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Design, modelling and optimisation of a small-scale Solar Organic Rankine Cycle system for rural power generation

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Abstract. This research study develops the design and model of a Solar Organic Rankine Cycle (SORC) coupled to a bio-digester for small-scale generation in rural areas, in Betulia, Colombia. Moreover, the model is optimised employing a Genetic Algorithm with the software Matlab and the thermodynamic library CoolProp. The objective variables were the mass flow rate of the working fluid, the pressure and temperature of the expander inlet, the solar collectors' type and the temperature of the water circuit for the bio-digester. The results indicate an overall efficiency between 8.42 and 9.45% with a Levelized Cost of Energy (LCE) between 3.85 and 5.63 £/W. Additionally, the power output is directly related to the mass flow rate of the working fluid. Likewise, increasing the scale of the SORC decreases the LCE. Finally, the results suggest that a superheated fluid reduces the efficiency and the LCE and can deliver more heat to the bio-digester. It is advisable the utilisation of a scroll expander and a counter-flow plate exchanger with a Direct Vapour Generation configuration. The model is a flexible tool capable of integrating more equations and components, with the evaluation of different fitness functions.

1. Introduction

The high consumption of resources such as coal, oil, natural gas and other fossil fuels coincides with the increase of environmental problems, especially the global warming, water contamination and solid waste [1]. Several renewable technologies have been improving during the last decade to relieve this harm to the environment. The main renewable alternatives currently promoted are wind turbines, photovoltaic solar panels, biomass digesters and geothermal systems [2]. However, some of them can be expensive for small scale and remote areas, where exist a lack of energy that requires attention, using simple but efficient technology.

In Colombia, according to reports from the Mining and Energy Planning Unit (UPME), around 66% of the national territory does not have public electricity service through the National Interconnected System (SIN). This is mainly due to the fact that in remote locations with difficult access it is costly and not feasible to carry out civil interconnection works. Also, some areas access is restricted by armed groups.

Due to the lack of electricity in the non-interconnected areas in Colombia, the population has opted for alternative energy supply routes, mainly using diesel generation plants. Although this type of plant has become the most common option in the rural population, its implementation implies a high cost of operation and maintenance, not to mention that it generates environmental impacts by producing greenhouse gases and noise pollution, directly affecting the quality of life of the peasant population.

Solar-thermal power systems have shown a solution and potential source of clean energy for rural communities. These systems are an engaging alternative since they contribute to the advantage of providing thermal energy and electrical power with the same equipment [3]. The Organic Rankine Cycle (ORC) is an independent and flexible system that employs heat source to electrical and thermal power. According to Quoilin *et al.* [4], the ORC in small-scale systems is suitable since they work with low working temperature, they show low maintenance requirements, and the systems are relatively simple. These advantages convert ORC technology attractive and suitable for this purpose and can be considered one of the most common and competitive cycle to generate electricity from thermal energy [5]. It is composed of a pump, an evaporator, a turbine or expander and a condenser.

Two main designs are considered in the literature: the Heat Transfer Fluid design (HTF) and the Direct Vapour Generation design (DVG). The HTF design is the most popular design in research since it is less sensitive to the heat source fluctuations. This type of system collects the heat from the source and flows in a closed-loop using a specific fluid, and using three heating exchange (HE): the evaporator, the regenerator and the condenser [6].

The DVG design uses solar collectors as evaporator. Therefore, it requires only one HE in the condensation process, as well as a regenerator. This configuration is more suitable for the solar heat source. It reduces the costs, the irreversibility, and the complexity of the system and increases the thermal efficiency with fewer components [6, 7]. Furthermore, the DVG design is less common in literature.

Considering that SORC is an efficient and environmentally friendly alternative, is projected as an attractive solution for non-interconnected areas. Moreover, there is no research dedicated to developing a Direct Vapour Generation SORC system that uses its waste heat to improve another low-temperature system. As an example, the production of biogas using a small bio-digester, which is suitable for rural areas, is raised by the heating of the waste at low temperatures.

