Economic Feasibility of Small - Scale Organic Rankine Cycle Driven by Solar Energy and Biomass

Mohammed Tardi

Submitted to the
Institute of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Master of Science
in
Mechanical Engineering

Eastern Mediterranean University
January 2019
Gazimağusa, North Cyprus

Approval of the Institute of Graduate Studies and Research

Assoc. Prof. Dr. Ali Hakan Ulusoy
Acting Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science in Mechanical Engineering.

Assoc. Prof. Dr. Hasan Hacışevki
Chair, Department of Mechanical Engineering

We certify that we have read this thesis and that in our opinion it is fully adequate in scope and quality as a thesis for the degree of Master of Science in Mechanical Engineering.

Prof. Dr. Uğur Atikol
Supervisor

Examining Committee

1. Prof. Dr. Uğur Atikol
2. Prof. Dr. Fuat Egelioğlu
3. Asst. Prof. Dr. Muhamad Abid

ABSTRACT

The current thesis provides energy and economic analyses for Organic Rankine Cycle (ORC) power plants driven by solar and bioenergy. The system comprises of an ORC power unit, an auxiliary gas heater with evacuated tube collectors or biomass-fired boiler. Electric power capacity range tested is between 35 kW and 110 kW. An optimisation process was conducted using SAM software to determine the optimal size of the solar ORC components. The result showed that the optimal size of the evacuated tube collector area, tilt angle, storage tank volume and the energy needed from the auxiliary unit for 35 kW system are 100 m^2, 45°, 4 m^3 and 1636 kWh/year respectively. The simulation result of the solar part shows that the temperature of the hot water never falls below 100 °C which is above the temperature determined by the ORC manufacturer to get the maximum power. Also, the solar fraction of the solar water heating is calculated to be 0.98. The proposed system of biomass-fired ORC power plant assumes that the hot water goes directly to the ORC evaporator. The biomass boiler size determined based on manufacturers information to match the operating temperature. The economic calculation results showed that solar ORC power plant is economically feasible while Biomass is not feasible under same operating conditions. Saving to Investment Ratio (SIR), Internal Rate of Return (IRR), Simple Payback Period (SPP) and Levelized Cost of Energy (LCOE) for 35 kW ORC power plants are 1.3, 9%, 5.9 years and 0.12 $/kWh respectively for solar ORC, and those values increase as the power capacity increase. For 35 kW biomass-fired ORC power plant the values are 0.9, 0%, 6.4 years and 0.19 $/kWh respectively and becomes slightly high for higher capacities. Furthermore, the sensitivity analysis results showed that Solar Organic Rankine Cycle (SORC) Power plant is not feasible when the operation

hours become less than 5000 hours and the system becomes more feasible as the power plant capacity increase while the biomass-fired ORC becomes feasible when the capacity is more than 40 kW.

Keywords: Solar Organic Rankine cycle, Evacuated Tube collector, Economic Analysis.

ÖZ

Mevcut tez güneş ve Biyoenerji tarafından yönlendirilen Organik Rankine Çevrimi (ORC) santraller için enerji ve ekonomik analizler sağlar. Sistem bir ORC güç ünitesi, tahliye Tüp koleksiyoncular veya biyokütle-ateş kazan ile bir yardımcı gaz ısıtıcı oluşur. Test edilen elektrik güç kapasitesi aralığı 35 kW ile 110 kW arasındadır. Bir optimizasyon süreci güneş ORC bileşenlerinin optimum boyutunu belirlemek için SAM yazılımı kullanılarak gerçekleştirildi. Sonuç olarak, tahliye tüpü toplayıcı alanının optimum büyüklüğü, eğim açısı, depolama tankı hacmi ve 35 kW sistemi için yardımcı üniteden gereken enerji 100 m^2, 45 °, 4 m^3 ve 1636 kWh/yıl olarak belirlendi. Güneş bölümünün simülasyon sonucu sıcak suyun sıcaklığının maksimum güç almak için ORC üreticisi tarafından belirlenen sıcaklığın üzerinde 100 °C ' nin altına düşmemiş olduğunu gösterir. Ayrıca, Güneş suyu ısıtma Solar fraksiyonu 0,98 olarak hesaplanır. Biyokütle tarafından önerilen sistem ORC elektrik santrali sıcak suyun ORC evaporatörüne doğrudan gittiğini varsayar. Üretici bilgilerine göre belirlenen biyokütle kazan boyutu çalışma sıcaklığına uyacak şekilde belirlenir. Ekonomik hesaplama sonuçları, Güneş ORC enerji santralinin ekonomik olarak uygun olduğunu, ancak biyokütle aynı çalışma koşullarında uygulanabilir olmadığını göstermiştir. Yatırım oranına (efendım) tasarruf, Iç dönüş oranı (ıRR), basit geri ödeme süresi (SPP) ve 35 kW ORC güç santralleri için enerji levelized maliyet (LCOE) 1,3%, 9, 5,9 yıl ve $0,12/kWh sırasıyla Solar ORC için, ve bu değerler güç kapasitesi olarak artar Artırır. 35 kW biyokütle-ORC elektrik santrali Için değerleri 0,9, 0%, 6,4 yıl ve 0,19 $/kWh sırasıyla ve yüksek kapasiteler için biraz yüksek olur. Ayrıca, hassasiyet analizi sonuçları, Güneş organik Rankine Çevrimi (SORC) güç santralinin çalışma saatleri 5000 saatten daha az olduğunda ve sistemin güç santrali kapasitesi artırken daha uygun hale geldiği zaman mümkün olmadığını göstermiştir Biyokütle ateşlenmiş ORC kapasitesi 40 kW 'dan fazla olduğunda uygulanabilir hale gelir.

Anahtar Kelimeler: güneş organik Rankine Çevrimi, vakumlu Tüp kollektör, ekonomik analiz.

ACKNOWLEDGEMENT

I would like to record my gratitude to Prof. Dr. Uğur Atikol for his supervision, advice, and guidance from the very early stage of this thesis as well as giving me extraordinary experiences throughout the work. Above all and the most needed, he provided me with constant encouragement and support in various ways. His ideas, experiences, and passions have truly inspired and enriched my growth as a student. I am indebted to him more than he knows.

Last but not the least; I would like to thank my family members especially my parents for all their support throughout my life. To my princess who stood by me and supported me in every moment of my life, I dedicate this work.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ORC	Organic Rankine Cycle
ODP	Ozone Depletion Potential
HTF	Heat Transfer Fluid
SHW	Solar Hot Water
$F_R$ta	Collector heat removal factor
F_RU_L	Thermal resistance characteristic factor (W/m^2K)
BTU	British Thermal Unit
i	Discount Rate (%)
n	Final year
Q	Heat required (kW) / Power output (kW)
t	Final year
CHP	Combined Heat and Power

Subscripts

SORC	Solar Organic Rankine Cycle
PTC	Parabolic Trough Collector
ETC	Evacuated Tube Collector
CPC	Concentrating Parabolic Collector
Gal	Gallon
η	Efficiency
hr	hours
HV	Heating Value (kJ/kg)
I	Total Investment
M	Maintenance Cost

F	Fuel Cost
E	Total Energy
I_T	Transmitted Irradiance
$\dot{m}$	mass flowrate
SF	Solar Fraction
Cp	Specific Heat
V_t	Tank Volume
E	Electricity Tariff
LPGC	Liquefied Petroleum Gas Cost
BC	Biomass Cost

Acronyms

SAM	System Advisor Model
LCOE	Levelized Cost of Energy
IAM	Incidence Angle Modifier

Chapter 1

INTRODUCTION

1.1 Background

The worldwide demand for energy is increasing continuously while traditional power sources such as fossil fuels are depleting and have many negative environmental impacts. As a result of the high consumption rate of fossil fuels, the emission of CO_2 and other gases will increase the greenhouse effect.

Using renewable energy resources such as solar, geothermal, wind, hydropower and biomass have an important role in reducing greenhouse gases by reducing CO_2 emissions and oil dependency. In general, the initial investment of renewable energy projects is more than those of fossil fuels, and the availability of renewable energy may not be uninterrupted. However, they can be cheaper over the life cycle of the projects. The energy market like every market is driven by economic opportunity. Public awareness, taxes and penalties affect the economic opportunity associated with safe and renewable energy technology.

There is a large variety of low-grade energy sources for which neither gas nor steam cycles offer a technically and economically feasible alternative for electricity generation. A new technology, Organic Rankine Cycle (ORC) has been developed to utilize such energy sources. ORC is a technology used with different energy sources and particularly with medium-low temperature heat sources. Also, ORCs have simpler plant layout characterised by a limited number of components in comparing with other closed power cycles which make ORCs competitive from an economic point of view.

1.2 What is ORC?

ORC and Steam Rankine Cycle have the same principle of operation, but instead of using water as working fluid, an organic fluid is used in ORCs. However, using an organic fluid as a working fluid in a Rankine cycle makes the heat recovery process better from low enthalpy heat sources to produce electricity or work due to its lower boiling temperature. Furthermore, ORCs are an attractive solution for decentralized, small-scale power plants due to the simplicity in using and availability of its components. [1]

ORC can utilize heat from renewable resources (Geothermal, solar or biomass combustion) or industrial waste heat. This work focuses on solar and biomass as the heat sources of the system. Solar ORCs use solar energy to generate electricity or mechanical power. The heat is obtained using solar thermal collectors which intercept incoming sunlight and collect or reflect solar radiation to collection element then heat is transferred to the heat transfer fluid which used to heat the organic fluid. Likewise, biomass is converted to heat by combustion of different types of biomass.

1.3 Thesis Objectives

The principle focus of this thesis is performing an economic analysis of small-scale biomass-fired and solar power plant driven by ORC unit and evacuated tube collectors. In addition, energy analysis is performed to see the performance of such plants in Cyprus. In this study, 35 kWe to 110 kWe power plant with Organic Rankine cycle driven by solar energy or bioenergy is taken as a case study to show the feasibility of such systems in small scale in Cyprus. The scope and objectives of the present work can be listed as follows:

a) Determining the optimum sizes of the solar collector array, hot water storage tank and other related system components for given ORC power plants.

b) Perform transient energy analysis for each ORC power plant.

c) Perform Life Cycle Cost (LCC) Analyses for each considered ORC system.

1.4 Thesis Organization

Chapter 1 is a general introduction about renewable energy, ORC, and the main objective of this work. In chapter 2, a comprehensive literature review is carried out and shows the previous work about ORC technology. Chapter 3 describes the proposed system for ORC power plants driven by solar energy and biomass. Chapter 4 discusses the results of the simulation of solar hot water part in the proposed system of ORC power plant driven by solar energy. Chapter 5 shows the cost analysis of the proposed systems with different scales. Finally, Chapter 6 is the conclusion of the thesis work.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

Many theoretical studies conducted to analyse the performance of ORC power plants from a technical point of view. In contrast, a few studies performed on the economic aspect of ORC plants due to the lack of economic data which kept reversed by manufacturers and suppliers. The focus of this chapter will be on the recent studies done by researchers related to ORC power plants driven by solar energy and biomass. This literature referred to studies performed to study the feasibility of SORC power plants technically and economically.

2.2 Solar Organic Rankine Cycle

Concentrating solar systems are beneficial technologies for power generation on a small scale such as Stirling engine and a large scale such as solar towers, parabolic trough collectors. The working principle is concentrating the solar energy using mirrors to heat a fluid (directly working fluid or heat transfer fluid). However, the steam cycles high pressure, temperature, and the installed capacity should be high to be economically feasible. Therefore, it is covering a large area compared with solar ORC with the ratio (200 to 1) [2] this make the ORCs competitive where the organic fluid can be heated directly [low operating pressure] or by heat transfer fluid [continuing the operating at night].

Furthermore, Quoilin, et al. [3] Simulated the performance of 3 kWe ORC coupled with parabolic trough collectors. The main component of the system was sized considering the physical and mechanical phenomena occurring in the cycle and the different working fluids were compared in a single stage and double stage expansion machine. The result of the simulation shows that the overall efficiency of the system ranged between 7% to 8% and the most efficient working fluid among those simulated was solkatherm. Baral, et al. [4] experimentally studied the technical performance and the feasibility of solar ORC in small scale for electricity generation. The experiment performed in the laboratory showed acceptable results. The maximum overall efficiency of the system was 6% at 120 °C with output ranges between 0.4 kW to 1.38 kW. The economic analysis conducted to find the electricity price (0.68 $/kWh) with payback period 19 years. Authors concluded that the cost of energy per kWh would become lower if the investment and the annual cost reduced. Furthermore, the small-scale SORC is expensive in comparing with medium and large scale, and this system could be successful for rural areas in developing countries where the electricity is lacking. Garg, et al. [5] conducted a study to investigate the specific costs of power for 16 different working fluids (zero ODP and positive condenser pressure) for heat transfer fluid supply temperatures between 125 °C and 275 °C. The analysis showed that specific costs of electricity can a achieve value between 1.25 and 2 $/W for solar ORC systems using a parabolic trough collector.

An experimental study to determine the cost of 3 kWe Solar ORC system-based parabolic trough collectors (PTC) was performed by Ref. [6]. The cost of the components of the plant was taken from suppliers. The result of this study shows that the installation cost of such plants is approximately 6 $/watt. Similarly, Thawonngamyingsakul, et al. [7] studied the potential of SORC power plant with evacuated tube collectors for electricity generation under Thailand weather conditions. The capacity of the plant considered in the study is 280 kWe, and the working fluid of ORC was R245fa. The Authors conclude that the cost of such plant is 1500 $/kWe with interest rate 7% and power plant efficiency 4.44%, while the levelized cost of energy (LCOE) was found to be 0.37 $/kWh.

Meanwhile, Freeman, et al. [8] studied the feasibility of SORC with three types of solar collectors (PTC with a Tracking system, PTC without tracking system and evacuated tube collectors) for domestic applications. Authors found that the performance of evacuated tube collectors (ETC) with SORC is high comparing with other collectors and can run the system for more hours than others. Furthermore, they found the installed cost and payback period, 54 pounds/W_e and 9.5 years respectively which is less than other collectors. The levelized electricity cost was calculated to be 0.44, 0.94 and 0.57 pound/kWh for ETC, PTC without tracking and PTC with Tracking respectively. Furthermore, Calise, et al. [9] presented a prototype of 6 kWe ORC power plant coupled with 76 m^2 ETC for electricity and heat purposes. The simulation results showed that the system capable of producing heat and electricity all year long. The study also showed that the economic performance of the system dramatically depends on the possibility of using the ORC waste heat which means the profitability of the system is scarce when the waste thermal energy of the ORC not used.

Proper design and sizing of the components of the system are critical to assure maximum benefit from the system. For solar water heating system, different constraints affecting the performance of the system such as collector area, storage tank capacity, tilt angle and solar fraction. These factors depend on the system type and configuration of the system. Kulkarni, et al. [10] proposed an optimisation methodology which can be applied for different configurations of solar water heating systems. The methodology represented by tracing constant solar fraction lines on the storage tank volume and area of the collector. The result showed that for given solar fraction the maximum and minimum area of the collector and storage tank volume exist. Based on that, the annual life cycle cost is minimum when the solar fraction is higher. Likewise, Assilzadeh, et al. [11] works on optimising the components size of solar water heating system to run a solar air conditioning system. This optimization process comes to achieve continuous optimum system by using the optimum value for each factor affecting the system performance. The results showed that the optimum storage tank when the amount from the auxiliary heater is minimum. Therefore, the optimum collector area needed to be determined based on the electricity saving which comes from using solar system. Rayegan, et al. [12] performed a study to determine the optimal temperature and collector type for power generation using SORC for net-zero energy commercial building. The study investigates the effect of the solar system on 11 working fluids for two temperature level 85 °C and 135 °C. The simulation results showed that the best collector area required is 722.54 m^2 and 728.16 m^2 low temperature evacuated tube solar collector with cyclohexane and isopentane as working fluid of ORC respectively. In addition, the result showed that the average incident solar radiation and the variation of power generation per collector unit has the same pattern. Authors also mention that the CPC collectors could be a good choice to reduce the required area, but the high cost of CPC collectors could be the main barrier to use it residentially or commercially.

