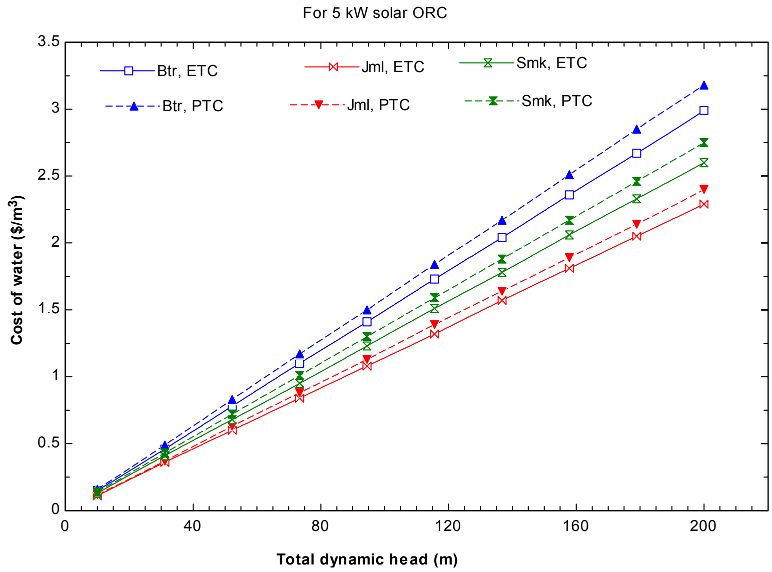

Figure 14. Variation of cost of water as a function of total dynamic head (5 kW).

In the 5-kW pumping system, the volume of water pumped is highest when the head is 10 m and lowest when it is 200 m. The maximum pumped water per year for a 10-m pumping head is 211,376 m^3 for Jumla, followed by Simikot (187,706 m^3) and Biratnagar (165,138 m^3). For the pumping head of 200 m, the volume of water pumped is 8257 m^3 for Biratnagar, 9385 m^3 for Simikot, and 10,569 m^3 for Jumla. This result is shown in Figure 15.

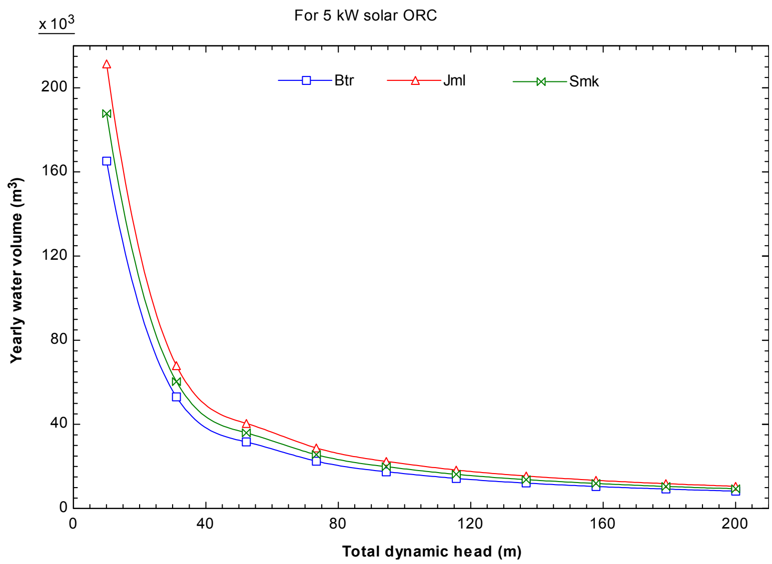

Figure 15. Yearly variation of water volume as a function of total dynamic head (5 kW).

5.2. Sensitivity Analysis

The price of the system's components, solar insolation, interest rate, and operation and maintenance (O&M) costs all change with place and time. The changes in their values directly affect the economic viability. In order to generalize the results under these varying conditions, a sensitivity analysis was conducted for the Simikot location. Table 5 shows different cases where values of parameters are varied by 30% from the base case. The table also describes the investigated cases and explains the expected causes of variation.

Table 5. Scenarios for sensitivity analysis.

Influencing Parameters	**Scenarios**	**Reasons**
	Base case	**No variation on systems parameters**
Capital cost (CC)	Increased by 30% Decreased by 30%	Increase in components cost Decrease in components cost
Operating cost (OC)	Increased by 30%	Labor cost increases High O&M cost Less durability of the system components
	Decreased by 30%	Low O&M costs Longer component life Decrease in labor cost
System productivity(SP)	Increased by 30%	Improvement in solar collector and ORC efficiency Higher solar insolation Optimized system performance
	Decreased by 30%	Poor collector and ORC efficiency Low solar insolation Not optimized system
Interest rate (IR)	Increased by 30%	Unstable country's GDP and political instability Ineffective banking system High inflation rate Supply/demand pattern un matched
	Decreased by 30%	GDP increased and political stable Decrease in inflation rate Government subsidizing policy Supply/demand pattern matched

