TECHNICAL AND ECONOMIC FEASIBILITY OF ORGANIC RANKINE CYCLE (ORC) A CASE STUDY OF LIBYA

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TECHNICAL AND ECONOMIC FEASIBILITY OF ORGANIC RANKINE CYCLE (ORC) A CASE STUDY OF LIBYA

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I certify that in my opinion the thesis submitted by Ahmed Gamalaldin ALSAWAIAH titled “TECHNICAL AND ECONOMIC FEASIBILITY OF ORGANIC RANKINE CYCLE (ORC) A CASE STUDY OF LIBYA” is fully adequate in scope and in quality as a thesis for the degree of Master of Science.

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The degree of Master of Science by the thesis submitted is approved by the Administrative Board of the Graduate Faculty of Technology, Karabük University.

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“I declare that all the information within this thesis has been gathered and presented in accordance with academic regulations and ethical principles and I have according to the requirements of these regulations and principles cited all those which do not originate in this work as well”

Ahmed Gamalaldin ALSAWAIAH

ABSTRACT

M. Sc. Thesis

TECHNICAL AND ECONOMIC FEASIBILITY OF ORGANIC RANKINE CYCLE (ORC) - A CASE STUDY OF LIBYA

Ahmed Gamalaldin ALSAWAIAH

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Organic Rankine Cycle (ORC) is one of the maturing renewable energy systems that has many application and types. The most common types of ORC are solar and waste heat applications. In this study, technical and economic are researched for ORC in Libya. After understanding the system and selecting a model developed by one of the leading developers with a high efficiency rate, the parameters of the studied system are set. Moreover, the potential solar and waste heat powers are calculated in Libya along with the country's plan to cover 25% of its demand from renewables. Based on that, the technical feasibility requires 16 solar ORC units with the capacity of 88.1 MW with an estimated cost of 3.475 billion American Dollars.

Keywords : Organic Rankine Cycle, feasibility, renewable energy, Libya.
Science Code : 928.1.233

ÖZET

Yüksek Lisans Tezi

ORGANİK RANKINE ÇEVRİMİNİN (ORÇ) LİBYA ŞARTLARINDA TEKNİK VE EKONOMİK FİZİBİLİTE ANALİZİ

Ahmed Gamalaldin ALSAWAIAH

Karabük Üniversitesi
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Organik Rankine Çevrimi (ORÇ), birçok uygulama ve türe sahip gelişmekte olan yenilenebilir enerji sistemlerinden biridir. ORÇ'nin en yaygın türleri güneş ve atık ısı uygulamalarıdır. Bu çalışmada Libya'da ORÇ için teknik ve ekonomik araştırmalar yapılmıştır. Sistemin çalışma prensibinden bahsedildikten sonra, yüksek verimlilik oranına sahip önde gelen geliştiricilerden biri tarafından geliştirilen bir model seçilip, sistem parametreleri belirlenmiştir. Ayrıca, potansiyel güneş enerjisi ve atık ısı güçleri, ülkenin yenilenebilir kaynaklardan gelen talebin 25%'ini karşılama planı ile birlikte Libya için hesaplanmıştır. Buna dayanarak, teknik fizibilite, 88.1 MW kapasiteli 16 güneş ORÇ sistemi için 3.475 milyar Amerikan Doları tahmini maliyet gerektirmektedir.

Anahtar Kelimeler : Organik Rankine Döngüsü, fizibilite, yenilenebilir enerji, Libya.
Bilim Kodu : 928.1.233

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SYMBOLS AND ABBREVIATIONS

SYMBOLS

A_C : area of collector
C_p : specific heat capacity of collector
$\dot{E}_{d\,,k}$: exergy destruction rate for device k
$\dot{E}_{x_Q}$: exergy rate due to heat transfer
$\dot{E}_{x_W}$: exergy rate due to work transfer
G_b : global radiation on the surface
h : specific enthalpy of the streams of the system working fluid
in : inlet
$\dot{m}$: mass flow rate
$\dot{m}\ ex$: exergy rates from the system
$\dot{m}_c$: mass flow rate of collector
out : outlet
$\dot{Q}$: heat transfer rate
T_0 : reference state temperature
T : boundary temperature at the heat transfer area
T_i : inlet temperatures of the collector
T_o : outlet temperatures of the collector
$\dot{W}$: Component boundaries
η_C : collector efficiency

ABBREVIATIONS

ASHRAE : American Society of Heating, Refrigeration and Air-Conditioning Engineers
DNI : Direct Normal Irradiance
GWP : Green Warming Potential
IHX : Internal Heat Exchanger
IRR : Internal Rate of Return
kW : Kilo Watt
MW : Mega Watt
MWh : Mega Watt hour
ODP : Ozone Depleting Potential
ORC : Organic Rankine Cycle
PTC : Parabolic Trough Collectors
USGS : United States Geological Survey

CHAPTER 1

INTRODUCTION

1.1. BACKGROUND

As the world spent more than $550 billion on fossil fuel energy generation in the past years, it is becoming more crucial to find alternative energy sources and methods in order to reduce the dependency on the conventional sources [1]. Other than looking onto using renewable energy sources such as wind, solar and biomass, the energy and engineering specialists are also drawing attention to the significant amount of energy loss that are resulting from various usages and applications. For instance, the United States Department of Energy confirmed that in all industries, the energy efficiency cannot exceed 85% of the total delivered energy [2]. Table 1.1 below shows the energy losses in different industrial applications.