However, solar energy is the best option for ORC systems due to their high capacity and lower replacement time. [13]

2.3 Biomass Organic Rankine Cycle

Ten years ago, there were around 100 facilities used biomass around the world as a source of heat in ORC (47% of them regarding quantity and 5.5% regarding power) with total capacity 88 MWe [14]. Traditional steam cycles rarely used in biomass projects due to the high pressure and temperature required for higher output and optimal efficiency, which leads to increase the engineering and maintenance cost which means that the capacity should be more than 5 MWe to be economically feasible, but ORC has low maintenance cost compared with using conventional Rankine Cycle. [15]. Ordinarily, the heat is transferring from the exhaust gases of combustion to the working fluid using a thermal oil to avoid overheating and make the heat exchange at atmospheric pressure, hence a suitable control. However, the working fluid should be selected carefully in ORC with biomass combustion because many working fluids has a quite higher vapour pressure. Therefore, the temperature is limited in this process to about 330 °C [16], and the turbine inlet temperature could be closed to flame temperature.

The commercial modules of ORC cost around 1600 €/kWe for 1 MWe used for biomass applications [17]. Duvia, et al. [18] show that the ORC cogeneration units are feasible when the price of electricity around 10 c€/ kWh for power plant larger than 1.5 MWe and at least 14 c€ / kWh for 1 MWe power plants. Meanwhile, Algieri, et al. [19] investigated the energetic performance and the feasibility of Combined Heat and Power (CHP) biomass ORC for a single-family. The result demonstrated that the biomass ORC – CHP systems very interested in single-family applications. Specifically, the payback period is eight years when the specific cost of the ORC is around 10,000 €/kWe and goes down by half when it becomes 5,000 €/kWe. In addition, Eyidogan, et al. [20] investigated the feasibility of ORC technology in turkey from the technical and economical point of view. The study shows that the feasibility of 1 MWe biomass ORC – CHP plants with payback period 2.7 years and annual benefits reaches 551,500 €/year.

Using of ORC in biomass combustion process has an advantage, which is appropriate for decentralised applications, and it is a proven technology for power generation up to 1 MWe [21]. The electrical efficiency for this process lies between 6% - 17%. In small scale, the cost of power generation is not competitive and to make sure the profitability from these types of investments the CHP generation is required [22].

Using the gasification process with ORC to generate electricity is more profitable compared with direct combustion process due to a higher power to thermal ratio, but the gasification process has higher Initial cost (about 75%) and higher O&M cost (about 200%) [23]. A study conducted by Rentizelas, et al. [21] shows the cost difference between gasification and direct combustion processes. The results showed that ORC has significantly lower O&M cost than gasification and it offers a solution for lower initial investment. On the other hand, there is a lack of standards of gasification process that could increase the risk associated with reliability and performance that may affect the decision of the investors [24], unlike ORC technology which is a proven technology and used. Generally, in a small-scale ORC power plant (few kW) control systems are preferred to reduce the operation cost by avoiding the need of an on-site operator. [25]

Finally, the cost ORC technology is not widely depated in the scientific literature, and general capital cost functions of ORC are difficult to find, and the available data is for a specific field. Manufacturers and suppliers are the only one who can provide reliable economic data, but generally, this information kept reversed and rarely conveyed.

Chapter 3

SYSTEM DESCRIPTION

3.1 Solar Organic Rankine Cycle

The layout of the SORC power plant under investigation is shown in Figure1. The proposed system consists of solar hot water (SHW) part with thermal storage tank and power generation part which is Organic Rankine Cycle unit. Evacuated tube solar collectors are utilised for capturing the solar energy and using the auxiliary gas heater. In the current configuration 35 kW, 65 kW and 110 kW ORC units from ElectraTherm company, USA are used.

An array of evacuated tube solar collectors coupled with a thermal storage tank is the primary heat source in the SORC system. The hot water is transferred to the evaporator of ORC. The working fluid leaves the evaporator at high pressure and enters the turbine to produce power. It then condenses as a saturated liquid in the condenser. The seawater is proposed to use in the condenser. A recuperator is used as a heat recovery unit to heat the working fluid before entering the evaporator to improve the cycle efficiency. The auxiliary unit used to keep the water temperature supplied to the ORC evaporator optimum and work all the time. This described process is shown in the T-S diagram in Figure 2. It should be noted that the working fluid used in the ORC unit is R245fa.

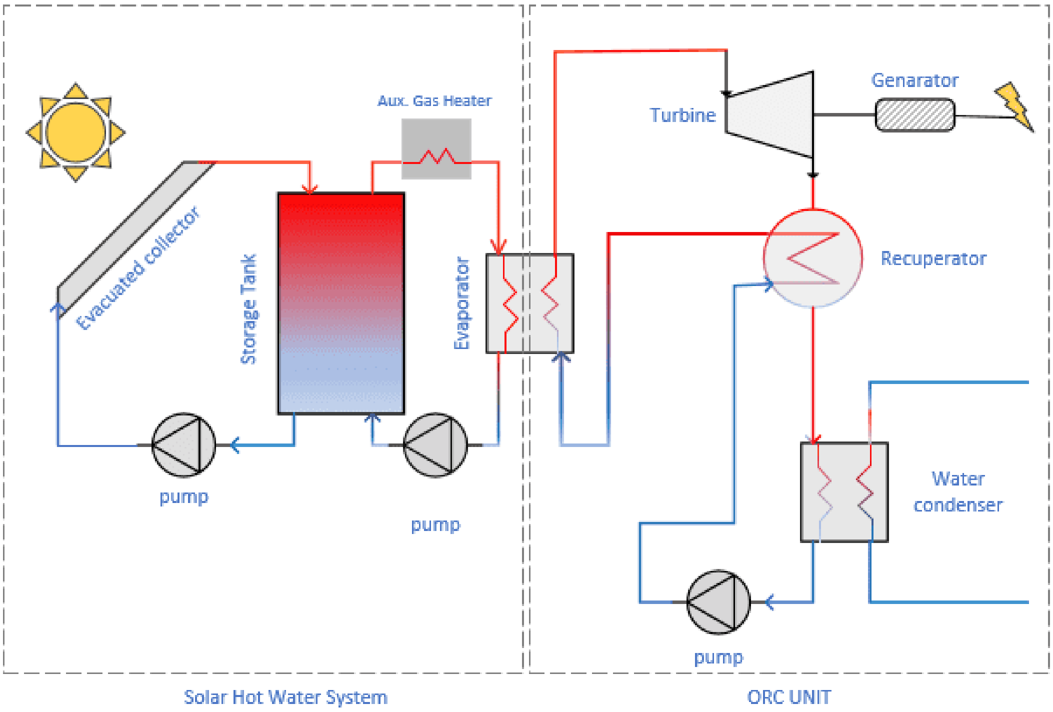


Figure 1: Proposed system layout

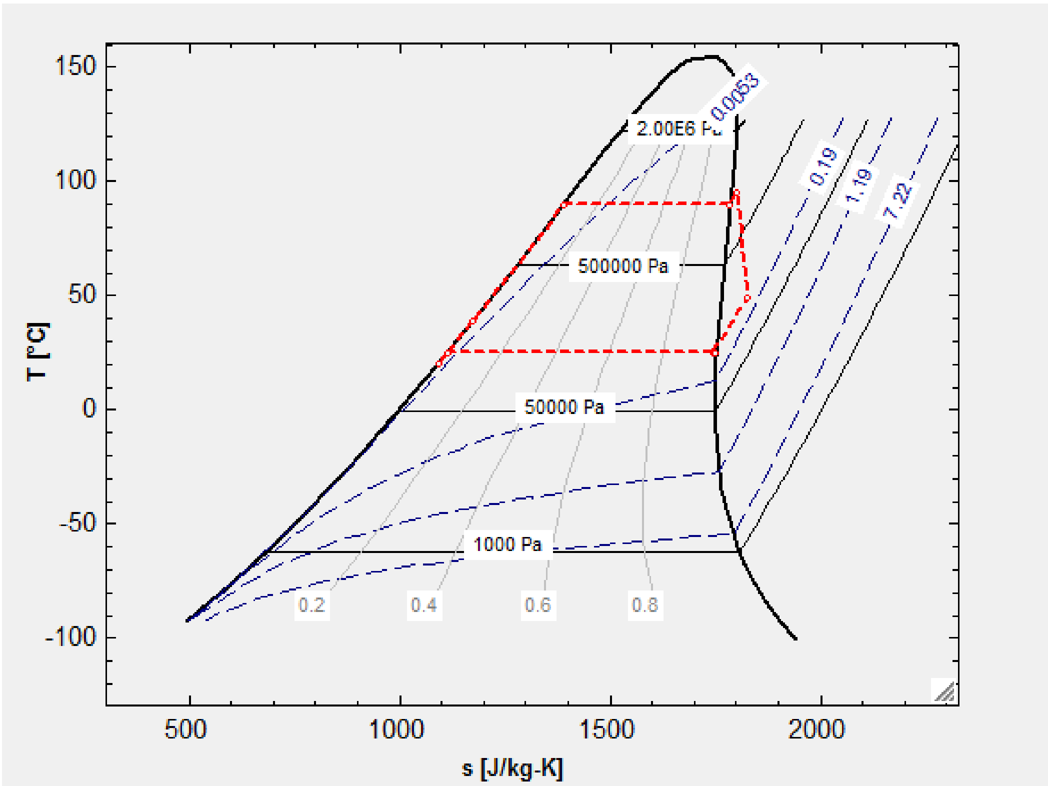


Figure 2: T-S diagram of the ORC (R245fa) used in the proposed system

3.2 The Main Components of System

3.2.1 ORC Unit

ElectraTherm is one of the major companies in the area of emission-free electricity from low-grade heat sources (77-90 °C) [26]. The unit used in this research is ORC stand-alone configuration type (model: ss-4200) with power output up to 35 kW. The unit specifications are shown in Table 1 below:

Table 1: ORC unit specification

Rating power	35 kW, 380-500 V
Ambient operation temperature	0-38 °C
Hot water input range	77-116 °C
Max efficiency	9 %
Hot water Flow rate range	3.2-12.6 Liter/s
Cooling water input range	4-65 °C
Cooling water flow rate range	13.9 Liter/s
Working fluid	R245fa (pentafluoropropane)
weight	3195 kg

Figure 3 shows the power output variation with the water temperature and flow rate. As can be seen, to get the maximum power from the ORC (35 kW) the hot water flow rate should be 6 litres/s at a water temperature of 99 °C.

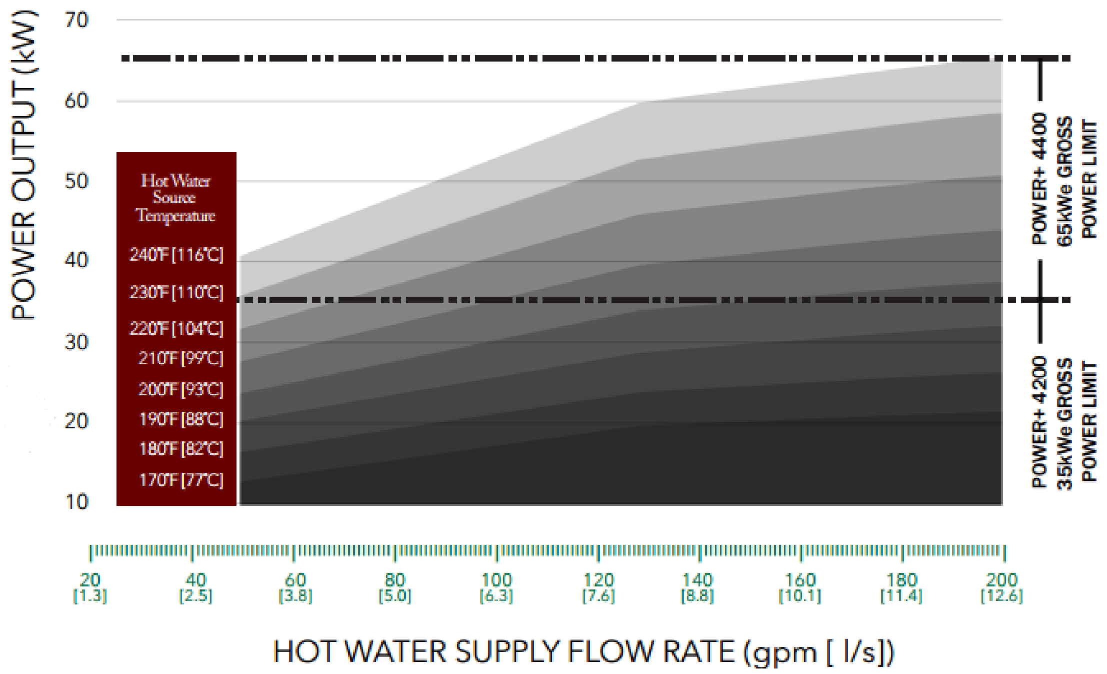


Figure 3: ORC power output with the temperature of the hot water and flow rate [26]

3.2.2 Evacuated Tube Collectors

Evacuated tube collectors are used in solar hot water systems as a heat source and it has a much higher temperature for a much longer time than flat plate collectors. Evacuated collectors consist of some parallel transparent glass tubes evacuated from the air connected to a header pipe as shown in Figure 4. The rounded shape of the glass makes the sun's rays perpendicular to the absorbing tubes most of the day. Furthermore, removing air between the two tubes acts as an insulator and reduce any heat loss to the surrounding.

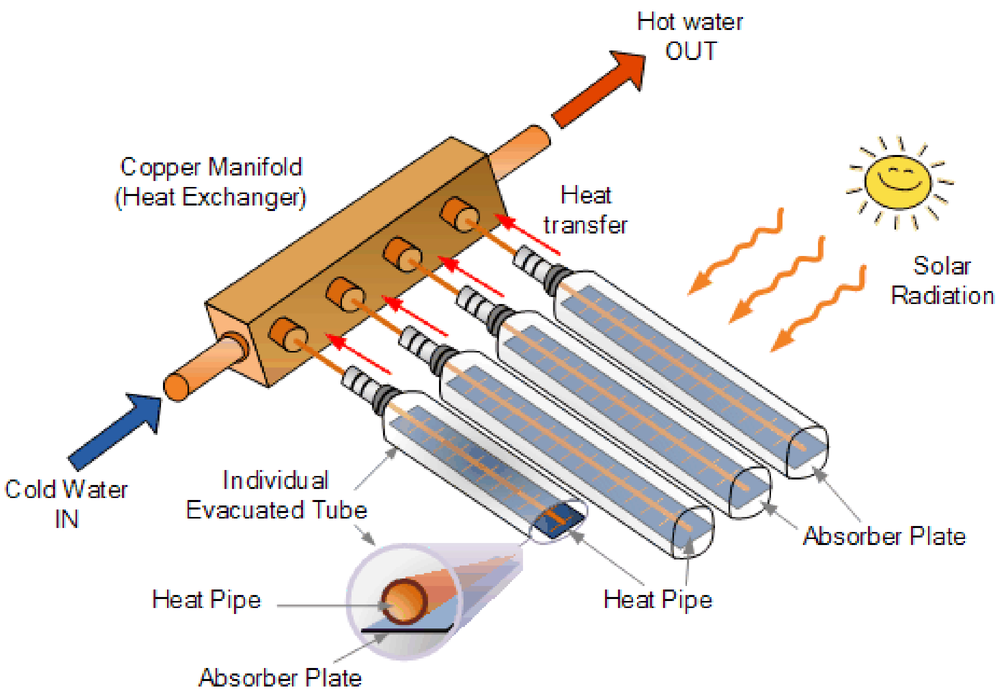


Figure 4: Evacuated tube collector configuration [27]

ORC is used to adapt low-temperature heat source for electricity generation. However, evacuated tube solar collectors can provide hot water/glycol at a temperature reaching more than 120 °C and using this hot fluid as a heat source of small-scale ORC for power generation and hot water production makes the system compete with other solar systems for small-scale applications [28]. The specifications of the evacuated tube collector used in the simulation process shown in Table 2.