Figure 16 shows that the most influential value in NPV is the capital cost, followed by the system production, interest rate, and operating cost for both power outputs. When the capital cost is decreased by 30%, the NPV, IRR, and PI are increased to $26,443, 15.53%, and 2.147 for 1 kW and to $127,697, 15.44%, and 2.13 for 5 kW, respectively. In this scenario, the payback period is sixyears. Similarly, when the capital cost is increased, the system is not feasible in both cases of power outputs. In those cases, IRR is lower than the interest rate—*i.e.*, 3.83%(1 kW) and 3.77% (5 kW)—and the payback period is 12 years.

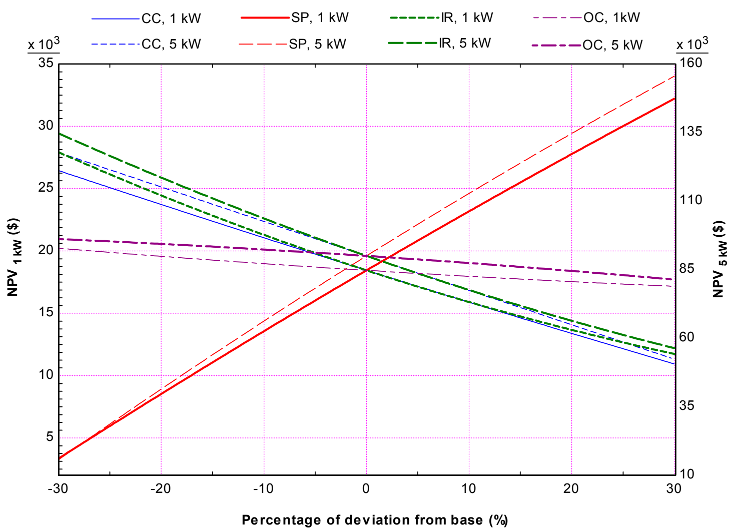

Figure 16. Variation of net present values as a function of various influencing parameters.

Another influencing parameter is the system productivity variation. When the solar radiation is low, less power is developed by the system, so less revenue is generated. In this case, the IRR is 1.57% with a long payback period (16 years). This pattern is observed for both the size of the systems, whereas the increase in system productivity yields a 13.41% IRR, six-year PBP, and NPVs of $32,218.9 for 1 kW and $155,543 for 5 kW. Additionally, the decrease in interest rate yields NPVs of $27,913.33 and $134,670.16 for 1 kW and 5 kW, respectively. The decrease in interest rate makes the systems infeasibility because the IRR is less than 8% (interest rate).

Finally, the last influencing parameter is the operating cost. The sensitivity graph shows that OC does not influence the NPV much in both systems. The NPVs are $20,210.65 and $96,154.9 when OC is decreased, whereas increasing the OC results in NPVs of $17,165.06 and $81,358.95 for 1 kW and 5 kW, respectively.

6. Conclusions

The concept of the solar ORC water pumping system has been investigated and the technology seems to be promising for developing countries including Nepal. This system can be modified for electrical power generation in addition to water pumping. The advantages of this system are the production of hot water, heating, and cooling applications with the same unit. The values of the cost of water were calculated without considering savings in fossil fuel cost and carbon emissions. If these costs were taken into consideration, the investigated cost of water through this technology would be much lower. The major conclusions are as follows:

- The solar ORC water pumping system can be used in drip irrigation, for pumping water for drinking and irrigation, and for organic farming to generate income in rural Nepalese villages.
- The technology can use a PTC or ETC for converting solar energy into power generation using R245fa as a refrigerant. The ORC based on a low temperature of 120 °C has an efficiency of around 8%. The efficiency is reduced when the solar collector efficiency is reduced, so a collector with high solar collecting efficiency is recommended.
- The stand-alone solar ORC water pumping system can be effective when there is no sunshine hours and on cloudy days because of the battery storage system.
- The specific cost of water ranges from $\$1.86/m^3$ to $\$2.47/m^3$ for the 1-kW system and from $\$1.71/m^3$ to $\$2.38/m^3$ for the for 5-kW system using the PTC. The maximum volumes of water pumped are 2806 m^3 and 14,208 m^3 yearly for 1-kW and 5-kW systems, respectively, in Jumla when the total dynamic head is 150 m. The cost of water is low when there is high solar insolation and more sunshine during the year. The results showed that Jumla has the lowest cost of water, followed by Simikot and Biratnagar.
- The system is more profitable when the influencing parameters vary. When the capital cost, interest rate, and operating cost are decreased, the system is highly feasible and the payback period is only six years. The investment is also acceptable when the productivity of the system increases.

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