Table 1.1. Energy loss in selected applications [2].

Industry Application	Equipment	Energy Loss Percentage
Steam Systems	Boilers	20%
	Steam pipes and traps	20%
	Heat exchangers	15%
Power Generation	Combined heat and power	24%
	Conventional power	45%
Energy Distribution	Fuel and energy distribution lines and pipes	3%
Energy Conversion	Process heaters	15%
	Cooling systems	10%
	Transport system within facility	50%
	Electrolytic cells	15%
Motor Systems	Pumps	40%
	Fans	40%
	Air compressors	80%
	Refrigeration	5%

Furthermore, the Organic Rankin Cycle (ORC) is an optimization assembly to recover the heat loss resulting from industrial facilities such as steel and cement factories, and power generation plants in order to reduce the power consumption of the facility from an external power supply [3]. Moreover, the ORC system can be integrated into a solar heat system that would use the heated fluid from the solar field in order to support the mechanism of the Organic Rankine cycle [4].

In the Libyan case, according to the 10th Arab Energy Conference, the total energy demand in country reached a maximum of 21,876 gWh in 2010 with a demand growth rate of 10.2%. Most of the energy generated in Libya is using the Natural Gas which forms around 65% from the total energy sources in the country. Moreover, by studying the two potential applications of ORC in Libya, more than 600 factories are found in the country in addition to 50% of the Libyan land exposed to a solar radiation between 2550 kWh/m^2 to 2100 kWh/m^2 [5].

Therefore, this research will focus on studying the Organic Rankine Cycle (ORC) from the technical and economic aspects in order to conclude its feasibility for use and the technical and commercial benefits of the country, which will allow Libya to catch the train of optimizing power use for industrial purposes. Furthermore, exploring such an opportunity will open the door for the country to utilize this technology in general power generation to support the increasing demands.

1.2. STUDY PROBLEM, SCOPE AND METHODOLOGY

The main issue this research is attempting to address is the increasing demands on energy in Libya for the different usages, and mainly the industrial sector. Therefore, this study proposes the Organic Rankine Cycle as a possible solution to reduce energy consumption for the industrial facilities, while it would be possible to even extend the benefits to general power generation as part of the country's plan to implement renewable energy sources' strategy in its new era. Moreover, the study will examine the possible applications of ORC in Libya and establish a feasibility study in order to reduce the wasted energy as well as benefiting from the high solar radiation in the country as a sustainable energy solution.

In order to be able to apply the proposed technology in Libya, the main scope of this thesis will include the following:

1. Study the Organic Rankine Cycle (ORC) assemblies as a concept and to understand its mechanism from the theoretical aspects.
2. Study other feasibility studies around the world to adopt methodologies and key points in performing feasibility studies in the energy and industrial sectors.
3. Review specific case studies of similar nature. This thesis will focus on two studies performed in Turkey and India.
4. Establish the technical and economic criteria that are essential to prove the feasibility of the technology in Libya.
5. Consolidate the Libyan demand for energy in the recent years and anticipate a projection of the growth in order to ensure the sustainability of the solution.
6. Perform a case study on the ORC in Libya from a technical and economic point of views.
7. Provide a discussion, set of recommendations and conclusions in order for the research to be comprehensive and open the doors for future research and investment in the sector.

Moreover, the methodology of this thesis would be mainly studying the theoretical components of the ORC system and its applications and performing a literature review on successful and potential study cases. Moreover, the thesis will adopt a study case about Libya by studying the heat waste energy in the Libyan Factories in addition to the potential usage of the solar radiation which is available efficiently in the country. The thesis will then apply the theoretical review to the Libyan case and study the technical and economic feasibility of the ORC against the current energy generation sources in Libya.

1.3. STUDY AIM AND QUESTIONS

The purpose of this thesis is to study the technical and economic feasibility of Organic Rankine Cycle (ORC) for Energy generation in Libya, as well as energy recovery from industrial facilities. Thus, the initial questions of the research are the following:

1: What is the working mechanism of the Organic Rankine Cycle (ORC)?

2: What are the components of the ORC in waste energy recycling and in solar energy?

3: How did the implementation of ORC project contribute to the power generation and energy recovery in other countries?

4: What is the energy demand in Mega Watt in Libya and what are the projected demands over the next years?

5: What are the current energy resources used for power generation in Libya?

6: How does an ORC project support the country's vision to implement renewable energy sources as an alternative for fossil fuels?

7: Why could the ORC be a solution for a sustainable energy in Libya?

8: How is the ORC a feasible solution for Libya from a technical and economic views?

1.4. STUDY STRUCTURE

The structure of the thesis is divided into five main chapters, which covers the whole purpose of this thesis. Therefore, the chapters include the following:

Chapter One: An introduction to the study, where background of the study is presented on the main research subjects; ORC and Libya. Moreover, the chapter includes the problem statement, scope and methodology in order to achieve the study goals. Furthermore, the main aim of the thesis is provided along with the research questions that are answered through the course of the thesis.