Table 2: Evacuated tube collector specifications

Total Area	2.660 m^2
Aperture Area	1.49 m^2
Max. Working Pressure	10 Bar
Max. Working Temperature	120°C
$F_R$ta	0.733
$F_R U_L$	2.237 W/m^2K
IAM	0.96

3.2.3 Auxiliary Gas Heater

The auxiliary gas heater is proposed with the model to increase the water temperature to the set value when the solar collector field cannot reach that temperature, and this process often occurs at night or sometimes during wintertime.

3.2.4 Storage Tank

An insulated hot water storage tank is used to store the heat coming from the solar collectors. The storage tank volume is a critical issue in the solar hot water system and should be optimised to save energy and money.

3.2.5 Pumps

The pumps are used to circulate the hot water between the solar collector and the storage tank and between the storage tank and the evaporator of the ORC.

3.3 Biomass Driven Organic Rankine Cycle

The layout of the biomass power plant under investigation is shown in Figure 5. The biomass fuel is fed into the feeder to take it to the combustion chamber of the boiler, the combustion gases heat the water using a heat exchanger and then the hot water goes directly to the ORC evaporator. The fuel choice should be made based on availability and individual needs. However, in this study, wood chips, logs, grass, and agricultural residue are considered as biomass fuel due to their availability in Cyprus. The heating value of these different fuels varies between 13 -17 MJ/kg. A value of 15 MJ/kg is considered in the economic calculations.

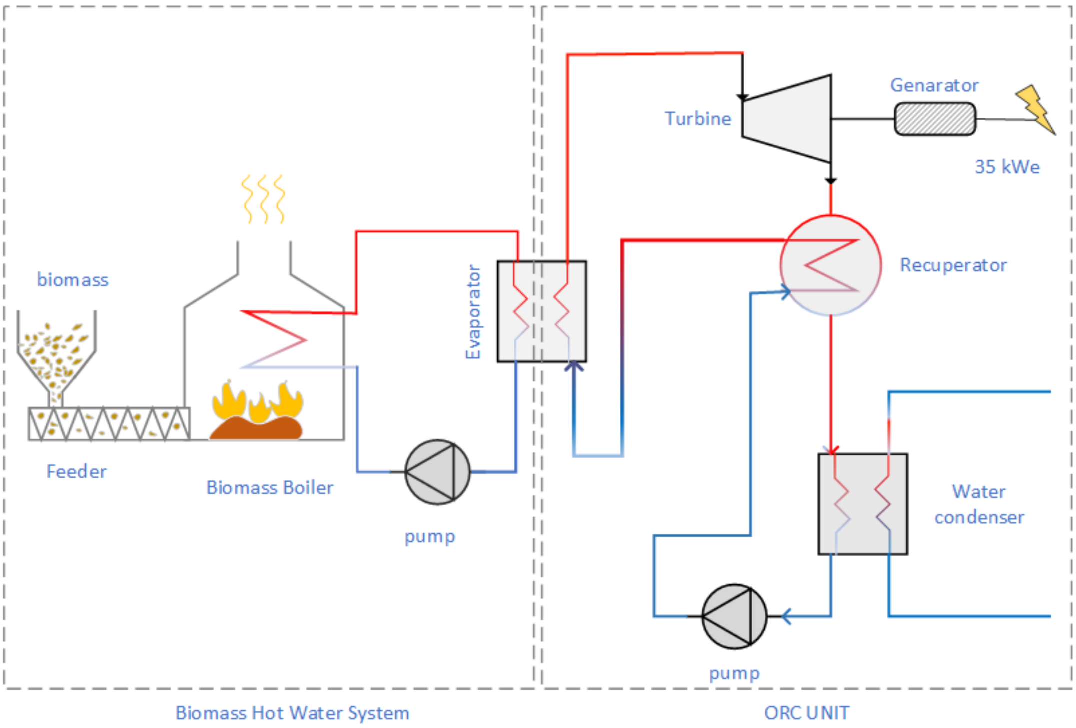


Figure 5: Biomass driven ORC power plant system layout

The available commercial biomass boilers in the market are manufactured for large scale applications and the lack of technical information about this component is an obstacle in determining the feasibility. Fortunately, there are some suppliers of biomass boiler such as Glenwood [29] for water heating. The chosen biomass boiler's technical data are shown in Table 3.

Table 3: Specific properties of the chosen biomass boiler [29]

Name	Glenwood industrial multi-fuel boiler
BTU Output	Up to 1,000,000
Thermal Efficiency	Up to 85 %
Biomass fuel	Wood chips, Logs, grass
Maximum working temperature	120 °C
water capacity	400 Gal.

Chapter 4

ENERGY PERFORMANCE SIMULATIONS

4.1 System Optimization

System Advisor Model software (SAM, USA 2005) is used to simulate the solar system. SAM is a software developed by the National Renewable Energy Laboratory (NREL) in collaboration with University of Wisconsin's Solar Energy Laboratory. A number of runs are performed to optimise the factors affecting the performance of the system. Larnaca weather data is considered in the simulation.

4.2 Mathematical Model

The energy equations used with SAM software are illustrated below.

Solar irradiance transmitted on tilted surface is

$$I_T = I_i \sin(\alpha + \beta) \qquad (1)$$

Where, I_T is the solar irradiance on tilted surface, I_i is the total incident solar radiation α and β are the elevation angle and tilt angle.

The useful energy collected by the collector is

$$\dot{Q}_{useful} = F_R\, A_c\, (I_T\, \tau\alpha - \ U_L\, (T_{f,i} - T_o) \qquad (2)$$

Where, $F_R\tau\alpha$ is optical losses coefficient, $F_R U_L$ is thermal losses coefficient, I_T is the transmitted solar radiation on tilted surface, $T_{f,i}$ is the inlet temperature of the fluid and T_o is the outside temperature.

The delivered energy by the solar collectors is calculated at the output of the storage tank as follows

$$\dot{Q}_{deliv} = \dot{m}\, Cp\, (T_{deliv} - T_{main}) \quad (3)$$

Where, $\dot{m}$ is the mass flow rate, Cp is the heat capacity, T_{deliv} is the delivered temperature, and T_{main} is the main temperature.

The energy required from the auxiliary to raise the water temperature to the set temperature is

$$\dot{Q}_{Aux} = \eta_{aux}\, \dot{m}\, Cp\, (T_{set} - T_{deliv}) \quad (4)$$

Where, $\dot{Q}_{Aux}$ is the energy needed from auxiliary unit to reach the set temperature, η_{aux} is the auxiliary unit efficiency, T_{set} is the set temperature.

The amount of energy that would be needed if solar energy was not used is

$$\dot{Q}_{Aux,only} = \eta_{aux}\, \dot{m}\, Cp\, (T_{set} - T_{main}) \quad (5)$$

Where, $\dot{Q}_{Aux,only}$ is the energy required from the auxiliary to reach the set temperature if the solar energy was not used.

The amount of the energy saved by use solar collectors is

$$\dot{Q}_{saved} = \dot{Q}_{Aux,only} - \dot{Q}_{Aux} - P_{pump} \quad (6)$$

Where, $\dot{Q}_{saved}$ is the energy saved by the use of solar collector, P_{pump} is the pumps power.

The solar fraction, which is the ratio of energy saved by the solar energy system to the total energy required if the solar energy was not used is expressed as

$$SF = \frac{\dot{Q}_{saved}}{\dot{Q}_{Aux,only}} \quad (7)$$

The solar tank heat losses to the room is

$$\dot{Q}_r = U\, A_t\, (T_t - T_r\,) \qquad (8)$$

Where, U is the heat loss coefficient, A_t is the tank surface area, T_t is the average temperature of the water in the tank, and T_r is the room temperature.

The mean tank temperature is given as follows during the heat collection process.

$$\frac{dT_t}{dt} = \frac{\dot{Q}_{useful} - \dot{Q}_r + \dot{m}\, Cp\, (T_t - T_{main}\,)}{\rho\, V_t\, Cp} \qquad (9)$$

Where, $\dot{Q}_r$ is the heat loss to the room, ρ density of the water, V_t tank volume.

The temperature of the water in the cold side of the tank is

$$\frac{dT_{cold}}{dt} = \frac{\dot{Q}_{r,cold} + \dot{m}\, Cp\, (T_{main} - T_{cold}\,)}{\rho\, V_{cold}\, Cp} \qquad (10)$$

Where, $\dot{Q}_{r,cold}$ is the heat loss from the cold side of the tank, and V_{cold} is the cold side volume.

The temperature of the water in the hot side of the tank is

$$\frac{dT_{hot}}{dt} = \frac{\dot{Q}_{r,hot}}{\rho\, V_{hot} Cp} \qquad (11)$$

Where, $\dot{Q}_{r,hot}$ is the heat loss from the hot side of the tank, and V_{hot} is the cold side volume.

The last three equation (9,10,11) are approximated for each hour.

4.3 System Optimization Results

4.3.1 The Collector Tilt Angle

Tilt angle of the solar collectors is the key to an optimum energy yield. When the sun's rays are perpendicular to the solar collectors, it will become more efficient and tracking systems are used for that purpose, but it makes the system more expensive. The fixed collectors (nonadjustable) should have optimum fixed angle to ensure that the sun rays are perpendicular for most of the time. The solar fraction and the amount of heat needed from the auxiliary gas heater for various tilt angles of the collector are shown in Figure 6. The tilt angle becomes optimum when the amount of heat from the auxiliary unit is minimum, and the solar fraction is maximum which is 45° for the evacuated tube solar collector.

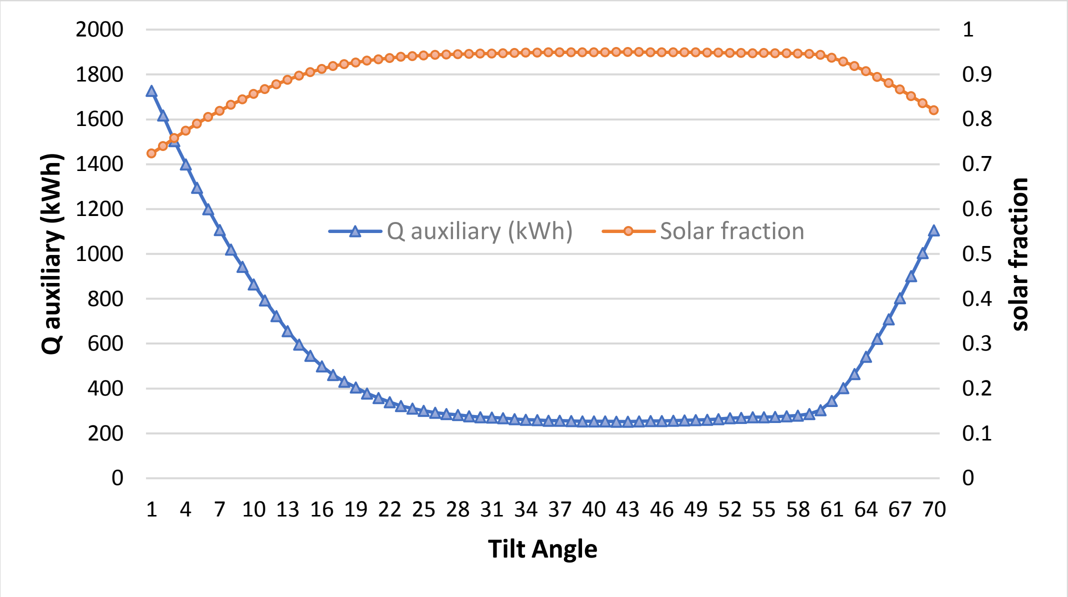


Figure 6: Effect of collector tilt angle on solar fraction and heat from the auxiliary

4.3.2 Pump Flow Rate

The effect of the pump flow rate on the solar fraction is shown in Figure 7. The system flow rate should be 6 litre/s to get the maximum power from the 35 kW ORC unit, and as observed, the system flow rate does not have a significant effect on the solar fraction. The optimum value comes at 0.5 kg/s where the solar fraction is maximum. Since at 6 kg/s the change in the solar fraction value is very small, so the system can work with flow rate 6 kg/s without a major effect on the energy collected from the solar collectors.

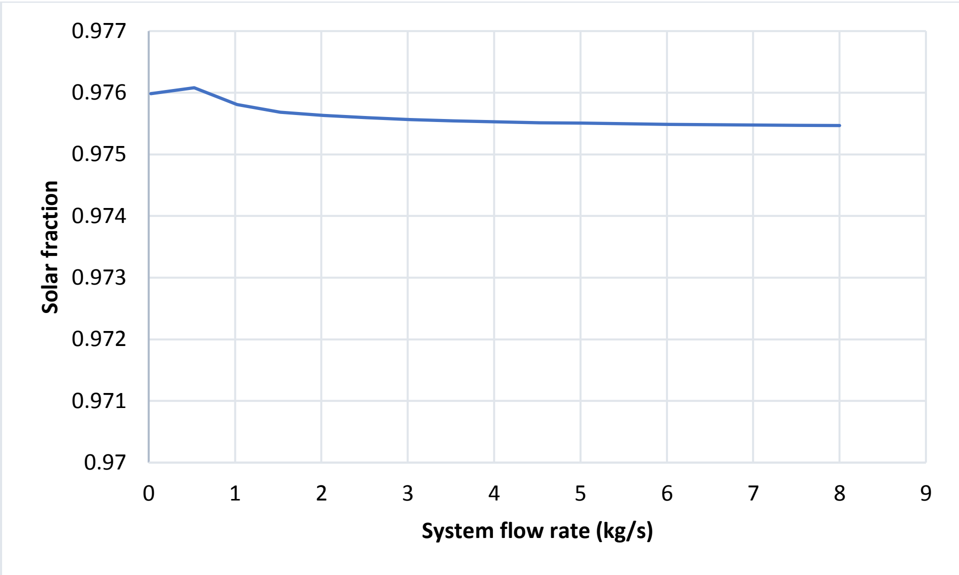


Figure 7: Effect of system flow rate on solar fraction

4.3.3 The Storage Tank Volume

Storage tank volume plays a vital role in the optimisation of the system. The amount of heat required from the auxiliary unit for different storage tank volume is shown in Figure 8. As can be seen, the optimum value of the storage tank volume is 4 m^3.

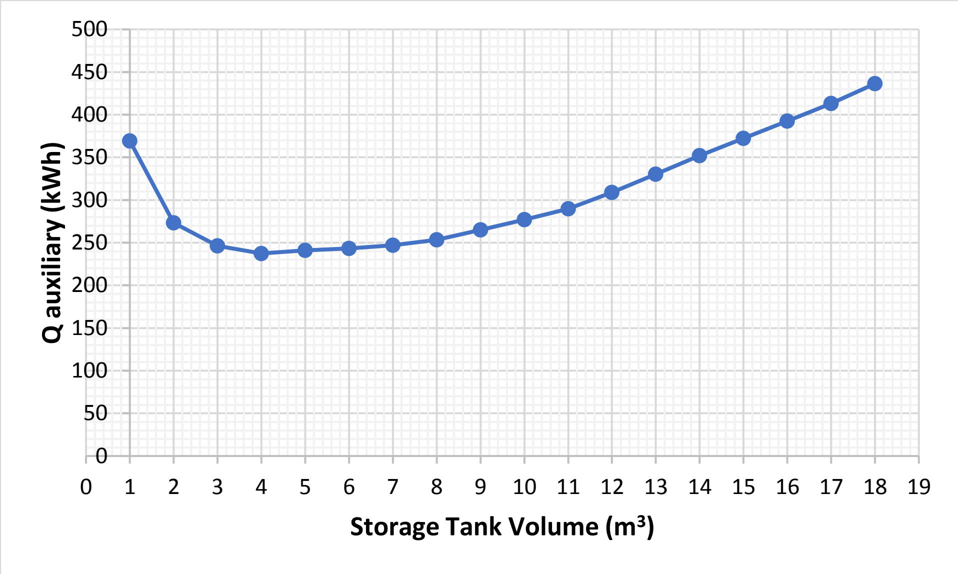


Figure 8: Effect of storage tank volume on the heat from the auxiliary unit

4.3.4 The Collector Area

The amount of heat from the auxiliary heater against the collector area is evaluated. As expected, the higher the collector area, the less the auxiliary heat needed as indicated in Figure 9. Therefore, the optimum value of the collector area needs to be decided from an economic point of view. As seen in Figure 10, as the area of the collector increases the energy saved by the solar system becomes constant after 100 m^2 and the solar fraction as well. That means increasing the area of the collector more than 100 m^2 will increase the cost of the investment without any additional energy saving so the optimum value of the collector area is 100 m^2.