The aim of this research study is to develop a model of a Solar Organic Rankine Cycle (SORC) system to produce small-scale power in rural areas. The design considers a bio-digester that absorbs the waste heat from the SORC to raise the production of biogas. This model is optimised to find the most suitable sizes of each component, pursuing the best efficiency and the lowest cost. The location of the project is Betulia, Colombia, where bio-digester is a real project led by the Industrial University of Santander. In this work the optimisation of the thermodynamic parameters of the SORC taking into account the efficiency and levelized cost of energy (LCE), as well as the integration of solar collectors, bio-digester, heat transfer model and ORC, taking into account the location.

2. Methodology

Initially the type of ORC design to work was selected. In this research the DVG design was selected due to this system has lower thermal inertia than the HTF system, making it faster to start [8]. Finally, the simplicity of DVG design will allow having easier maintenance with fewer components.

The SORC proposed (Figure 1) use as heat source the solar collectors, and contemplate three added components: the pump, the expander, and the heat exchanger. The type of collector is a variable that is optimised in the model, being dependent on the efficiency and the price. Since it collects heat with solar collectors, it will work during daylight. The bio-digester has a volume of $6m^3$ and it is developed by Universidad Industrial de Santander.

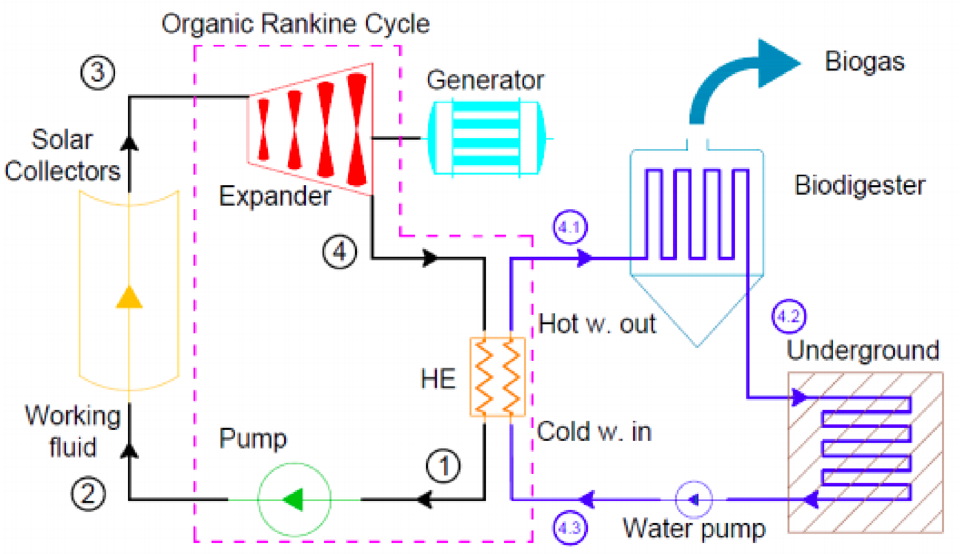

Figure 1. Schematics of the Solar Organic Rankine Cycle system coupled with Bio-digester.

The proposed system uses the heat waste from the SORC to increase the temperature in the bio-digester and accelerate the process of biogas generation. Since it is a need to decrease the temperature of the working fluid in point 1, the water circuit must cool after the bio-digester. For this, the pipes pass through the underground since the temperature is constant. This passive method gives stability to the system. The hourly ground temperatures were provided by Universidad Industrial de Santander from data measured for fifteen days, obtained a mean value of 21.084 ºC.

The fluid selected was R-245fa since it requires smaller equipment is a worldwide-cheap refrigerant, is available in Colombia and has a low critical temperature, which benefits the performance of the ORC. Aditionally, this fluid has low toxicity and non-flammable, make it safe for the rural people. Regardless of its high GWP, the lifetime of the fluid in the atmosphere is 7.2 years [9]. Furthermore, its non-ODP, make the fluid friendly with the environment.

About the solar collector type, the optimisation procedure will find the best collector taking into account the objective function. Currently, the model can evaluate the efficiency and the levelized cost of energy. However, with more develop of the model, other factors will apply, such as the availability.

To select a software some characteristics was considered, such as flexibility, licence availability, complexity and others. The properties of the main software available were compared, considering five aspects for the final selection: the price and the availability in the University, the robustness and prestige, the thermophysical library, popularity, and previous knowledge of the software. Examining this, Matlab was selected [10].