Chapter Two: A theoretical review of the mechanism and technologies that are used in the Organic Rankine Cycle worldwide. The technical components of the technology are reviewed against technical performance and efficiency. Moreover, case studies from different parts of the world are reviewed to unveil the advantages and challenges of the ORC system in recovery and power generation.

Chapter Three: A research of the Libyan energy case in terms of current and projected energy demands according to the growth rate of the country.

Furthermore, this chapter will establish the criteria on which the technical and economic aspects of the study are performed.

Chapter Four: The main case study of the thesis the Organic Rankine Cycle technology is reviewed according to the technical feasibility within Libya. The major success factors in this case are the hundreds of industrial facilities that are operating in the country, as well as the high availability of solar energy. Subsequently, the economic aspect is studied to highlight the possible costs and savings that may result from implementing the technology in a wide scale.

Chapter Five: Starts with a discussion of the case study outcomes in order to highlight the advantages of the study and the possible implementation challenges. Thereafter, the thesis will provide a set of recommendations for future investments and studies, along with the study conclusions.

CHAPTER 2

ORGANIC RANKINE CYCLE (ORC)

2.1. ORC MECHANISM AND TYPES

The Rankine Cycle technology has been one of the promising methods for energy generation from renewable or industrial heat sources, which allows for a workable system under low and medium temperatures. Moreover, an Organic Rankine Cycle refers to the same system but using an organic compound as the working fluid instead of water [6]. The organic compounds are used in ORC in order to reach to a boiling point, where the working fluid can be vaporized under lower temperature points than water [7].

The Rankine cycle, as most of the steam engine systems, goes through cycle that can be presented by the Temperature-Entropy (T-s) diagram shown in Figure 2.1, which is for working fluid being water, and explained as the following [8]:

1. Segment 6-1: pump compresses the working fluid, which its non-compressibility and the pump being isentropic lead to the relative position between points 1 and 6.
2. Segment 1-2: preheating the fluid, e.g. using internal heat exchanger.
3. Segment 2-3: working fluid vaporizes after getting saturated with the heat. At this point the temperature remains the same, but the entropy increases.
4. Segment 3-4: Vapor overheats, where the temperature and the entropy are both increased.
5. Segment 4-5: this part depends on the properties of the working fluid, which is explained later in this chapter. Therefore, the vapor expands entering the turbine. However, the increase or decrease of entropy depends on the working fluid.

6. Segment 5-6: the vapor is condensed returning the working fluid into the cycle. At this step the temperature remains constant, while the entropy decreases.

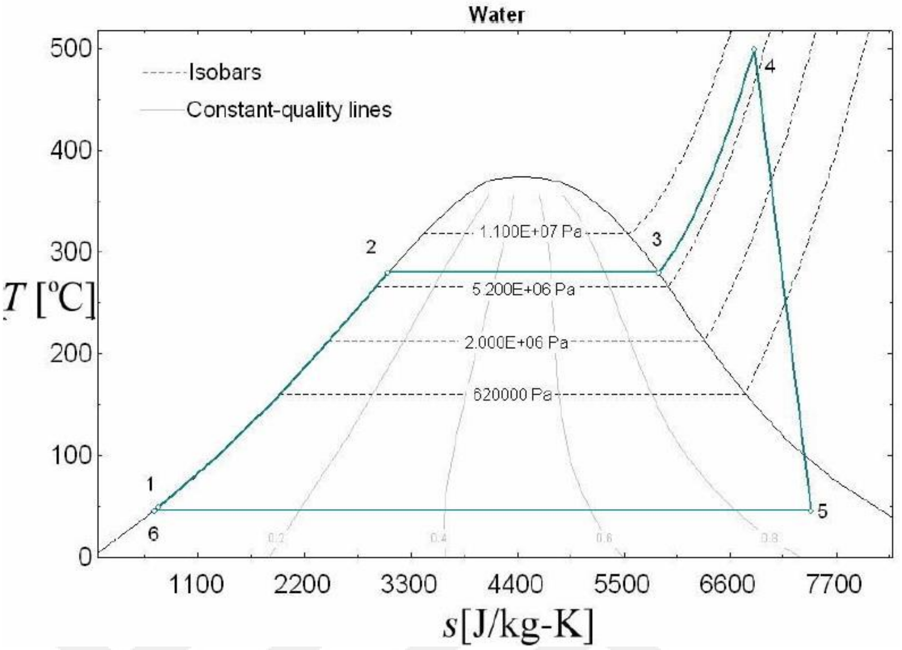

Figure 2.1. Temperature-Entropy diagram for Rankine cycle using water [8].

There are several types and application for Rankine cycle, which could be also used for ORC [6]:

1. Solar radiation: using a PTC (Parabolic Through Collector) the solar power is used to create a concentrated heat source over the pipe point, heating up the working fluid.
2. Biomass: using an internal or external combustion engine, biomass can be used to generate the heat needed for the ORC.
3. Geothermal: using geothermal plants to transfer the heat from the plant fluid into the working fluid of the ORC.
4. Waste heat: using the heat generated by factories and industries, e.g. metal manufacturing, to produce the heat required to heat up the working fluid of the ORC.