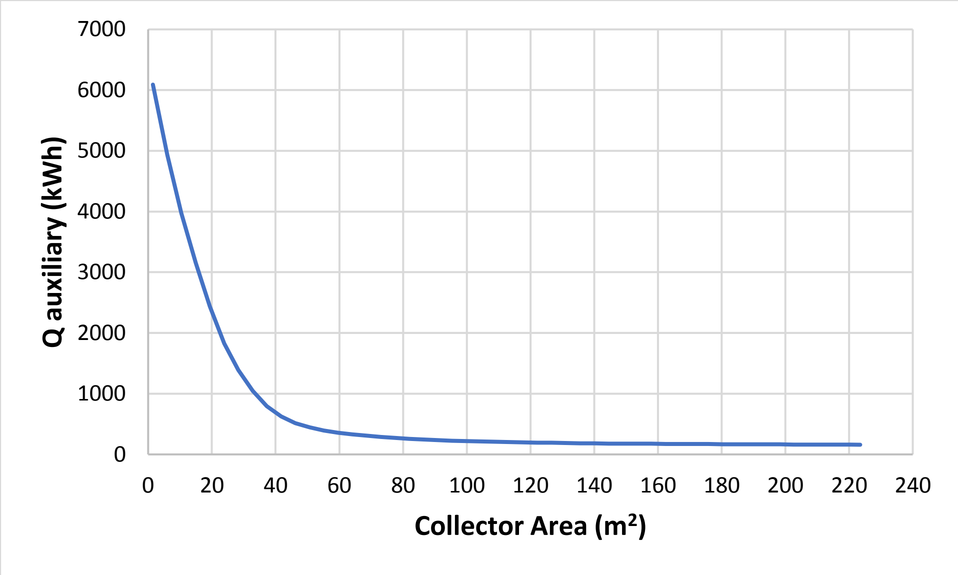


Figure 9: The collector area against the heat from the auxiliary unit

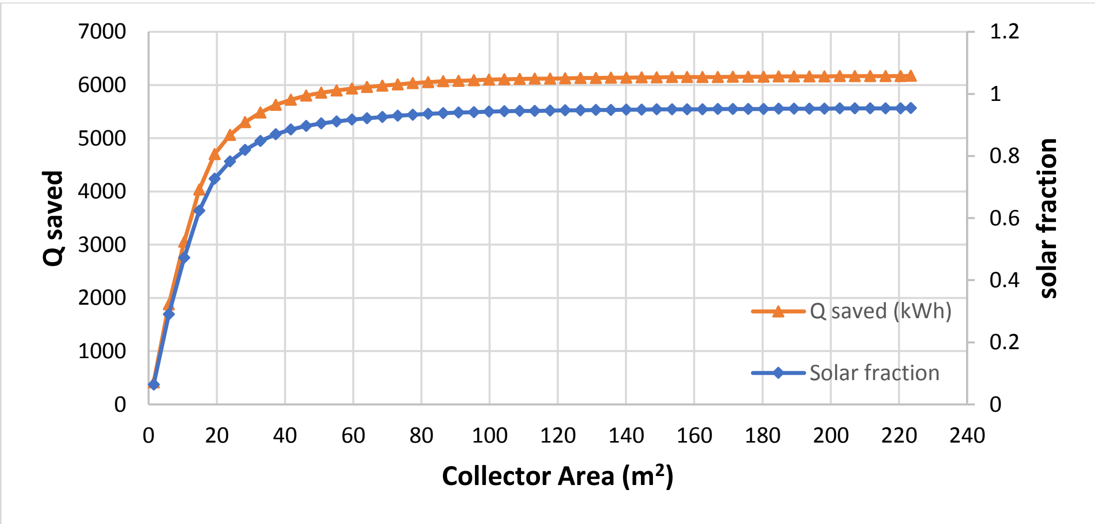


Figure 10: The collector area against energy saved by the system

4.4 System Simulation Results

The hot water solar system is simulated using SAM software to evaluate the water temperature. As mentioned in the previous section, to get the maximum power from the ORC unit, the inlet hot water temperature should be 99 °C with flow rate 6 litres/s. The optimum value of each component was performed in the previous section also used in the simulation, and the results are presented as follow:

4.4.1 Collector System Performance

The variation of the outlet water temperature from the solar collector and the solar energy gain for 1st July is presented in Figure 11. The temperature of the water inside the collector starts to increase at 8:00 am when the sun starts to rise. The rising of the temperature increases dramatically to reach the maximum value at around 12:00 pm and then the temperature starts to decrease exponentially. The system should be pressurised to prevent the evaporation of water.

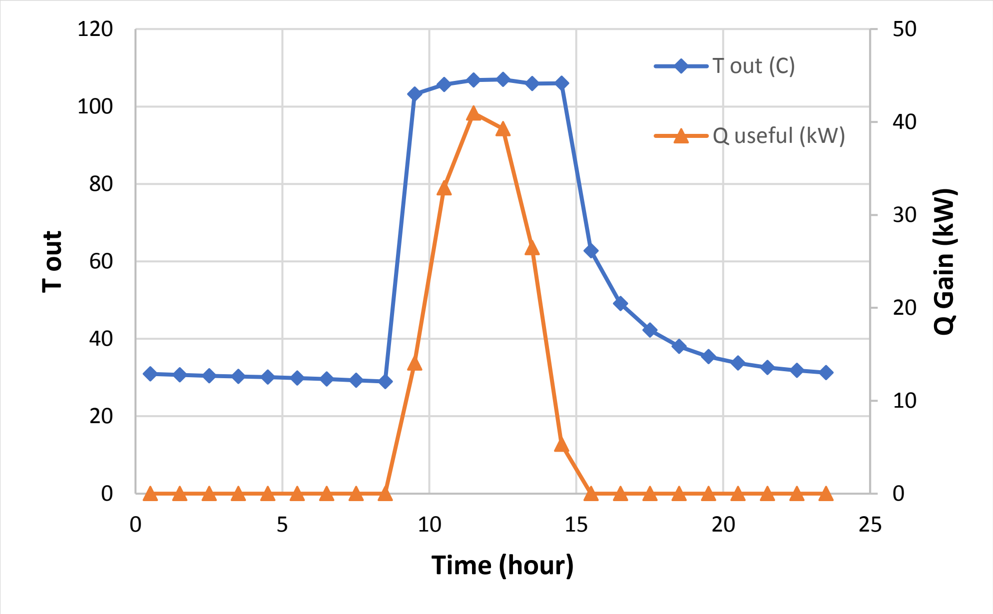


Figure 11: Hourly solar collector temperature and energy gain (1st July)

4.4.2 Storage Tank

The variation of the water temperature from the storage tank is shown in Figure 12. As can be seen from Figure 12, the load temperature never falls below 100 °C which means the tank should be pressurised to avoid steam generation.

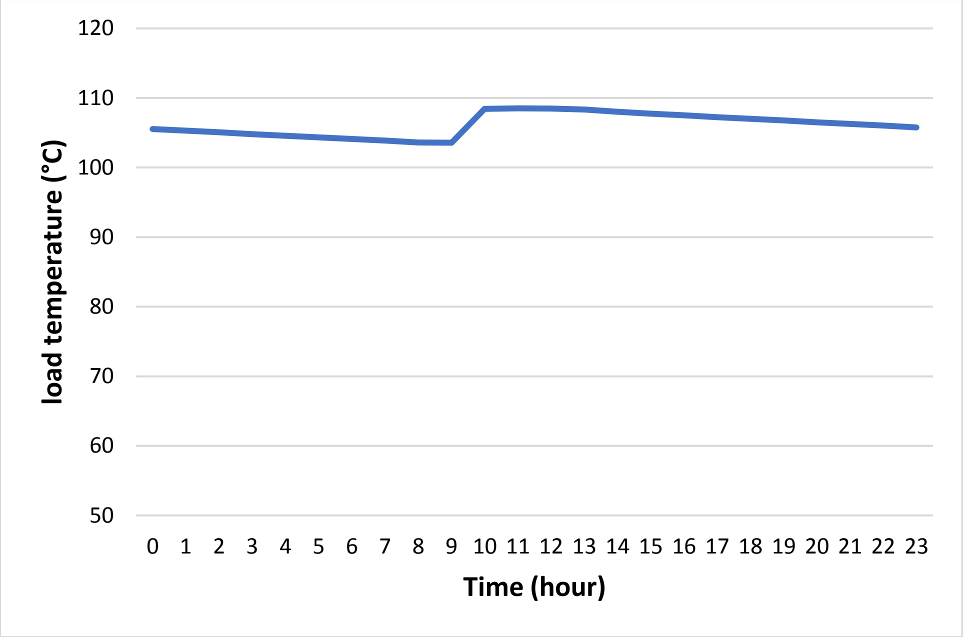


Figure 12: Hourly temperature of the hot water in the storage tank (1st July)

4.4.3 Auxiliary Gas Heater

The auxiliary gas heater is used to maintain the outlet set temperature. The heater will be switched on automatically when the temperature is less than the set temperature. SAM software assumes that an electric gas heater is used to raise the water temperature to the set temperature, but it also provides a macro code to calculate the energy needs from an auxiliary gas heater based on the burning efficiency and the tank losses. The simulation results show that when the auxiliary gas heater’s thermal efficiency is 0.85, the amount of energy needed to reach the set temperature is 1636 kWh/year.

It is worth mentioning that the same optimisation procedures are performed for the other scenarios (65 kW and 110 kW) in Appendix A. The optimisation and simulation summary of the proposed solar ORC power plant components are shown in Table 4.

Table 4: The optimization and simulation results summary

Component	**Size**		
ORC capacity (kW)	35	65	110
Evacuated tube collector area (m^2)	100	149	194
Storage tank volume (m^3)	4	7	3
31 kW Auxiliary gas heater (kWh/year)	1636	1404	1755
Solar Fraction	0.98	0.98	0.97

Biomass ORC components are biomass boiler and ORC unit connected directly without additional components and there is no need for optimization process.

Chapter 5

ECONOMIC FEASIBILITY ANALYSIS

5.1 Introduction

Economic calculations are performed for different scenarios of power generation using ORC technology to show the feasibility of such systems. The cost of the systems component was taken from the suppliers, some books and publications. Some additional formulas used in the economic calculation are discussed in next section. Calculations were done based on present worth technique.

5.2 Economic Equations

The cost of the gas needed is

$$Gas\ Cost = \dot{E}_{need}(kWh) \times F \times price(\frac{\$}{kg}) \quad (12)$$

Where, $\dot{E}_{need}$ is the energy required from the Auxiliary gas heater in the solar system, $F = 0.074\,\frac{\mathrm{kg}}{\mathrm{kWh}}$ is the factor represent how much energy in 1 kg gas, and the price is considered to be $1\,\frac{\$}{\mathrm{kg}}$ in Cyprus.

To calculate how much money the project saves, equation below is used.

$$\mathrm{Savings} = \mathrm{P\ (kW)} \times \mathrm{H(hour)} \times \mathrm{E}(\frac{\$}{\mathrm{kWh}}) \quad (13)$$

Where, P is the power plant capacity, H is the operating hours, and E is the electricity tariff and it considered to be $0.166\,\frac{\$}{\mathrm{kWh}}$ in Cyprus.

The cost of biomass fuels each year is determined as follows:

$$Biomass\ Cost = \frac{\frac{(\dot{Q}_{th})(\frac{kJ}{s})}{\eta_{th}}}{HV(\frac{kJ}{kg})} \times (3600)\frac{s}{hr} \times (H)\frac{hr}{yr} \times (cost)\frac{\$}{kg} \quad (14)$$

Where, $\dot{Q}_{th}$ is the thermal power needed in ORC (from data sheet of ORC), η_{th} is thermal efficiency of biomass boiler, HV is the heating value of biomass (considered 15000 kJ/kg), H is the operating hours, and the cost of biomass is taken as $0.01\frac{\$}{kg}$

Levelized Cost of Energy (LCOE) determined using equation below

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I+M+F}{(1+i)^t}}{\sum_{t=1}^{n} \frac{E}{(1+i)^t}} \quad (15)$$

Where, I is the initial cost, M is the maintenance cost, F is the fuel cost, i is discount rate, E is the energy produced, and t is the year.

Net Present Value (NPV) is calculated using equation below to determine if the investment of the project will yield net loss or a net profit.

$$NPV\ (i, n) = \sum_{t=0}^{n} \frac{R_t}{(1+i)^t} \quad (16)$$

Where, R_t is the net cash flow after the initial investment, i is discount rate, t is the year.

Internal Rate of Return (IRR) calculated using equation below.

$$IRR\ (IRR, n) = \sum_{t=0}^{n} \frac{R_t}{(1+IRR)^t} = 0 \quad (17)$$

Where, R_t is the net cash flow after the initial investment. IRR equal i when the NPV equal zero.

Saving to Investment Ratio (SIR) is expressed as

$$SIR = \frac{\sum PV\ Annual\ saving}{\sum PV\ life\ cycle\ Investment} \quad (18)$$

Where, PV means the present value.

Simple Payback Period determined as follows

$$SPP = \frac{I}{Annual\ saving} \quad (19)$$

Where, I is the initial investment.

An excel sheet is prepared in order to perform the economic calculations (see Appendix C)

5.3 Solar Organic Rankine Cycle Power Plant

The cost analysis calculations of the SORC power plant were performed for different capacities, 35 kW, 65 kW and 110 kW respectively. Table 5 shows the economic calculations of proposed system (35 kW SORC power plant) with evacuated tube and auxiliary gas heater. The cost of the components collected from the suppliers of these components and an average value is taken. The other values such as construction cost and insurance were taken from related publications and books. Table 6 and Table 7 show the economic calculations for 65 kW and 110 kW power plant capacity and the same economic values considered in these calculations. It is worth mentioning that the proposed systems should be automated which means labour cost considered in these calculations is for monitoring the system and doing maintenance but for biomass system, it is different because the system needs to be fed with biomass fuel which needs manual work.