For the calculation of thermodynamics of the fluid was chosen CoolProp, due to it is an open-source and a recognised library developed by the National Institute of Standards and Technology of U.S. Department of Commerce [11, 12]. This tool can calculate the state thermodynamic properties of a fluid by knowing another two properties of state using high-accuracy Helmholtz energy formulation and cubic equation of state and fitting algorithms [13].

For the optimisation method the model uses the Genetic Algorithm (GA) for two main reasons. The first one is related to previous knowledge acquired during the studies of the author. The GA can find different solutions for problems with nonlinear constraints, searching in several regions of a space at the same time. Moreover, the fitness function implemented in the code involves nonlinear equations. GA can solve problems when the objective function is stochastic, discontinuous, and highly nonlinear [14]. The diagram of optimisation approach is shown on Figure 2.

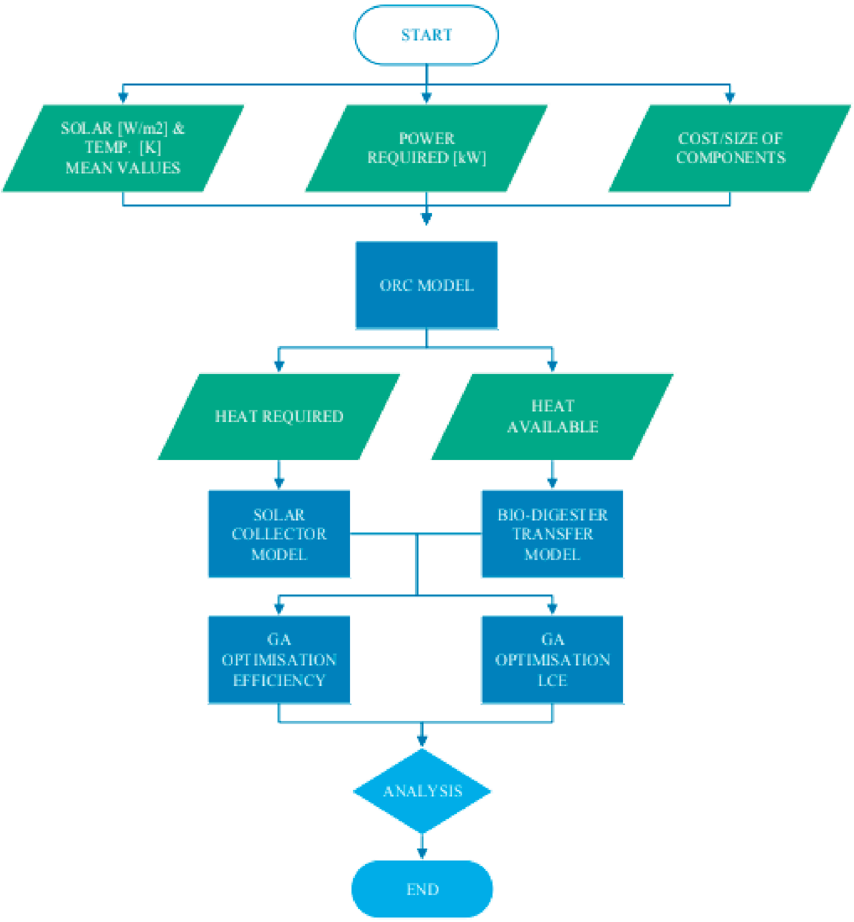

Figure 2. Diagram of processes of the SORC

The ORC system is based on equations that mostly all authors from literature review apply in their RC models. On the other hand, it is necessary to mention that the model assumes the value of some variables called ‘optimisation variables’: mass flow rate of the working fluid, the pressure in point 2, the temperature in point 3, the type of solar collectors and the temperature of water in point 4.
Three main inputs start the model. For one side, the location gives the solar radiation, ground temperature and ambient temperature. Table 1 gives these values. On the other hand, the power required to lead to the size of the SORC components. In this case, this value is between 1000 and 1100 Watts. Finally, the cost of each component is an input that could vary according to the location. However, these values are derived from the literature review.