2.2. ORC APPLICATIONS

The organic Rankine cycle has been used in different applications around the world. The main point of all the applications is finding an adequate and usable heat sources in order to activate the Rankine cycle using an organic working fluid. This section highlights the main applications of the ORC and the worldwide examples of each application.

2.2.1. Geothermal

The geothermal energy is naturally produced from the earth through the decay and release of temperatures within the earth layers, which is illustrated naturally by volcanos and hot springs. Figure 2.2 below shows an illustration of the geothermal energy.

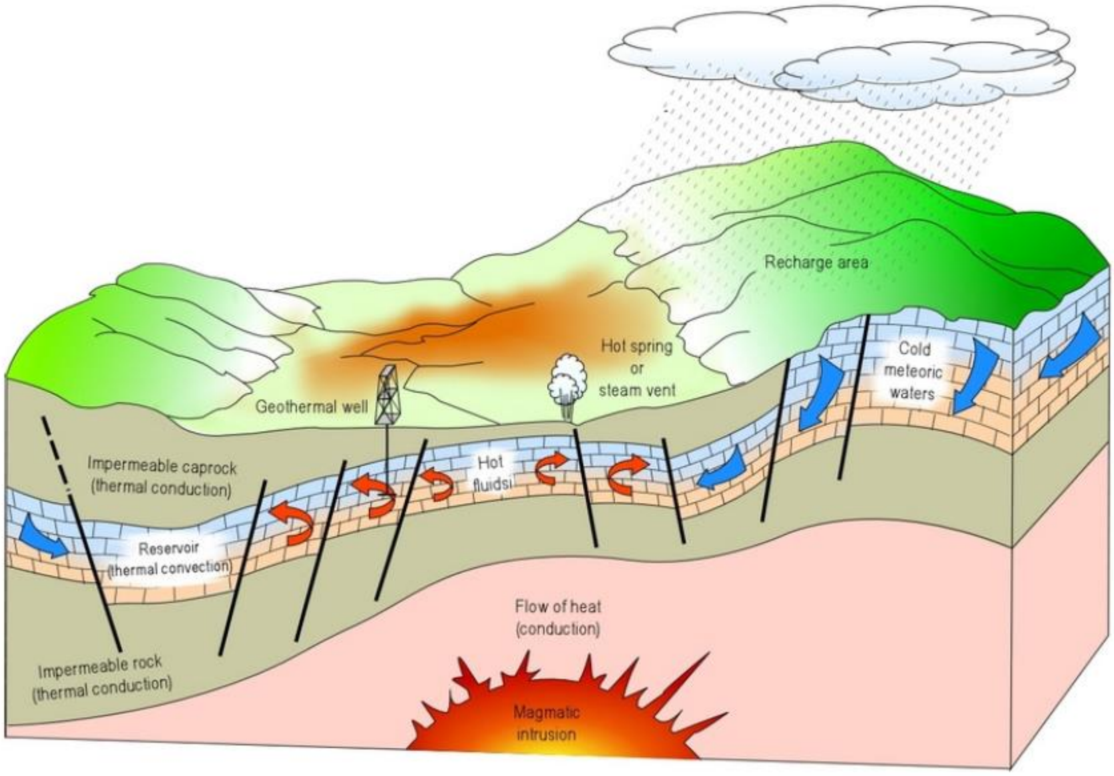

Figure 2.2. Geothermal energy [9].

The system basically pumps the thermal water from the geothermal wells, which could reach up to 3 kilometers below the earth surface, and form a second loop which heats and preheats the working fluid in the ORC system, as illustrated in Figure 2.3 below. The geothermal ORC is considered one of the most utilized applications for power production. The United States, Philippines and Indonesia are the top three countries using this application with 16,603 GWh/year, 10,311 GWh/year, and 9,600 GWh/year, respectively [9].