5.3.1 35 kW Power Plant

Table 5: The cost analysis of 35kW SORC power plant

Units / Ref.	Description	Cost
Operation hours		8000
Evacuated tube collectors / [30-32]	$\text{collectors cost} = 100\ \text{m}^2 \times 185\frac{\$}{\text{m}^2}$	18 500 $
ORC unit (35 kWe) / [26]	(The price from ElectreTherm company including shipping cost)	189 587 $
Storage Tank (4000 liter) / [31,32]	$\text{Tank cost} = 2.3\frac{\$}{\text{liter}} \times 4000\ \text{liter}$	9 200 $
Aux. gas heater, gas and pumps / [32-34]	• $\text{Gas cost} = 1636\ \text{kWh} \times 0.074\frac{\text{kg}}{\text{kWh}} \times 1\frac{\$}{\text{kg}}$ • $\text{pump cost} = 2\ \text{pumps} \times 330\frac{\$}{\text{pump}}$ • $\text{Aux. Cost} = 1\ \text{gas heater} \times 1000\ \$$	1 781 $
Construction and engineering cost (10% equipment. cost) / [35]	10% from previous component Cost	21 907 $
Others (control parts, pipes, special equipment) (1.8% of Investment cost) / [35]	1.8% from the total	4 338 $
Total capital cost		**245 313 $**
Labor cost/year (doing maintenance and monitoring system) / [35]	$\text{LC} = 1.5\frac{\$}{\text{hr}} \times 8000\frac{\text{hr}}{\text{yr}}$	12 000 $
O&M equipment cost (1% of investment cost) / [35]	1% from total capital cost	2 453 $
Insurance (0.6% of investment cost) / [30,35]	0.6% from capital cost	1 472 $
Total operating & maintenance cost		**15 925 $**

5.3.2 65 kW Power Plant

Table 6: The cost analysis of 65 kW SORC power plant

Units	Description	Cost
Operation hours		8000
Evacuated tube collectors	$\text{collectors cost} = 149\ \text{m}^2 \times 185 \frac{\$}{\text{m}^2}$	27 565 $
ORC unit (65 kWe)	(The price from ElectraTherm company including shipping cost)	219 924 $
Storage Tank (7000 liter)	$\text{Tank cost} = 2.3 \frac{\$}{\text{liter}} \times 7000\ \text{liter}$	16 100 $
Aux. gas heater, gas and pumps	• $\text{Gas cost} = 1404\ \text{kWh} \times 0.074 \frac{\text{kg}}{\text{kWh}} \times 1 \frac{\$}{\text{kg}}$ • $\text{pump cost} = 2\ \text{pumps} \times 330 \frac{\$}{\text{pump}}$ • $\text{Aux. cost} = 1\ \text{gas heater} \times 1000\ \$$	1 763 $
Construction and engineering cost (10% equipment. cost)	10% from previous component Cost	26 535 $
Others (control parts, pipes, special equipment) (1.8% of Investment cost)	1.8% from the total	5 250 $
Total capital cost		**297,137 $**
Labour cost/year (doing maintenance and monitoring system)	$\text{LC} = 1.5 \frac{\$}{\text{hr}} \times 8000 \frac{\text{hr}}{\text{yr}}$	12 000 $
O&M equipment cost (1% of investment cost)	1% of the total capital cost	2 969 $
Insurance (0.6% of investment cost)	0.6% from capital cost	1 782 $
Total operating & maintenance cost		**16 750 $**

5.3.3 110 kW Power Plant

Table 7: The cost analysis of 110 kW SORC power plant

Units	Description	Cost
Operation hours		8000
Evacuated tube collectors	$\text{Collectors cost} = 194\ \text{m}^2 \times 185\,\frac{\$}{\text{m}^2}$	35 890 $
ORC unit (110 kWe)	(The price from ElectraTherm company including shipping cost)	316 400 $
Storage Tank (3000 liter)	$\text{Tank cost} = 2.3\,\frac{\$}{\text{liter}} \times 3000\ \text{liter}$	6 900 $
Aux. gas heater, gas and pumps	• $\text{Gas cost} = 1755\ \text{kWh} \times 0.074\,\frac{\text{kg}}{\text{kWh}} \times 1\,\frac{\$}{\text{kg}}$ • $\text{pump cost} = 2\ \text{pumps} \times 330\,\frac{\$}{\text{pump}}$ • $\text{Aux. cost} = 1\ \text{gas heater} \times 1600\ \$$	2 390 $
Construction and engineering cost (10% equipment. cost)	10% from previous component Cost	36 158 $
Others (control parts, special equipment) (1.8% of Investment cost)	1.8% from the total	7 159 $
Total capital cost		**404,897 $**
Labour cost/year (doing maintenance and monitoring system)	$\text{LC} = 1.5\,\frac{\$}{\text{hr}} \times 8000\,\frac{\text{hr}}{\text{yr}}$	12 000 $
O&M equipment cost (1% of investment cost)	1% of the total capital cost	4 042 $
Insurance (0.6% of investment cost)	0.6% from capital cost	2 425 $
Total operating & maintenance cost		**18 467 $**

Incomes from the power plant are coming from electricity sale. Saving is calculated with less amount of the electrical output from the plant (31 kW) to consider the fluctuations that could happen to the water temperature and the system flow rate. Furthermore, to consider the downtime of the system during maintenance time. The electricity tariff in North Cyprus is used in the calculation which is 0.16 $/kWh. The economic values that used in the calculation shown in Table 8.

Table 8: Economic values considered in the calculations

Savings	$\mathbf{31\ kW \times 8000 \frac{hr}{yr} \times 0.166 \frac{\$}{kWh}}$
Discount Rate	3%
Depreciation Period	20 years
Residual Value	10% of the capital cost

5.3.4 Results of Economic Calculations

The economic calculations were done using an excel sheet to calculate NPV, SIR, IRR and SPB. As can be seen from Table 9, the proposed solar ORC power plant is economically feasible as NPV is positive value and SIR above 1 and the values increases as the capacity of the plant increases.

Table 9: Economic calculation results of different scales of SORC power plant

Solar Organic Rankine Cycle Power Plant			
Plant Capacity	35 kW	65 kW	110 kW
Net Present Value (NPV)	$154 855	$689 101	$1455 485
Savings-to-Investment Ratio (SIR)	1.3	2.3	3.3
Internal Rate of Return (IRR)	9%	21%	30%
Simple Payback (years)	5.9	3.7	2.9

5.4 Biomass-fired Organic Rankine Cycle Power Plant

Economic calculations for different capacities of biomass-fired ORC power to compare the results with SORC power plant. The cost of the components was taken from suppliers, publications and books.

5.4.1 35 kW Biomass Power Plant

Table 10: The cost analysis of 35 kW biomass fired ORC power plant

Unit / Ref.	Description	Cost
Operation hours		8000
ORC unit (35 kWe)	(The price from ElectraTherm company including shipping cost)	189,587 $
Biomass boiler / [29,40]	(the price from supplier of biomass boilers, average value is taken)	30,000 $ - 40,000 $
Biomass cost/year / [37-39] Equation (14)	$BC = \frac{\frac{450\frac{kJ}{s}}{0.80}}{15000\frac{kJ}{kg}} \times 3600\frac{s}{hr} \times 8000\frac{hr}{yr} \times 0.01\ \frac{\$}{kg}$	10,800 $
Construction and engineering cost (10% equipment. cost)	10% from previous component Cost	23,539 $
Others (pumps, pipes, control system) (1.8% of Investment cost)	1.8% of the total	4661 $
Total capital cost		**263,587 $**
Labor cost/year / [37]	$LC = 2\frac{\$}{hr} \times 8000\frac{hr}{yr}$	16,000 $
O&M equipment cost (1% of investment cost)	1% from total capital cost	2,636 $
Biomass cost/ year		10,800 $
Insurance (0.6% of investment cost)		1,582 $
Total operating and maintenance cost		**31,018 $**

5.4.2 65 kW Biomass Power Plant

Table 11: The cost analysis of 65 kW biomass fired ORC power plant

Unit	Description	cost
Operation hours		8000
ORC unit (65 kWe)	(The price from ElectraTherm company including shipping cost)	219,924 $
Biomass boiler	(the price from supplier of biomass boilers)	30,000 $ - 40,000 $
Biomass cost/year	$\text{BC} = \frac{\frac{650\,\frac{\text{kJ}}{\text{s}}}{0.80}}{15000\,\frac{\text{kJ}}{\text{kg}}} \times 3600\,\frac{\text{s}}{\text{hr}} \times 8000\,\frac{\text{hr}}{\text{yr}} \times 0.01\,\frac{\$}{\text{kg}}$	15,600 $
Construction and engineering cost (10% equipment. cost)	10% from previous component Cost	27,053 $
Others (pumps, pipes, control system) (1.8% of Investment cost)	1.8% from the total	5,356 $
Total capital cost		**302,933 $**
Labor cost/year	$\text{LC} = 2\,\frac{\$}{\text{hr}} \times 8000\,\frac{\text{hr}}{\text{yr}}$	16,000 $
O&M equipment cost (1% of investment cost)	1% from total capital cost	3,029 $
Biomass cost/ year		15,600 $
Insurance (0.6% of investment cost)		1,818 $
Total operating and maintenance cost		**36,447 $**

5.4.3 110 kW Biomass Power Plant

Table 12: The cost analysis of 110 kW biomass fired ORC power plant

Unit	Description	cost
Operation hours		8000
ORC unit (110 kWe)	(The price from ElectraTHerm company including shipping cost)	316,400 $
Biomass boiler	(The price from supplier of biomass boilers)	30,000 $ - 40,000 $
Biomass cost/year	$\mathrm{BC} = \frac{\frac{1600\,\frac{\mathrm{kJ}}{\mathrm{s}}}{0.80}}{15000\,\frac{\mathrm{kJ}}{\mathrm{kg}}} \times 3600\,\frac{\mathrm{s}}{\mathrm{hr}} \times 8000\,\frac{\mathrm{hr}}{\mathrm{yr}} \times 0.01\,\frac{\$}{\mathrm{kg}}$	38,400 $
Construction and engineering cost (10% equipment. cost)	10% from previous component Cost	38,980 $
Others (pumps, pipes, control system) (1.8% of Investment cost)	1.8% from the total	7 718 $
Total capital cost		**436 498 $**
Labor cost/year	$\mathrm{LC} = 2\,\frac{\$}{\mathrm{hr}} \times 8000\,\frac{\mathrm{hr}}{\mathrm{yr}}$	16 000 $
O&M equipment cost (1% of investment cost)	1% from total capital cost	4 365 $
Biomass cost/ year		38 400 $
Insurance (0.6% of investment cost)		2 618 $
Total operating and maintenance cost		**61 383 $**

5.4.4 Economic Calculation Results

The economic values such as discount rate and residual value are taken like that for SORC power plant to determine the feasibility of the biomass ORC power plant at different capacities. The calculation results listed in Table 13.

Table 13: Economic calculation results of different scales of biomass power plant

Biomass-Fired Organic Rankine Cycle Power Plant			
Plant Capacity	35 kW	65 kW	110 kW
Net Present Value (NPV)	-$78 596	$401 334	$810 277
Savings-to-Investment Ratio (SIR)	0.9	1.5	1.6
Internal Rate of Return (IRR)	0%	14%	18%
Simple Payback (years)	6.4	3.7	3.1

As NPV for 35 kW plant capacity is negative, we can conclude that the system is not feasible and this is because of the higher initial investment of the biomass boiler compared with evacuated tube collectors. Also, the operating cost of the biomass power plant is slightly more than that for solar power plant due to the annual cost of biomass fuel while the solar energy is free.

5.5 Sensitivity Analysis

The sensitivity analysis is done for different parameters to see their effect on the economic performance of the solar and biomass ORC power plants. The effect of the ORC power output on the feasibility of both systems (solar and biomass) is performed as shown in Figure 13. For solar ORC power plant, SIR is increasing as the output power increases and it would be not feasible if the power output is less than 30 kW since SIR becomes less than 1. For biomass-fired ORC power plant, the power output should be more than 40 kW to be feasible, and for higher power output SIR is going to be constant.

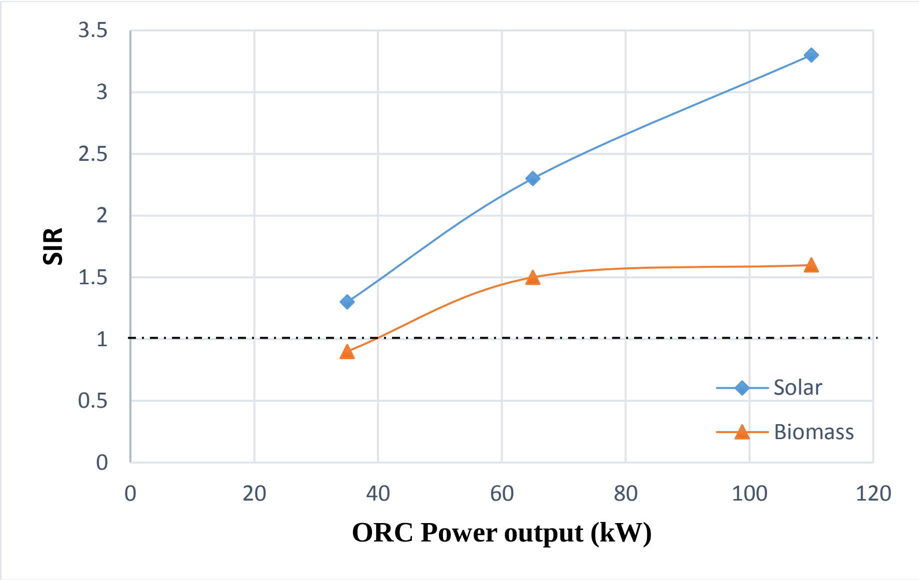


Figure 13: Effect of ORC power output on SIR for 8000 hours of operation

NPV with different power output is also investigated as shown in Figure 14. The relationship between power output and NPV is completely linear for solar ORC power plant which is not for biomass-fired ORC power plant.

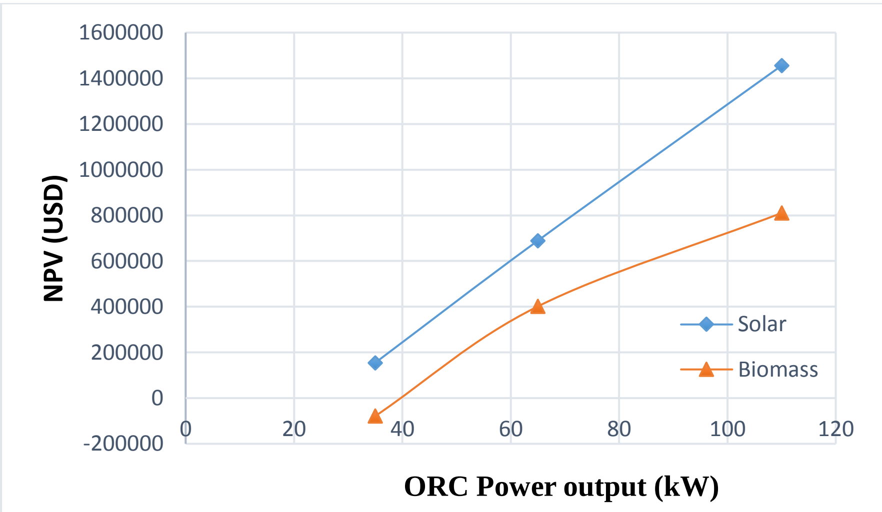


Figure 14: Effect of ORC power output on NPV for 8000 hours of operation

Figure 15 shows the effect of the power output on the IRR for both powerplants. As can be seen, the IRR for the solar power plant is much higher than that for biomass and the difference increases as the output power increases.

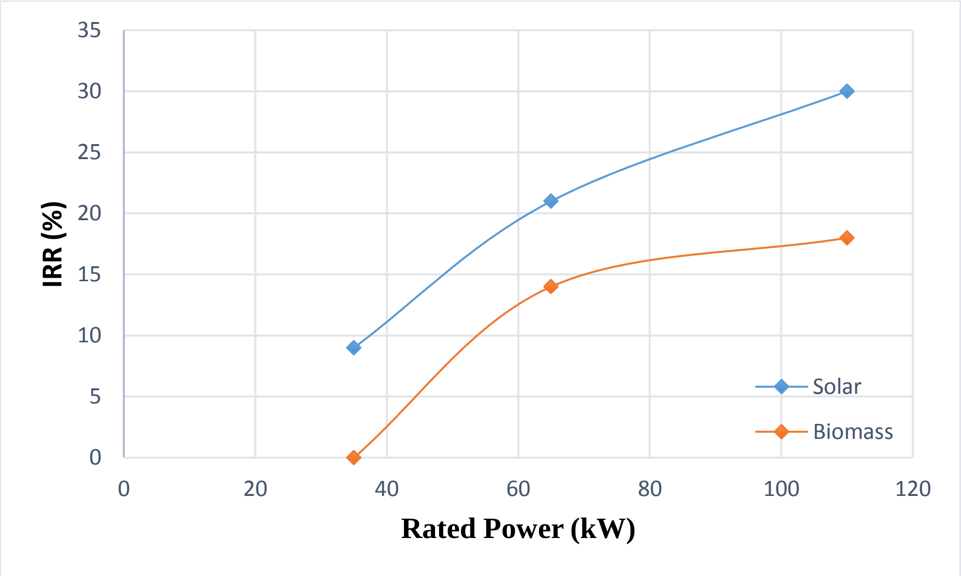


Figure 15: Effect of ORC power output on IRR for 8000 hours of operation

Power plants operation hours is an essential parameter due to its effect on the feasibility of the plants. The economic performance of the plant directly affects the hours of operation. However, the effect of the operation hours on the feasibility of both power plants at different capacities is investigated as shown in Figure 16 and Figure 17. For the solar power plant, the feasible operation hours decrease to half when the capacity of the plant doubled. For higher capacity (110 kW), any change in the operating hours changes the SIR significantly which makes the system much more feasible.