Table 1. Local Data of Betulia, Colombia.

Variable	Value	Unit
Ambient temperature	294.84	K
Ground Temperature	294.234	K
Blackbody sun temperature	5800	K

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The final step of the model is optimisation. As it was noted, the optimisation variables are the values that genetic algorithm changes and mutates to optimise the system to find the minimum or maximum value of the objective function. Furthermore, two different functions are assessed separately: the efficiency of the system and the Levelized Cost of Energy (LCE).

3. Results and Analysis

The model begins with the calculation of thermodynamic parameters of point 1 (Figure 1). Here, the temperature of the working fluid is similar to ground temperature. Also, its state is saturated (quality of vapour=0). Using CoolProp library were calculate all parameters in this point, such as pressure P_1, enthalpy H_1, entropy S_1, density D_1, viscosity V_1 and others. Then, the ideal entropy of point 2 (S_2) is assumed as the same as S_1. Using the optimisation variable P_2, it is calculated the ideal enthalpy H_2.

Different analysis can be done with the model. In this case, two main results are reviewed. To begin with, the efficiency optimisation gives a result of 9.45% of the overall system as the objective function. Also, the LCE is 5,63£/W. Figure 3 displays the T-S diagram of the SORC.

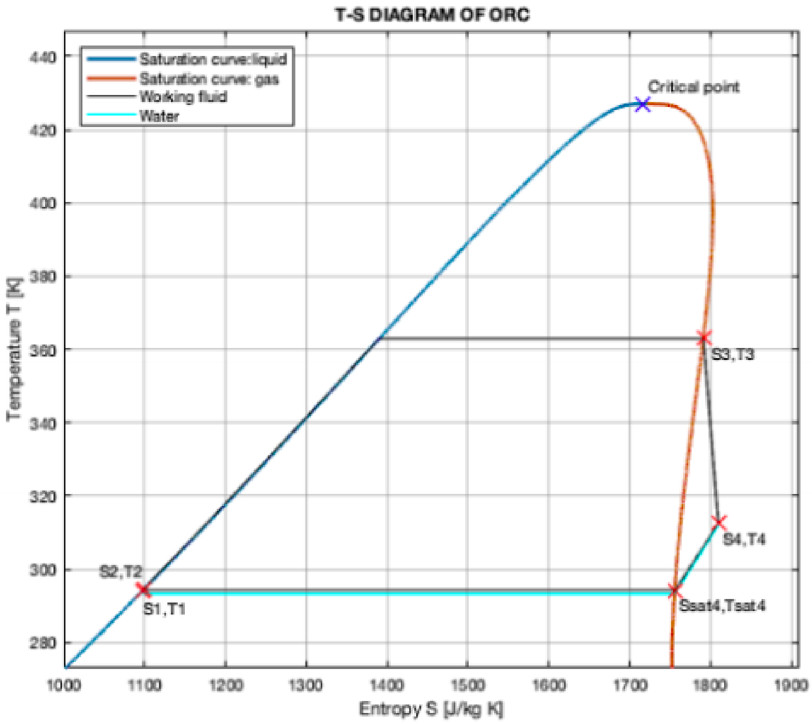

Figure 3. T-S SORC diagram from efficiency fitness with R-245fa fluid**.**

Due to the algorithm is looking for the maximum efficiency, the model sets the minimum heat required from solar collectors to obtain an output of 1000 Watts.

Consequently, the fluid is heated until the fluid achieves the saturated vapour point. Looking at the constraints, temperature T3 must be higher or equal as the saturated temperature, to not damage the expander with two-phase fluid. Also, the model selects the EFCP collectors, since it presents the best efficiency at temperature T3.

On the other hand, this configuration is available to give a small quantity of heat to the bio-digester, since the temperature in point four is 39.26 ºC. According to the second law of thermodynamics, this is the maximum temperature that the bio-digester circuit can achieve. The UIS recommends a temperature of 80 ºC for the bio-digester. Nevertheless, the main aim of the project is the generation of electrical power. Moreover, any temperature gained in the bio-digester increases the efficiency of it.