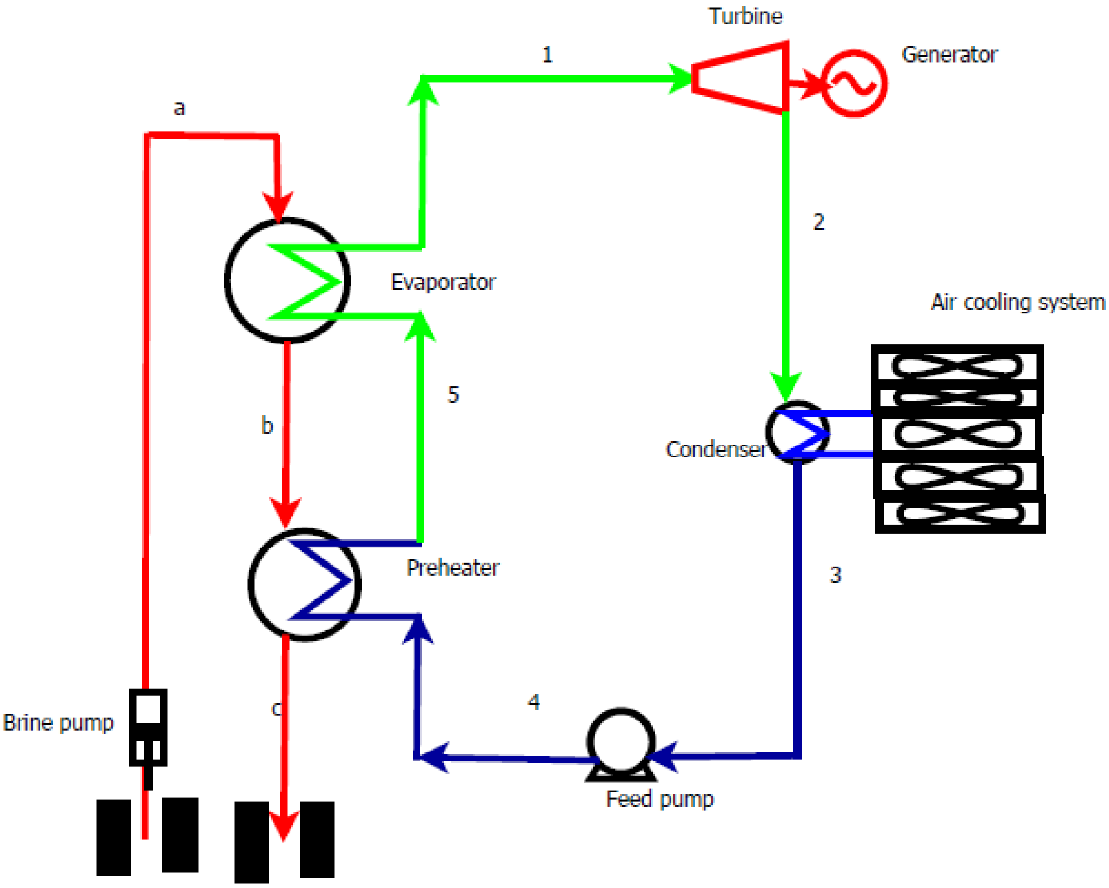

Figure 2.3. Geothermal ORC schematic diagram [9].

2.2.2. Solar

The usage of solar energy in ORC is one of the most developing technologies for ORC, which is attributed to the maturity of the solar renewable energy assemblies and the high efficiency achieved through their utilization. Another advantage that helps the development of this technology for ORC is the possibility to use it for smaller and domestic scales, e.g. housing projects, in comparison with other systems such as geothermal ORC and waste heat ORC [10] presented a model, where solar collectors can be used for heating and power applications using an organic Rankine cycle as shown in Figure 2.4 below.