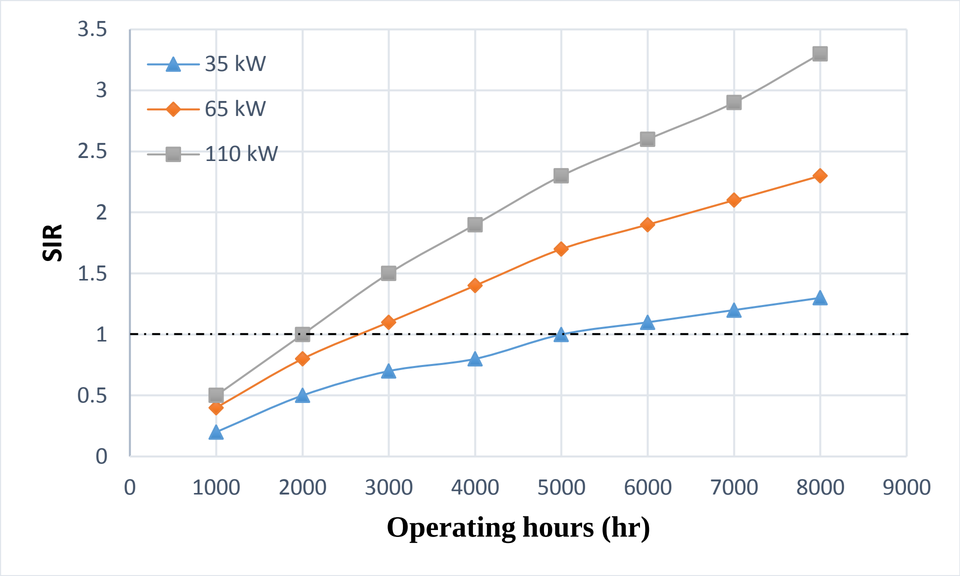


Figure 16: Effect of operation hours on the SIR of SORC power plant

Meanwhile, the effect of operation hours on the biomass power plant has a different pattern. For small capacity (35 kW) the plant can never be feasible, but for higher capacities (65-110 kW) the plant becomes feasible when it is working more than 3000 hr/year.

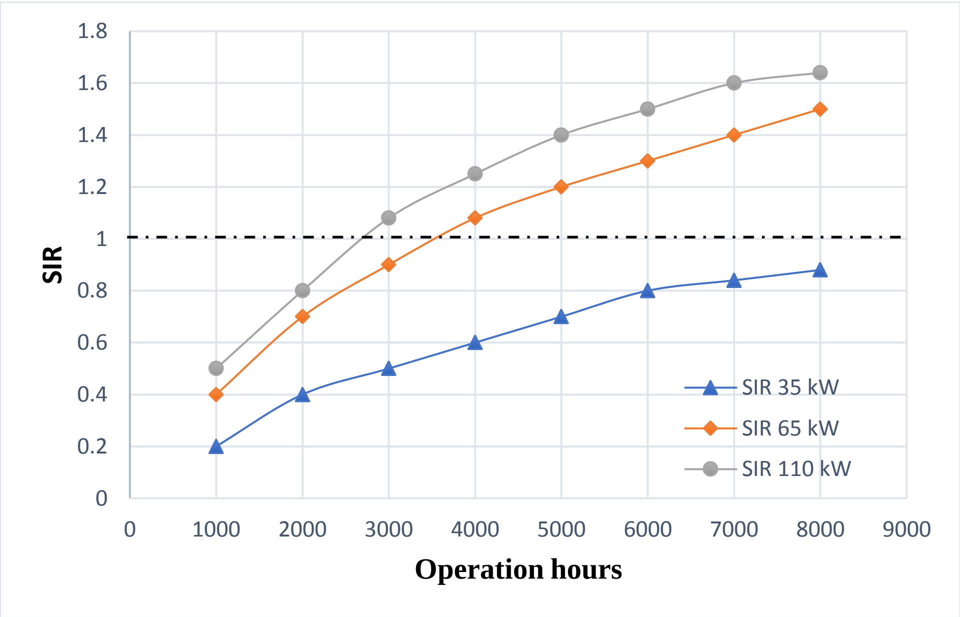


Figure 17: Effect of operation hours on the SIR of Biomass-fired ORC power plant

Levelized Cost of Energy (LCOE) is a measure used to compare different method of power generation by determining the lifetime break-even electricity price. LCOE is an economic assessment of the average total cost divided by the total energy output over the project lifetime. The LCEO of both power plants is investigated in Figure 18. As expected from the previous result, the LCOE for the solar power plant is less than that for biomass, and it decreases as the capacity increases, but it becomes constant for biomass power plant when the capacity is more than 80 kW. LCOE for the solar power plant is 0.12 $/kWh at plant capacity 35 kW, and it is decreasing dramatically to be 0.05 $/kWh when the capacity becomes 110 kW. On the other hand, LCOE for biomass power plants starts from 0.18 $/kWh; then it is going down sharply to become steady after 80kW.

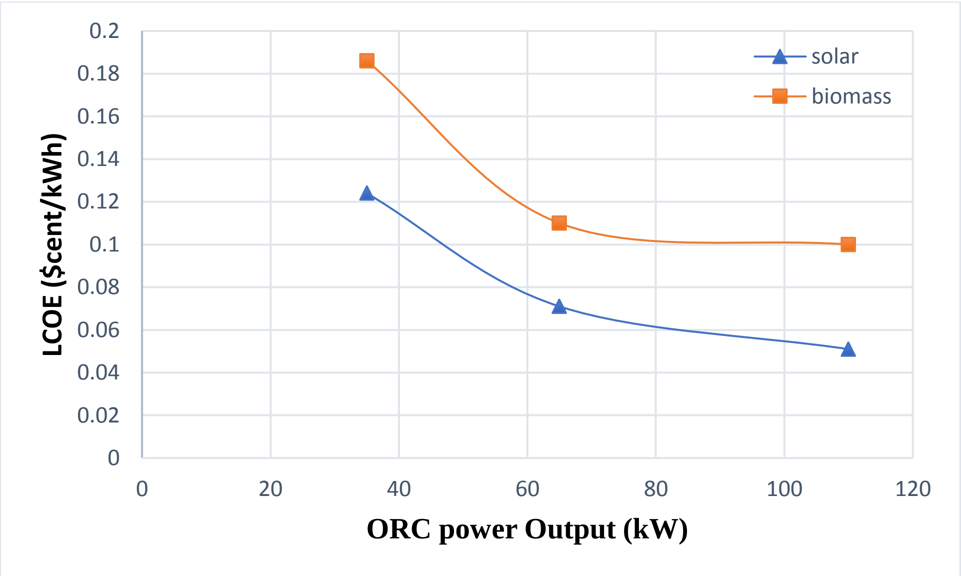


Figure 18: Effect of power plant capacity on LCOE for Biomass and Solar ORC at 8000 hours.

Chapter 6

CONCLUSION AND DISCUSSION

In the current research, a feasibility analysis of small-scale commercial ORC power plants driven by solar energy and biomass is performed. The proposed system of solar ORC power plant consists of two parts: solar water heating part using evacuated tube collectors assisted with auxiliary gas heater and decentralised ORC unit. An optimisation process was performed on the solar water heating part using SAM software to determine the optimal component size. The results showed that the optimal collector area, tilt angle, storage tank volume and the energy needed from the auxiliary unit are 100 m^2, 45°, 4 m^3 and 1636 kWh/year respectively. The simulation results of the solar system showed that the delivered water temperature is above 99 °C around the year which, matches the manufacturer's proposed temperature to get the maximum power.

The proposed system of biomass-fired ORC power plant consists of biomass boiler and ORC connected directly without storage tank and an auxiliary unit. The biomass boiler was selected based on the manufacturer technical data and the cost taken from the suppliers.

The economic calculation for both systems showed that solar ORC power plant is economically feasible, while the biomass is feasible when the plant capacity is more than 65 kW. The unfeasibility of the biomass power plant (35 kW) comes from the higher initial cost of the biomass boiler. Furthermore, biomass fuel is not free by means the biomass cost take place in operational cost as compared to solar energy that is available everywhere and is a free source of energy. SIR, SPB and LCOE calculated for both proposed systems with different capacities to find that SORC power plant is much more feasible than biomass in small-scale, and the feasibility has a linear relationship with the capacity of the plant while biomass ORC power plant has a nonlinear relationship which makes the feasibility less than that of solar by half.

The sensitivity analysis was performed to investigate the effect of operating hours and the capacity of the plant on the feasibility of the system. The result showed that for solar ORC power plant the minimum operating hours should be 5000 hours/year to make a profit and as the capacity of the plant increases, the profit increases on the same operating hours. On other hand, biomass-fired ORC power plant can be economically feasible when the capacity becomes more than 40 kW. Nevertheless, this type of plants could be feasible if it is working as CHP plants.

However, the result of the economic analysis of both the systems showed that solar ORC power plant with evacuated tube collectors and auxiliary gas heater is much more feasible than Biomass ORC power plant which makes small-scale, decentralized solar ORC power plants attractive to build in rural areas and can preserve the lives of millions of underprivileged people in developing countries.

REFERENCES

[1] Tocci, L., Pal, T., Pesmazoglou, I., & Franchetti, B. (2017). Small scale organic rankine cycle (orc): A techno-economic review. *Energies*, *10*(4), 413.

[2] Turboden s.r.l, Inc. Italy. (11.03.2018) Retrieved from: https://www.turboden.com

[3] Quoilin, S., Orosz, M., Hemond, H., & Lemort, V. (2011). Performance and design optimization of a low-cost solar organic Rankine cycle for remote power generation. Solar energy, 85(5), 955-966.

[4] Baral, S., Kim, D., Yun, E., & Kim, K. C. (2015). Experimental and thermoeconomic analysis of small-scale solar organic Rankine cycle (SORC) system. *Entropy*, *17*(4), 2039-2061.

[5] Garg, P., Orosz, M. S., & Kumar, P. (2016). Thermo-economic evaluation of ORCs for various working fluids. *Applied Thermal Engineering*, *109*, 841-853.

[6] Orosz, M., Mueller, A., Quoilin, S., & Hemond, H. (2009). Small-scale solar ORC system for distributed power. *Civil and Environmental Engineering*, (508) 245-6199.

[7] Thawonngamyingsakul, C., & Kiatsiriroat, T. (2012). Potential of a solar organic rankine cycle with evacuated-tube solar collectors as heat source for power generation in Thailand. *Energy Science and Technology*, *4*(2), 25-35.

[8] Freeman, J., Hellgardt, K., & Markides, C. N. (2015). An assessment of solar-powered organic Rankine cycle systems for combined heating and power in UK domestic applications. *Applied Energy*, *138*, 605-620.

[9] Calise, F., d'Accadia, M. D., Vicidomini, M., & Scarpellino, M. (2015). Design and simulation of a prototype of a small-scale solar CHP system based on evacuated flat-plate solar collectors and Organic Rankine Cycle. *Energy Conversion and Management*, *90*, 347-363.

[10] Kulkarni, G. N., Kedare, S. B., & Bandyopadhyay, S. (2007). Determination of design space and optimization of solar water heating systems. *Solar Energy*, *81*(8), 958-968.

[11] Assilzadeh, F., Kalogirou, S. A., Ali, Y., & Sopian, K. (2005). Simulation and optimization of a LiBr solar absorption cooling system with evacuated tube collectors. *Renewable Energy*, *30*(8), 1143-1159.

[12] Rayegan, R., & Tao, Y. X. (2013). Optimal collector type and temperature in a solar organic Rankine cycle system for building-scale power generation in hot and humid climate. *Journal of Solar Energy Engineering*, *135*(1), 011012.

[13] Hermann, W. A. (2006). Quantifying global exergy resources. *Energy*, *31*(12), 1685-1702.

[14] David, G., & Michel, F. (2008). Small scale biomass power plant using organic Rankine cycle technology. *SAS Enertime*. 12(2), 1823-1832

[15] Schuster, A., Karellas, S., Kakaras, E., & Spliethoff, H. (2009). Energetic and economic investigation of Organic Rankine Cycle applications. *Applied thermal engineering*, *29*(8-9), 1809-1817.

[16] Drescher, U., & Brüggemann, D. (2007). Fluid selection for the Organic Rankine Cycle (ORC) in biomass power and heat plants. *Applied thermal engineering*, *27*(1), 223-228.

[17] Delgado-Torres, A. M., & García-Rodríguez, L. (2007). Comparison of solar technologies for driving a desalination system by means of an organic Rankine cycle. *Desalination*, *216*(1-3), 276-291.

[18] Duvia, A., Guercio, A., & Rossi, C. (2009, June). Technical and economic aspects of Biomass fuelled CHP plants based on ORC turbogenerators feeding existing district heating networks. In *17th European Biomass Conference, Hamburg, Germany, June*(pp. 2030-2037).

[19] Algieri, A., & Morrone, P. (2014). Techno-economic analysis of biomass-fired ORC systems for single-family combined heat and power (CHP) applications. *Energy Procedia*, *45*, 1285-1294.

[20] Eyidogan, M., Kilic, F. C., Kaya, D., Coban, V., & Cagman, S. (2016). Investigation of Organic Rankine Cycle (ORC) technologies in Turkey from the technical and economic point of view. *Renewable and Sustainable Energy Reviews*, *58*, 885-895.

[21] Rentizelas, A., Karellas, S., Kakaras, E., & Tatsiopoulos, I. (2009). Comparative techno-economic analysis of ORC and gasification for bioenergy applications. *Energy Conversion and Management*, *50*(3), 674-681.

[22] Moro, R., Pinamonti, P., & Reini, M. (2008). ORC technology for waste-wood to energy conversion in the furniture manufacturing industry. *Thermal Science*, *12*(4), 61-73.

[23] Rentizelas, A., Karellas, S., Kakaras, E., & Tatsiopoulos, I. (2009). Comparative techno-economic analysis of ORC and gasification for bioenergy applications. *Energy Conversion and Management*, *50*(3), 674-681.

[24] Rentizelas, A., Tziralis, G., & Kirytopoulos, K. (2007). Incorporating uncertainty in optimal investment decisions. *World Review of Entrepreneurship, Management and Sustainable Development*, *3*(3-4), 273-283.

[25] Quoilin, S., Orosz, M., Hemond, H., & Lemort, V. (2011). Performance and design optimization of a low-cost solar organic Rankine cycle for remote power generation. *Solar energy*, *85*(5), 955-966.

[26] Electratherm, Inc. Bitzer, (15.07.2018) USA. Retrieved from: https://www.electratherm.com.

[27] Energy tutorials, (15.07.2018) Retrieved from https://www.alternative-energy-tutorials.com.

[28] Ksayer, E. B. L. (2011). Design of an ORC system operating with solar heat and producing sanitary hot water. *Energy Procedia*, *6*, 389-395.

[29] Obadiah's, Inc. Montana, (15.09.2018) USA. Retrieved from: https://woodstoves.net.

[30] Thawonngamyingsakul, C., & Kiatsiriroat, T. (2012). Potential of a solar organic rankine cycle with evacuated-tube solar collectors as heat source for power generation in Thailand. *Energy Science and Technology*, *4*(2), 25-35.

[31] Central solar hot water guide, US army corps of engineering, USA (15.09.2018). Retrieved form: https://www.solarthermalworld.org

[32] Regulus spol.s r.o,Inc, Prague. (23.09.2018) Retrieved from: https://www.regulus.eu.

[33] Baucom, J., Pogue, W., Thomas, J., & Qidwai, M. (2005, August). Hydrocarbon fuels as multifunctional structure-power for unmanned air vehicles. In *3rd International Energy Conversion Engineering Conference* (p. 5530).Orosz, M., Mueller, A., Quoilin, S., & Hemond, H. (2009). Small scale solar ORC system for distributed power.