The second analysis is done by using LCE optimisation. The best result shows an efficiency of 8.42% and an LCE of 3.85 £/W. Figure 4 shows the T-S diagram of the SORC for this case.

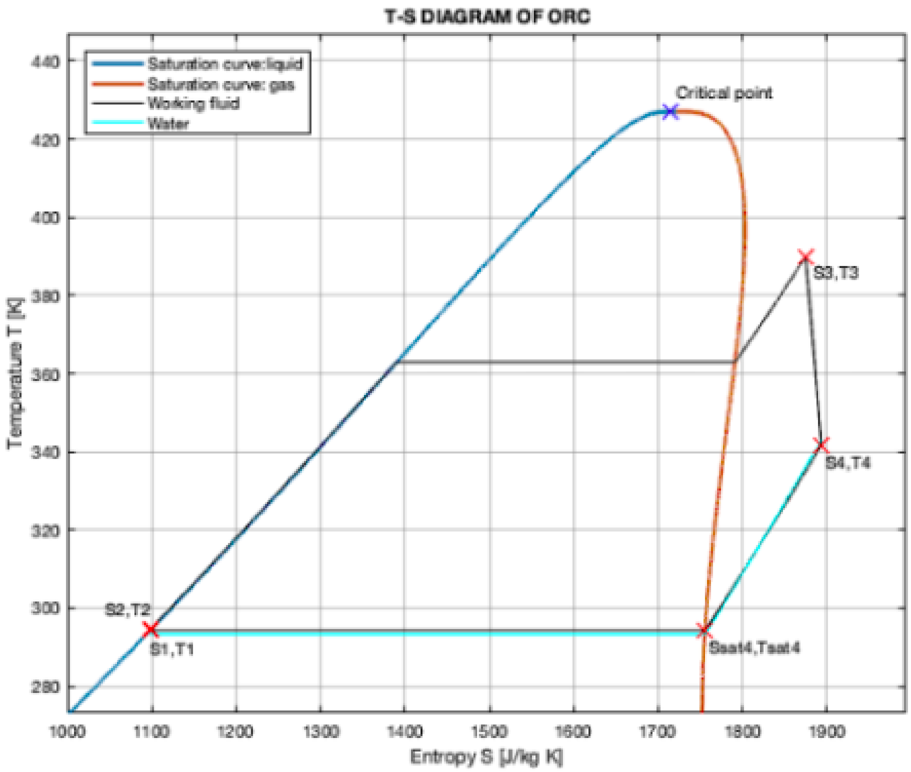

Figure 4. T-S SORC diagram from LCE fitness with R-245fa fluid

In this case, the algorithm searches for the lowest cost. As a consequence, two main changes appear. Firstly, the fluid achieves a superheated temperature in point three. Different factors explain this behaviour. Firstly, a higher temperature permits the system to get a smaller pump, reducing the consumption and costs. At the same time, it also enables getting a higher power output from the expander. Thus, these factors reduce the LCE, due to the costs are not altered in a significant way. In other words, delivering more power with the expander and a similar pump consumption decreases the LCE. For this, it is necessary to achieve super-heated fluid. Secondly, the type of solar collector differs from the previous result.

Additionally, the heat available for the bio-digester is larger than the preceding configuration, achieving a maximum temperature in point 4 of 66 ºC. Table 2 displays the comparison of the results of both fitness functions.

Firstly, the LCE function tends to get the highest power (upper constraint of 1100 Watts). The efficiency function gives the opposite result (lower constraint of 1000 Watts). Also, the LCE function permits to give around 800W more of thermal power to the bio-digester with greater temperature, improving the production of gas. Moreover, the difference in final cost between both results is more than 1400 £, which is a considerable amount of budget, taking into account the conditions of the real project. The difference is mainly related to the cost of the collectors.

The most suitable configuration is the LCE function results considering the input data, the lower budget and the simplicity of the collectors. It is important to mention that costs such as pipelines, structure and control systems are not included.

Firstly, the output power of the SORC varies the LCE result. As the power output is increased, the LCE decreases. For instance, a simulation with no constraint regarding the 1000-1100 watts limit, gave an LCE of 2.44 £/W, with an output power of 330.3 kW and an efficiency of 8.56%. The reason for this is due to the cost ratio increase slower as the power output ratio.