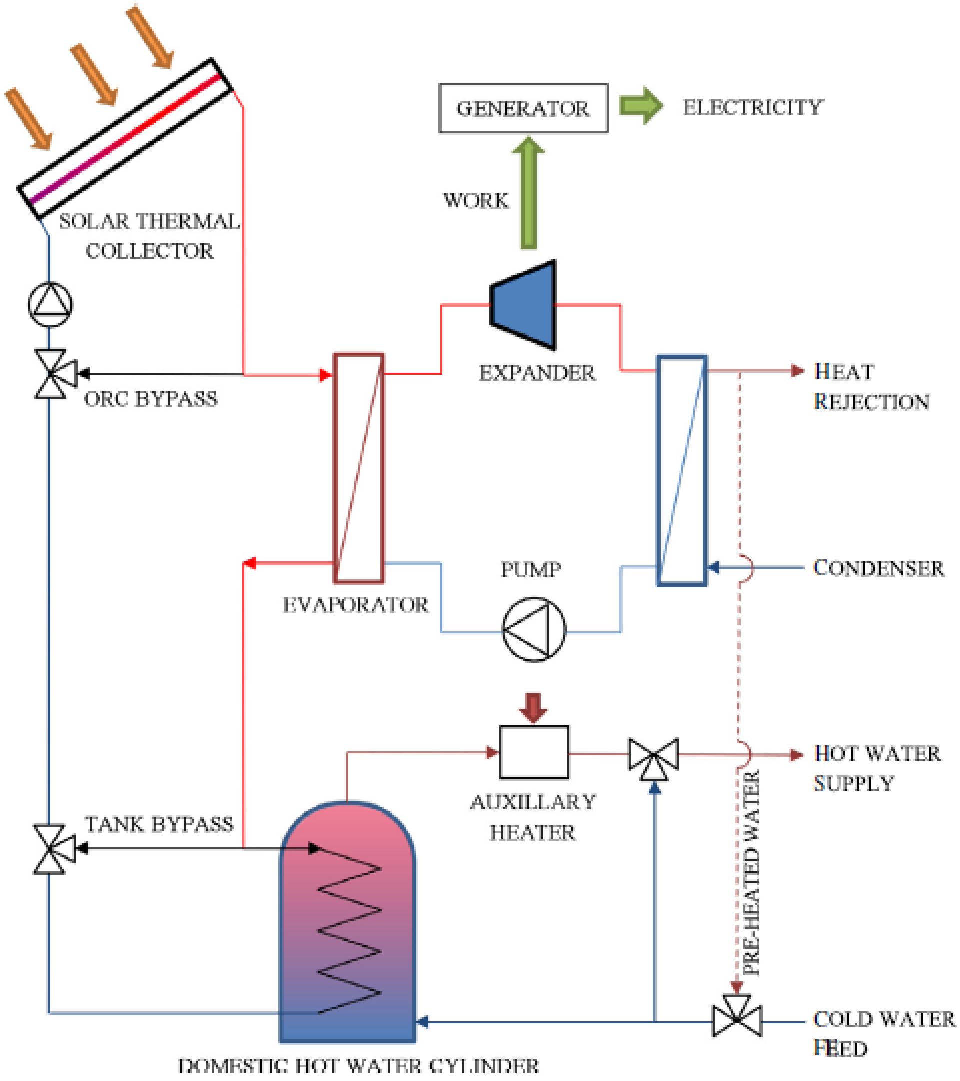

Figure 2.4. Solar ORC application for heating and power [10].

2.2.3. Waste Heat

ORMAT, which is one of the leading companies in manufacturing and maintaining ORC systems on a global scale, provided two main examples Figure 2.5 below shows an example of a heat recovery ORC assembly. The report mentions an application to a German cement factory, which generates 1300 kW of power and contributing more than 10% of the energy used by the plant. A second application is mentioned for a power plant in Canada, where the working fluid is RB211 and generating a net power to grid of 6.5 MW [3].

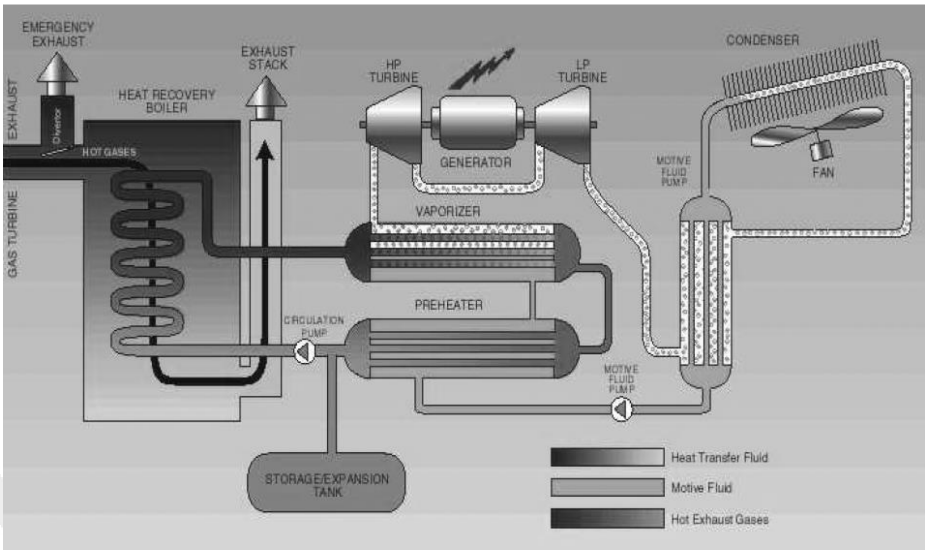

Figure 2.5. ORC assembly application for heat recovery by ORMAT [3].

2.3. SYSTEM CONCEPT AND COMPONENTS

The liquid fluid is pressured by the pump then injected into the evaporator, where the fluid’s status changes to vapor under heat. Thereafter, the vapor expands in the turbine, which is connected to the electric generator. The vapor is condensed and pulled by the pump in order to move it back to the starting point of the cycle [11]. An Internal Heat Exchanger (IHX) can be added to the system between the pump and the evaporator and between the turbine and the condenser in order to increase the efficiency of the system [6,12]. Figure 2.6 and 2.7 show the components of the ORC without and with the Internal Heat Exchanger, respectively.

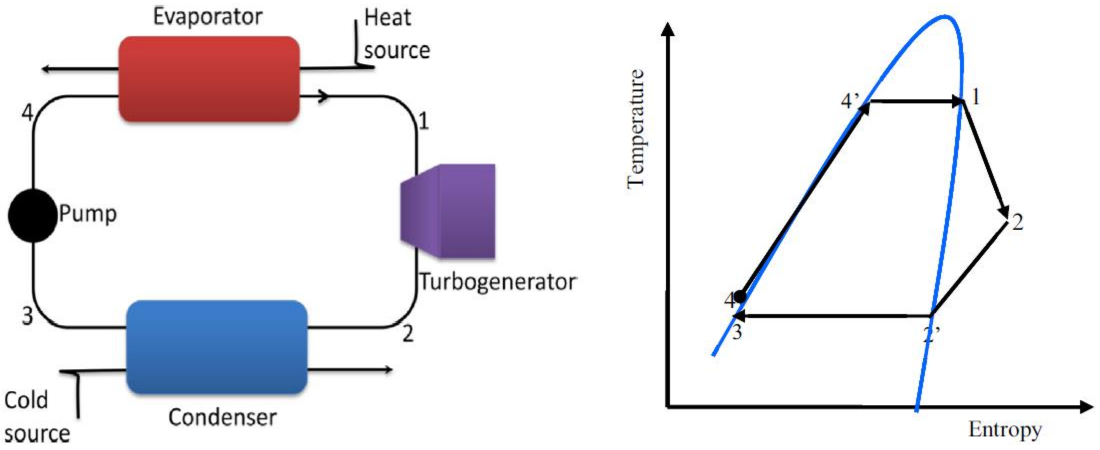

Figure 2.6. ORC without internal heat exchanger [13].