[34] W.W Grainger, Inc. Chicago, USA. (23.09.2018) Retrieved from: https://www.grainger.com.

[35] Humphreys, K. K. (2004). *Project and cost engineers' handbook*. CRC Press.

[36] Eyidogan, M., Kilic, F. C., Kaya, D., Coban, V., & Cagman, S. (2016). Investigation of Organic Rankine Cycle (ORC) technologies in Turkey from the technical and economic point of view. *Renewable and Sustainable Energy Reviews*, *58*, 885-895.

[37] Asumadu-Sarkodie, S., & Owusu, P. A. (2016). Feasibility of biomass heating system in Middle East Technical University, Northern Cyprus Campus. *Cogent Engineering*, *3*(1), 1134304.

[38] O'Mahoney, A., Thorne, F., & Denny, E. (2013). A cost-benefit analysis of generating electricity from biomass. *Energy Policy*, *57*, 347-354.

[39] De Wit, M., & Faaij, A. (2010). European biomass resource potential and costs. *Biomass and bioenergy*, *34*(2), 188-202.

[40] Isimek, Ltd. Ankara, Turkey. (12.10.2018) Retrieved from: https://www.isimek.com.tr/

APPENDIXICES

Appendix A: 65 kW and 110 kW Solar System Optimization Results

The optimum collector area and storage tank volume for 65 kW system is 149 m^2 and 7 m^3 respectively.

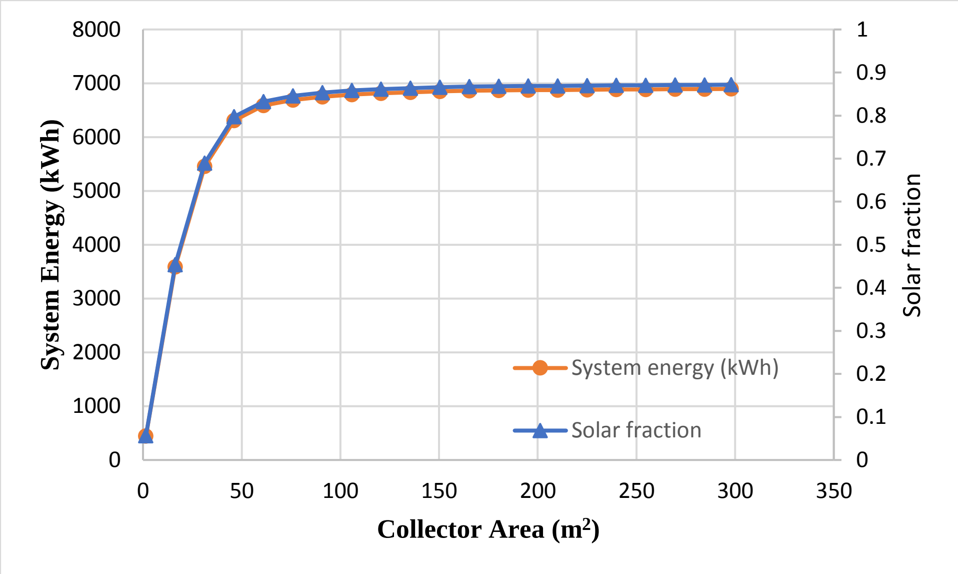


Figure 19: Effect of collector area on energy saved by the system for 65 kW system

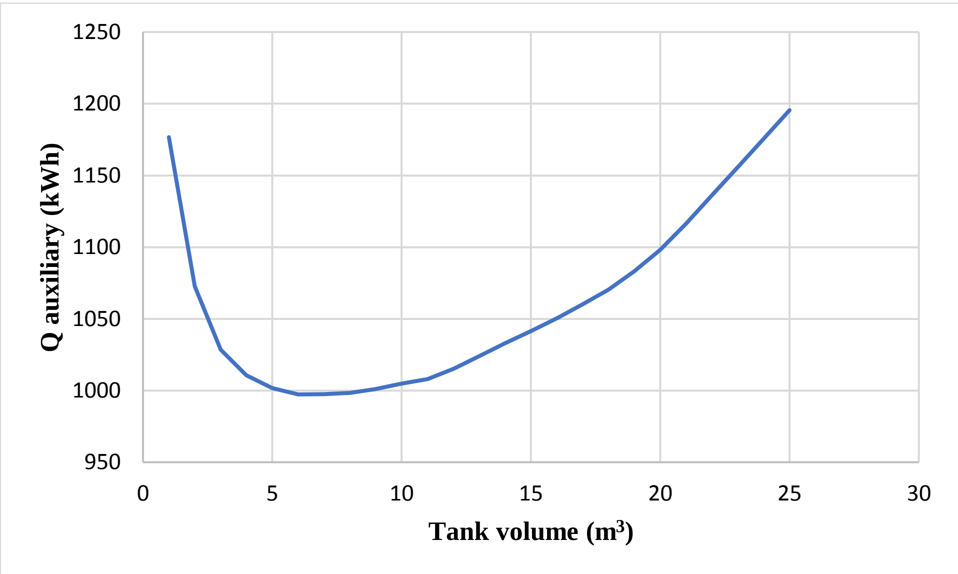


Figure 20: Storage tank volume effect on the heat from the auxiliary unit for 65 kW system

The optimum collector area and storage tank volume for 110 kW system is 194 m^2 and 3 m^3 respectively.

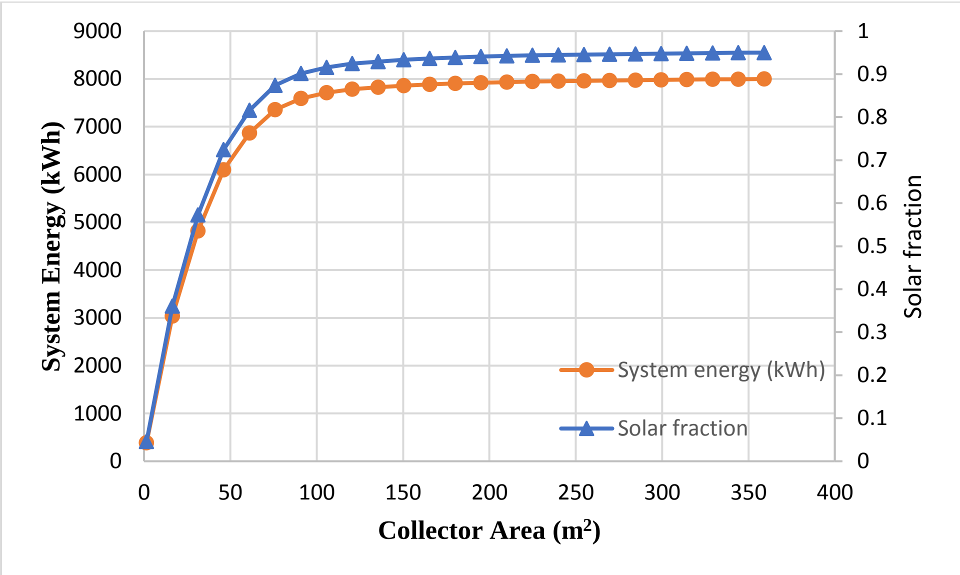


Figure 21: Effect of collector area on energy saved by the system for 110 kW system

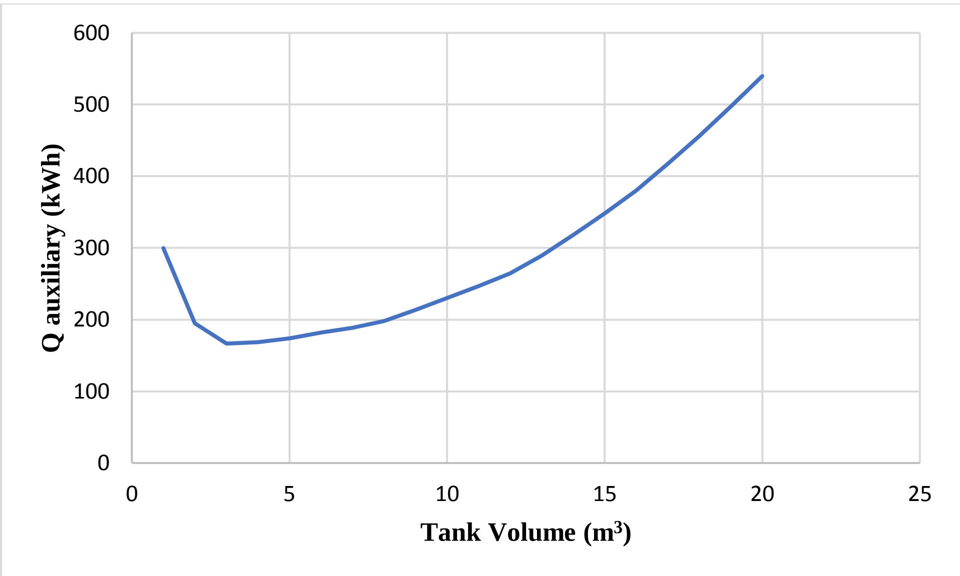


Figure 22: Storage tank volume effect on the heat from the auxiliary unit for 110 kW system

Appendix B: Data Sheets of The Main Components of The Systems

35 kW and 65 kW ORC Data Sheet


ELECTRATHERM BY BITZER GROUP

4200 Specification Sheet

POWER+ GENERATOR®

ElectraTherm's Power+ Generator* produces fuel-free, emission-free power from low grade waste heat using the Organic Rankine Cycle (ORC) and proprietary technology. The company's proven, patented twin screw expander enables its heat-to-power generating system to make electricity from waste heat instead of fossil fuel. ElectraTherm's Power+ Generator represents a dramatic change from radial or axial turbine technologies, providing a more cost efficient, robust machine to generate fuel-free and emission-free electricity from a variety of heat sources.

ElectraTherm's twin screw expander offers distinct advantages for small-scale ORCs. These advantages include a simple and compact design, low speed operation with the ability to handle heat input variations and dual phase flow of the working fluid, significant part load capability, no gear box or oil pump, attractive payback and proven technology.

4200 Power+ CONFIGURATIONS - Up to 35kWe

ElectraTherm's Power+ Generator* is available in two configurations:

4200 Stand Alone Specifications

- Dimensions*: 2.4 x 2.0 x 2.3 m
- Weight: 3,195 kg / 7,044 lbs
- Customizable balance of plant
- Indoor or outdoor installation
- Manufacturer's Suggested Retail Price**: $173,587

4200-FL Specifications

- Dimensions*: 12 x 2.4 x 2.9 m
- Weight: 6,095 kg / 13,438 lbs
- Turnkey inc. liquid loop radiator, all piping/pumps, no concrete foundation required, minimal engineering
- Manufacturer's Suggested Retail Price**: $251,935

** Renderings may not be exact representations of final Power+ product.*

*** Certification fees for certain countries may apply.*

HEAT TO POWER APPLICATIONS

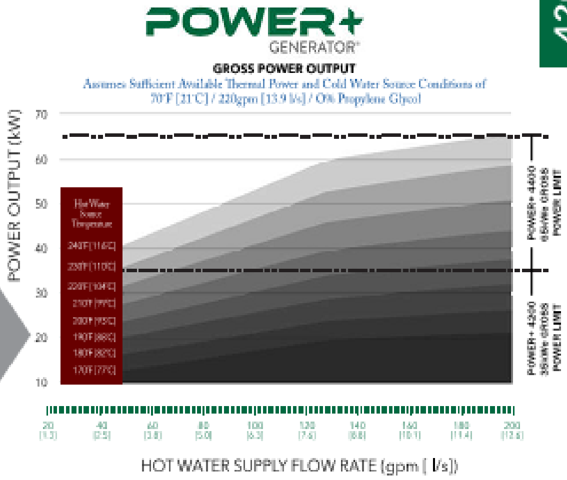
ElectraTherm generates electricity from various heat sources, including:

4200 PERFORMANCE PARAMETERS - Up to 35kWe

ElectraTherm's Water Cooled Condensing System Performance

4200

Hot Water Input Parameters	Hot water input temp range	°F	170 - 240
		[°C]	[77 - 116]
	Thermal input range	MMBTU/hr	1.02 - 2.22
		[kWth]	[300 - 650]
	Flow rate range	gpm	50 - 200
		[l/s]	[3.2 - 12.6]
Water Cooled Condensing Parameters	Cooling water input temp range	°F	40 - 150
		[°C]	[4 - 65]
	Heat rejected to cooling water range	MMBTU/hr	1.02 - 2.0
		[kWth]	[300 - 600]
	Cooling water flow rate	gpm	220
		[l/s]	[13.9]
Liquid Loop Radiator (LLR)* *4200-FL Only	LLR approach to ambient air temp	°F	20
		[°C]	11
	Heat rejected to LLR	MMBTU/hr	1.02 - 2.0
		[kWth]	[300 - 600]



PERFORMANCE CHARACTERISTICS

Nominal Rating	Up to 35kWe* @ 380 - 500V / 3 phase / 50 & 60 Hz
Ambient Operation	0°C - 38°C (32°F - 100°F)**
Power Factor Correction	Load and Site Dependent - from 0.9 to 1
Total Harmonic Distortion	2% for Voltage; 10% for Current
Emissions	Zero (Closed Binary Cycle)

DESIGN ATTRIBUTES

Refrigerant Plumbing	Built to ASME and CE Standards
Energy Block	Twin Screw Expander
Generator	Grid-Tied Induction (Brushless Construction, Asynchronous)
Heat Exchangers	Compact, Brazed Plate Construction
Design Life	20 Years
Lubrication	Process Lubrication
Transient Voltage/Surge Suppression	Basic Protections are Standard
Grid Protective Relay (GPR)	External Additional GPR Interface Included

SYSTEM DESCRIPTION

Working Fluid	R245fa (Pentafluoropropane)***
Heat Source	Hot Water 77°C - 116°C (170°F - 240°F)
Cooling Requirement	Water 4°C - 65°C (40°F - 150°F)
Controls	Custom Controls Software using Standard Programmable Logic Controller
Remote Monitoring	Will Support Internet Protocol, 3G Cellular, Satellite Communications, Wireless
Operation	Designed for Unattended Operation
Cabinet	NEMA 3R Outdoor Rated /IP 54 Compliant
Shipping	Ships from Flowery Branch, GA, USA
Dimensions	Various Configurations Available (see first page)
Weight	Various Configurations Available (see first page)
Sound Pressure	80db at 1 meter. Sound Attenuated Option: <72db at 1 meter

FEATURES INCLUDE:

- Automated Control System
- Remote Monitoring
- Low Maintenance
- Modular and Scalable
- Robust, Twin Screw Expander Power Block
- CE Certified
- Zero Emissions, Zero Toxic By-products and Zero Fossil Fuel Requirements
- Dual-Heat Stream Input + Radiator Option Available

*Output depends on hot and cold resources
**Extreme environments require optional equipment
***R245fa is a non-flammable, non-toxic and non-ozone depleting working fluid

ELECTRATHERM® BY BITZER GROUP
ElectraTherm, Inc. - 4080 Enterprise Way, Flowery Branch, Georgia 30542 USA
P: +01 775-398-4680 - Toll Free: 1-877-883-7101 - www.electratherm.com

4200/Revised (1.25.18)

110 kW ORC Data Sheet

ELECTRATHERM
BY BITZER GROUP

6500 Specification Sheet

POWER+
GENERATOR®

ElectraTherm's Power+ Generator® produces fuel-free, emission-free power from low grade waste heat using the Organic Rankine Cycle (ORC) and proprietary technology. The company's proven, patented twin screw expander enables its heat-to-power generating system to make electricity from waste heat instead of fossil fuel. ElectraTherm's Power+ Generator represents a dramatic change from radial or axial turbine technologies, providing a more cost efficient, robust machine to generate fuel-free and emission-free electricity from a variety of heat sources.

ElectraTherm's twin screw expander offers distinct advantages for small-scale ORCs. These advantages include a simple and compact design, low speed operation with the ability to handle heat input variations and dual phase flow of the working fluid, significant part load capability, no gear box or oil pump, attractive payback and proven technology.