Table 2. Comparison of output data for the SORC, using Efficiency fitness and LCE fitness

Variable	Efficiency Result	LCE Result	Unit
T3	363	390	K
T4	312.41	341.71	K
P1	128280	128280	Pa
P3	1000000	998821	Pa
Qcond	-6695.1	-7357.3	W
Q available	507.11	1343.9	W
Qcoll	7700.1	8456.1	W
Wturb	1029.3	1122.3	W
Wpump	24.23	23.51	W
eff	9.45	8.42	%
lce	5.63	3.85	£/W
Acoll	26.77	32.85	m^2
Solar collector	EFPC	FPC	
Costexp	780	780	£
Costpump	288.32	287.93	£
Costhe	904	504.14	£
Costcoll	3686.5	2661	£
Total cost	5658.82	4233.07	£
Woutput	1005.07	1098.79	W

For this case, the upper limit for power is the mass flow rate. Therefore, the power output depends directly on the flow rate. This result is similar to Xu *et al.* [7]. Their work suggests that "to maintain a reasonable outlet temperature under higher solar radiation, larger flow rate is needed. Therefore, higher solar radiation and a larger flow rate can provide more power and more efficiency" [7]. The second aspect is that efficiency is not affected by the output or the mass flow rate. According to the model, the efficiency does not vary changing the overall power output. Based on the results, an approach of real components can be done.

During the developing of the project, some deviations appeared concerning the research design. For instance, at the beginning it was considered just an optimisation of solar collectors. Also, the Rankine Cycle was considered just as a mathematical model. However, the research found that it is necessary to optimise the RC and the heat source at the same time. Therefore, the model is more flexible. In contrast, the combination between the SORC and the bio-digester was assumed as a black box. However, the heat exchanger model is more complex than it was expected. Its development required a longer time.

Nevertheless, a first approach of the SORC coupled with the bio-digester was settled successfully, using the software and data input considered in early stages. More research must be considered regarding the real-life project, such as the costs of the pipeline and physical structure, and a deeper heat-transfer model between the HE and the bio-digester. Also, a next step must be considered regarding control, since the SORC should adapt itself to the variations of the heat source. Therefore, it is meaningful to investigate and integrate control strategies [15]. For this, an hourly input performance must be developed.

The parameters of the model can change depending on the objectives and constraints. For instance, it is possible to prioritize thermal generation for the bio-digester with a simple modification to the code. Also, it is possible to add new solar collectors, expanders and other components. The model can evaluate the changes quickly. Furthermore, it can also change the working fluid.
For instance, the model must improve the calculation of costs, regarding pipelines, accessories and structure, maintenance, and lifetime. Also, this work does not contain the limit temperature of the collectors, which could affect the selection of it.

4. Conclusions

The present study describes the development of an optimisation model of a small-scale Solar Organic Rankine Cycle focused on rural areas, coupled with a bio-digester. This project was carried out with the Industrial University of Santander (UIS). The final aim is to continue the improvement of the model, to build a real project in Betulia, a village located in Colombia. It was used the Matlab software and the thermodynamic library CoolProp. The optimisation model considered as optimisation variables the mass flow rate of the working fluid, the work pressure, the maximum temperature, the type of collectors and the maximum temperature of water for the bio-digester circuit. With this, the sizes of the components were calculated.
The results give an important approach of the real behaviour that the system could get, giving the most suitable parameters, depending on the location, the budget and real characteristics of the components. Moreover, some considerations have been proved and must be considered in the future. For instance, the output of the SORC (which depends on the mass flow rate) vary the LCE. As the power output increases, the cost per Watt decrease. This factor does not affect the overall efficiency. Similarly, a superheated fluid decreases efficiency but improves the LCE. Additionally, more heat can be released to the bio-digester.
Some challenges are expected to solve in the future. The main one consists of the optimisation of the system using hourly data. With this, the model analysis will be more realistic. Moreover, this will help to generate a control system to get the most suitable configuration of the components since the input conditions are changing constantly, such as solar radiation and the ambient temperature. Also, the implementation of new objective functions can expand the possibilities of final configurations.

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