Figure 2.6 illustrates a basic Rankine cycle with a schematic diagram and a T-s diagram showing four basic processes of the Rankine cycle, which are [13]:

1. Fluid vapor expansion in turbine (1-2)
2. Heat released from the fluid at the condenser (2-3)
3. Fluid compressed by the pump (3-4)
4. Fluid heating up (4-1)

In the T-s diagram, points 2’ and 4’ refer to variations of the process depending on working fluid type and preheating processes, respectively [13].

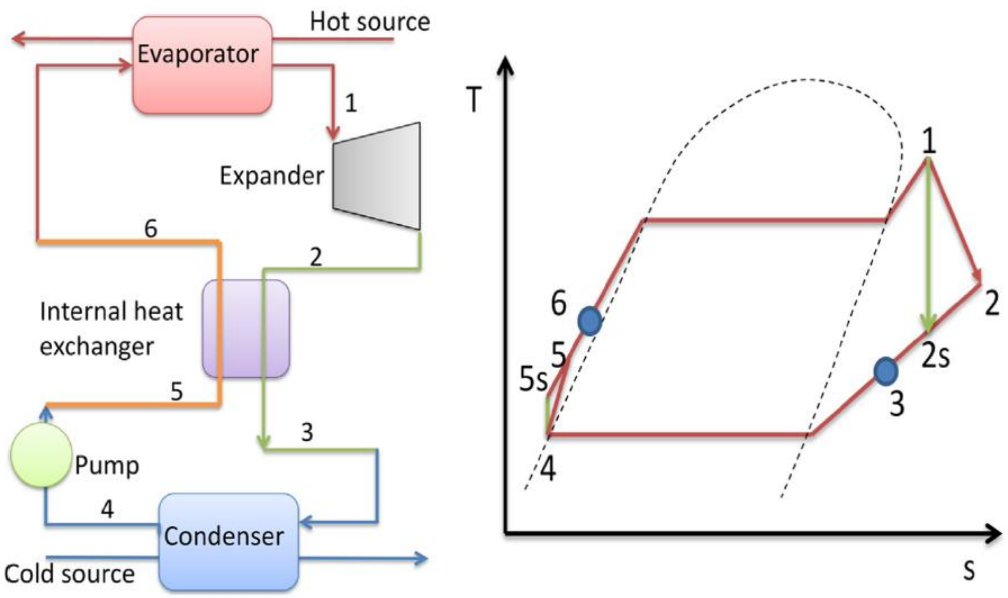

Figure 2.7. ORC with internal heat exchanger [13].

The selection of the working fluid is based on several factors in order to empower the most efficient thermodynamic properties to be used in the ORC. Based on studies these factors are summarized as the following [6]:

1. Environmentally friendly: based on the international agreements and the scientific research, the fluid used in ORC must satisfy certain limits of Ozone Depleting Potential (ODP), and Greenhouse Warming Potential (GWP) in order to prevent harms to the ozone layer protecting the earth and the creation of a greenhouse effect.
2. Safe: there are three requirements under this factor, using ASHRAE classification, which intend to ensure no harms to humans operating or living by the system, as well as the safety of the of the equipment used to build the system. Therefore, the fluid must be non-toxic, non-corrosive, and non-flammable.
3. Stable: the fluid need to reserve its chemical properties during the function of the system to prevent toxic or unfavorable impacts of any resulting compounds.
4. Pressure required for efficiency: this factor is related to the cost of the system. The higher the pressure requirement of the fluid for efficiency would result into a higher cost as it needs to endure more resistance.
5. Available quantity: as the fluid is more available, this impacts its costs, which works better for ORC applications from an economic point of view.
6. Latent heat and molecular weight: more energy is absorbed by a fluid with high latent heat and higher molecular weight, which increases the efficiency of the system, making it possible to reduce the flow rate from the pump to the evaporator.
7. Freezing point: to prevent blockage in the system, the fluid needs to have a point of freezing lower than the ORC's lowest temperature.
8. Curve of saturation: there are three profiles for the curve of saturation, which are illustrated in Figure 2.8 below and represent the wet, isentropic and dry profiles of the 1-2 segment, respectively. Those profiles (dT/ds) are also referred to negative (a), vertical (b) and positive (c), respectively. The reason

this factor is crucial for selection of the working fluid is that an overheating of the vapor may cause damages to the turbine and reduces the efficiency of the cycle.