6500 Power+ CONFIGURATIONS - Up to 110kWe

ElectraTherm's Power+ Generator is available in two configurations:

6500 Stand Alone Specifications

- Dimensions*: 3 x 2.4 x 2.6 m
- Weight: 4,853 kg /10,699 lbs
- Customizable balance of plant
- Indoor or outdoor installation
- Manufacturer's Suggested Retail Price**: $297,200

6500-FL Specifications

- Dimensions*: 12 x 2.4 x 2.9 m
- Weight: 8,553 kg / 19,518 lbs
- Turnkey inc. liquid loop radiator, all piping/pumps, no concrete foundation required, minimal engineering
- Manufacturer's Suggested Retail Price**: $409,159

** Renderings may not be exact representations of final Power+ product.*
*** Certification fees for certain countries may apply.*

HEAT TO POWER APPLICATIONS

ElectraTherm generates electricity from various heat sources, including:

Stationary Engines

Biomass/Biogas

Boilers & Process Heat

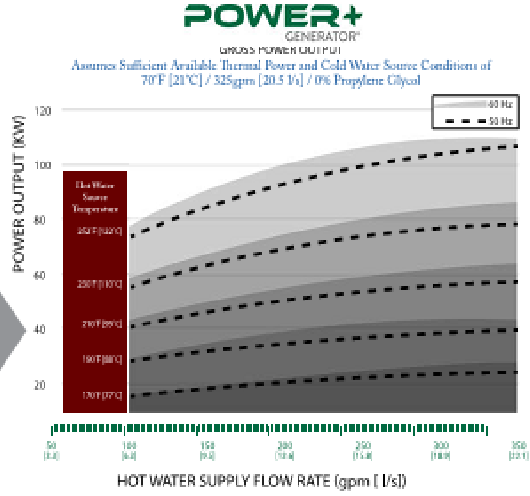
Oil & Gas, Geothermal

Solar Thermal

6500 PERFORMANCE PARAMETERS - Up to 110kWe

ElectraTherm's Water Cooled Condensing System Performance

Hot Water Input Parameters	Hot water input temp range	°F	170 - 252
		[°C]	[77 - 122]
	Thermal input range	MMBTU/hr	1.2 - 5.4
		[kWth]	[330 - 1600]
	Flow rate range	gpm	100 - 350
		[l/s]	[6.4 - 22.1]
Water Cooled Condensing Parameters	Cooling water input temp range	°F	40 - 150
		[°C]	[4 - 65]
	Heat rejected to cooling water range	MMBTU/hr	1.1 - 5.1
		[kWth]	[320 - 1500]
	Cooling water flow rate	gpm	325
		[l/s]	[<22.1]
Liquid Loop Radiator (LLR)* *6500-FL Only	LLR approach to ambient air temp	°F	25
		[°C]	[14]
	Heat rejected to LLR	MMBTU/hr	1.1 - 5.1
		[kWth]	[320 - 1500]



PERFORMANCE CHARACTERISTICS

Nominal Rating	Up to 110kWe* @ 380 - 500V / 3 phase / 50 & 60 Hz
Ambient Operation	0°C - 38°C (32°F - 100°F)**
Power Factor Correction	Load and Site Dependent - from 0.9 to 1
Total Harmonic Distortion	2% for Voltage; 10% for Current
Emissions	Zero (Closed Binary Cycle)

DESIGN ATTRIBUTES

Refrigerant Plumbing	Built to ASME and CE Standards
Energy Block	Twin Screw Expander
Generator	Grid-Tied Induction (Brushless Construction, Asynchronous)
Heat Exchangers	Compact, Brazed Plate Construction
Design Life	20 Years
Lubrication	Process Lubrication
Transient Voltage/Surge Suppression	Basic Protections are Standard
Grid Protective Relay (GPR)	External Additional GPR Interface Included

SYSTEM DESCRIPTION

Working Fluid	R245fa (Pentafluoropropane)***
Heat Source	Hot Water 77°C - 122°C (170°F - 252°F)
Cooling Requirement	Water 4°C - 65°C (40°F - 150°F)
Controls	Custom Controls Software using Standard Programmable Logic Controller
Remote Monitoring	Fully Controllable via Customer Internet Connection
Data Logging	Major System Parameters Logged, KEPserver/OPC Available for Site SCADA
Operation	Designed for Unattended Operation
Electrical Panels / Components	NEMA 3R Outdoor Compliant /IP 54 Compliant
Shipping	Ships from Flowery Branch, GA, USA
Dimensions	Various Configurations Available (see next page)
Weight	Various Configurations Available (see next page)

*Output depends on hot and cold resources
**Extreme environments require optional equipment
***R245fa is a non-flammable, non-toxic and non-ozone depleting working fluid

FEATURES INCLUDE:

- Automated Control System
- Remote Monitoring
- Low Maintenance
- Modular and Scalable
- Robust, Twin Screw Expander Power Block
- CE Certified
- Zero Emissions, Zero Toxic By-products and Zero Fossil Fuel Requirements
- Dual-Heat Stream Input + Radiator Option Available

ELECTRATHERM BY BITZER GROUP
ElectraTherm, Inc. - 4080 Enterprise Way, Flowery Branch, Georgia 30542 USA
P: +01 775-398-4680 - Toll Free: 1-877-883-7101 - www.electratherm.com

6500/Revised (1.25.18)

Evacuated tube collector data sheet

KTU 15 SOLAR COLLECTOR

Evacuated tube collector of 1090 W output (at 1000 W/m² irradiance), designed for on-roof portrait installation. A tube consists of 2 coaxial glass tubes with vacuum between them. An aluminium lamella fitting closely to the glass tube collects heat from the whole inner surface of the evacuated tube, giving it away into solar fluid inside the copper pipe. These copper pipes join the collector header, insulated with 30 mm of mineral wool.

Code: 7127

Dimensions and weight	
height x width x thickness	1970 x 1350 x 141mm
installation width	1430mm
total area	2.660 m²
aperture area	1.49 m²
absorber area	1.220 m²
empty weight	60kg
Glazing	
material	borosilicate glass - 15 evacuated tubes
thickness	1.8mm
Absorber	
material	borosilicate glass
surface finish	AlN/Al-N/Al-N/Al-N/Al-N
design type	evacuated tube
material and size of connection pipes	copper 4 x Ø 22mm × 1mm
material and size of absorber tubes	copper 15 x Ø 8mm × 0.5mm
max. working pressure	10 bar
max. working temperature	120°C
stagnation temperature	309.9°C
heat transfer fluid	water solution of monopropylene glycol 1:1, 2.4 l
recommended flow rate	60 - 120 l/h
Thermal insulation	
absorber	vacuum
header	mineral wool, 30mm
Frame	
frame material	aluminum alloy and steel AISI 304 SS
frame color	silver
case material	steel AISI 304 SS, 0.8mm thick
Collector efficiency parameters related to aperture/absorber surface area	
η_{0a}	0.733/0.894
a_{1a}	2.237/2.73 W/m²K
a_{2a}	0.0025/0.0031 W/m²K²

Mount and connection kits (portrait mount)		Code
Connection kit		7710
Kit for 1 collector	[for 4 roof anchors or 2 supports + 1 strut]	7414
Kit for 2 collectors	[for 6 roof anchors or 3 supports + 1 strut]	7245
Kit for 3 collectors	[for 8 roof anchors or 4 supports + 1 strut]	7246
Kit for 4 collectors	[for 10 roof anchors or 5 supports + 1 strut]	7247
Extension kit for mounting and connecting 1 collector	[for 4 roof anchors or 2 supports + 1 strut]	11990

The Connection kit contains an inlet elbow (Cu22 x 3/4" F), outlet pipe cross (Cu22 x 3/4" F + 3/8" F for an air vent valve and 1/2" F for a temperature sensor sheath), sheath with a temperature sensor and 2 straight couplers (Cu22x3/4" F) with a plug and gaskets.

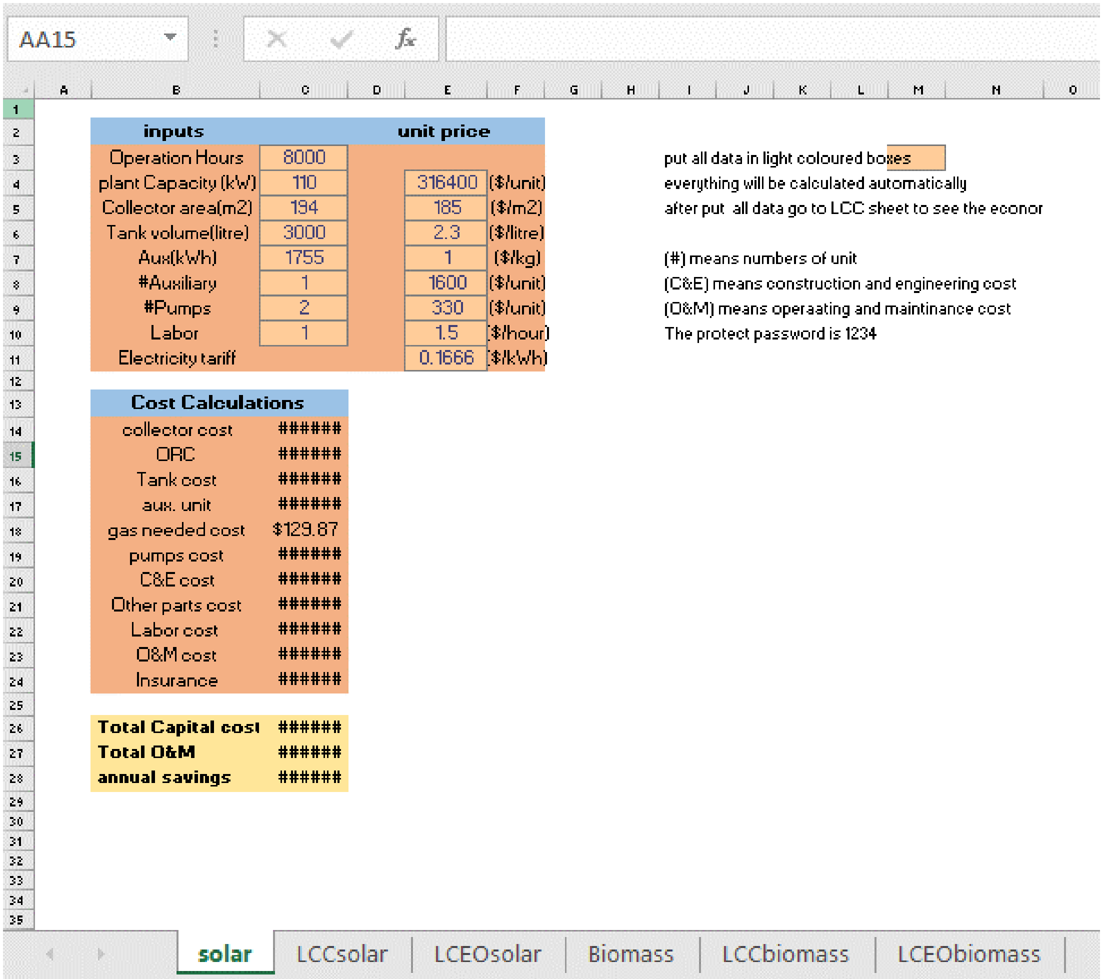
The mount and connection kits consist of aluminum mounting rails, retaining clamps, bolts and nuts, straight couplers (2 and more collectors) and pipe insulation.

Solar Thermal System

Energy-saving solutions

11

Appendix C: The Excel Sheet used to Perform the Economic Analysis



inputs		unit price	
Operation Hours	8000		
plant Capacity (kW)	110	316400	($/unit)
Collector area(m2)	194	185	($/m2)
Tank volume(litre)	3000	2.3	($/litre)
Aux(kWh)	1755	1	($/kg)
#Auxiliary	1	1600	($/unit)
#Pumps	2	330	($/unit)
Labor	1	1.5	($/hour)
Electricity tariff		0.1666	($/kWh)

Cost Calculations	
collector cost	######
ORC	######
Tank cost	######
aux. unit	######
gas needed cost	$129.87
pumps cost	######
C&E cost	######
Other parts cost	######
Labor cost	######
O&M cost	######
Insurance	######

Total Capital cost	######
Total O&M	######
annual savings	######

put all data in light coloured boxes
everything will be calculated automatically
after put all data go to LCC sheet to see the econor

(#) means numbers of unit
(C&E) means construction and engineering cost
(O&M) means operaating and maintinance cost
The protect password is 1234

solar | LCCsolar | LCEOsolar | Biomass | LCCbiomass | LCEObiomass

TABLE 1

Life Cycle Investment Schedule, from Steps 1, 2, and

Year	New	Old	Net Amount
0			$0
1			$0
2			$0
3			$0
4			$0
5			$0
6			$0
7			$0
8			$0
9			$0
10			$0
11			$0
12			$0
13			$0
14			$0
15			$0
16			$0
17			$0
18			$0
19			$0

Annual Savings	$141,277	(from Step 3)
Discount Rate	3%	(from Step 4)
Analysis period (years)	20	(from Step 5)
Residual value	$40,489.71	(from Step 6)

TABLE 3: Savings Calculations Formula: PV Annual Savings = Annual Savings / (1 + Discount Rate)^{year} (from Step 7)

Year	0										
Annual Savings	$0										
PV Annual Savings	$0										
PV Annual Savings	$0										

TABLE 4: Investments Formula: PV Life Cycle Investment = Life Cycle Investment / (1 + Discount Rate)^{year} (from Step 8)

Year	0										
Net Life Cyle Investments	$0										
PV Life Cycle Investments	$0										
PV Life Cycle Investments	$0										

Net Cash Flows	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0

TABLE 5: Results	OUTPUTS	
Net Present Value (NPV)	$1454 683	(from Step 9)
Savings-to-Investment Ratio	3.2	(from Step 10)
Internal Rate of Return (IRR)	30%	(from Step 10)
Simple Payback (years)	2.9	

Discount Rate	3%
Analysis period (years	20
LCOE ($/kWh)	**0.052**

year	It	Mt	I+M/i	Et
0	########	0	404897	848000
1	0	########	17940	823301
2	0	########	17418	799321
3	0	########	16910	776040
4	0	########	16418	753437
5	0	########	15940	731492
6	0	########	15475	710187
7	0	########	15025	689502
8	0	########	14587	669419
9	0	########	14162	649921
10	0	########	13750	630992
11	0	########	13349	612613
12	0	########	12960	594770
13	0	########	12583	577447
14	0	########	12216	560628
15	0	########	11861	544299
16	0	########	11515	528446
17	0	########	11180	513054
18	0	########	10854	498111
19	0	########	10538	483603

Levelized Cost of Energy (LCOE) calculated by following equation

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+i)^t}}$$

where

It is the initial cost
Mt is the maintinance cost
Ft is the fuel cost
i is the discount rate
Et is the energy produced

	A	B	C	D	E	F	G	H	I	J	K
1											
2		**inputs**			**unit price**						
3		Operation Hours	8000								
4		biomass HV(kJ/kg)	15000		0.01	($/kg)					
5		boiler effeciency	80			%					
6		plant Capacity (kW)	35		189587	($/unit)					
7		boiler output (kWth)	450		35000	($/unit)					
8		Labor	1		2	($/hour)					
9		Electricity tariff			0.1666	($/kWh)					
10											
11		**cost calculations**									
12		boiler cost	$ 35,000.00								
13		ORC	$ 189,587.00								
14		biomass cost	$ 10,800.00								
15		C&E cost	$ 23,538.70								
16		Other parts cost	$ 4,660.66								
17		Labor cost	$ 16,000.00								
18		O&M cost	$ 2,635.86								
19		Insurance	$ 1,581.52								
20											
21		**Total Capital cost**	$ 263,586.36								
22		**Total O&M**	$ 31,017.38								
23		**annual savings**	$ 41,283.48								
24											

solar | LCCsolar | LCEOsolar | **Biomass** | LCCbiomass | LCEObiomass