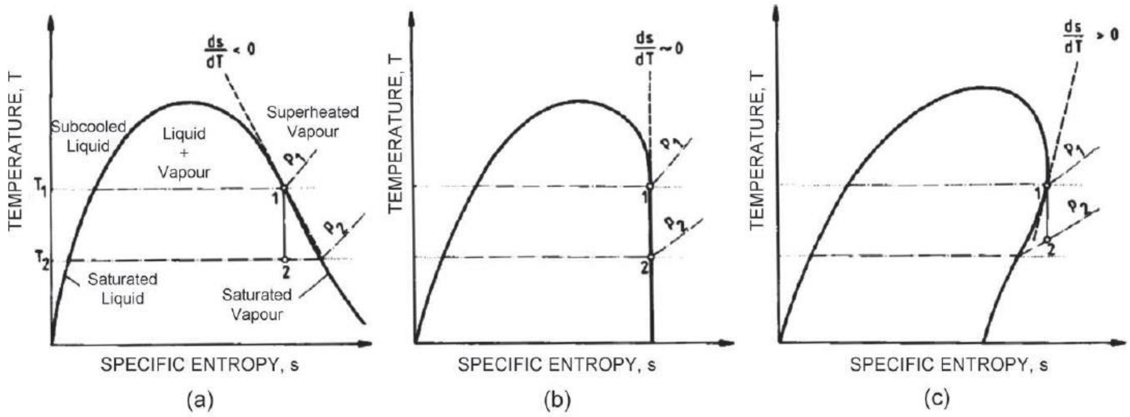

Figure 2.8. Temperature-Entropy profiles for ORC working fluids [6].

Due to the many requirements that rules the choice of the working fluid of the ORC, this subject is one of the most important criteria that dominate the design and functionality of any system, and there are many studies that tested the best fluids to be used for ORC. However, the selection of the fluid must be specific to a system and the temperature, which the ORC is intended to be operating under [6].

Furthermore, working fluids are often mixed together in order to get a certain performance criterion as presented in Table 2.1. The mixture percentages differ in efficiency according to the heat source temperature. The working fluids of the ORC system are known to affect the performance of the ORC, which makes them one of the most researched topics in ORCs [14,15] Therefore, Figure 2.9 shows the efficient mixtures curves for natural hydrocarbons (a) ad fluorinated hydrocarbons.

Table 2.1. Working fluids properties [16].

Fluid Mix	$T_{G,max}$ (T_1=25ºC)	$T_{G,max}$ (T_4=25ºC)	dT/ds
R134a/ R236fa	6.05	4.00	-/+
R134a/ R245fa	15.14	11.13	-/+

(Table 2.1. Continuing)

R134a/ RC318	5.17	3.52	+
R152a/ R245fa	12.70	8.99	-/+
R227ea/ R245fa	9.51	6.33	+
R236fa/ R365mfc	15.63	12.22	+
R245fa/ R365mfc	6.50	5.92	+
Propane/ isobutane	7.21	5.14	-/+
n-butane/ n-pentane	10.45	8.60	+
Isobutane/ isopentane	12.21	9.90	+
n-pentane/ n-hexane	8.55	7.27	+
Isohexane/ n-pentane	4.32	3.67	+

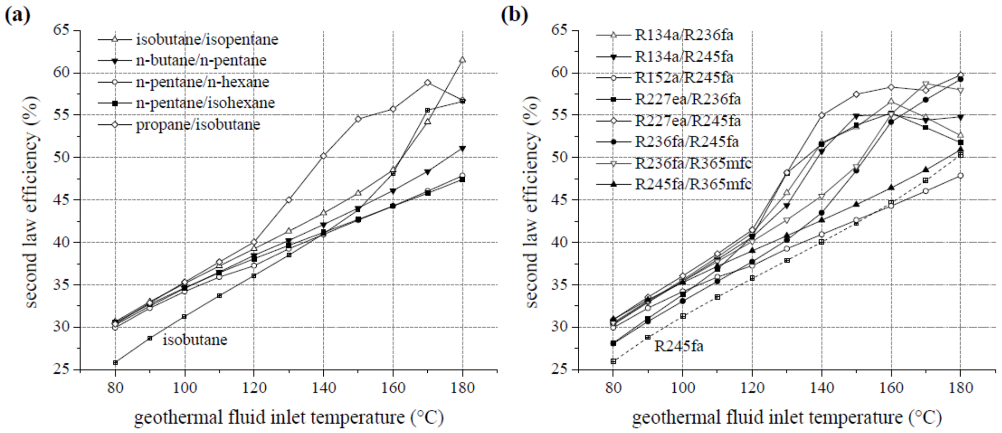

Figure 2.9. Efficient zeotropic mixtures for ORC [16].

2.4. ORC EVALUATION, EFFICIENCY AND FEASIBILITY

The evaluation of an organic Rankine cycle is often divided into two main stages, which are the technical and economic evaluations. Therefore, this section reviews the technical assessments carried out in the literature along with the different commercial assessments.

2.4.1. Technical Evaluation

In order to evaluate the feasibility of an ORC system, a calculation for the power output based on the application is necessary [17]. Calculated the energy output of a solar ORC using the conventional model presented in Figure 2.10 below. The calculations are also verified with other studies [18-21].

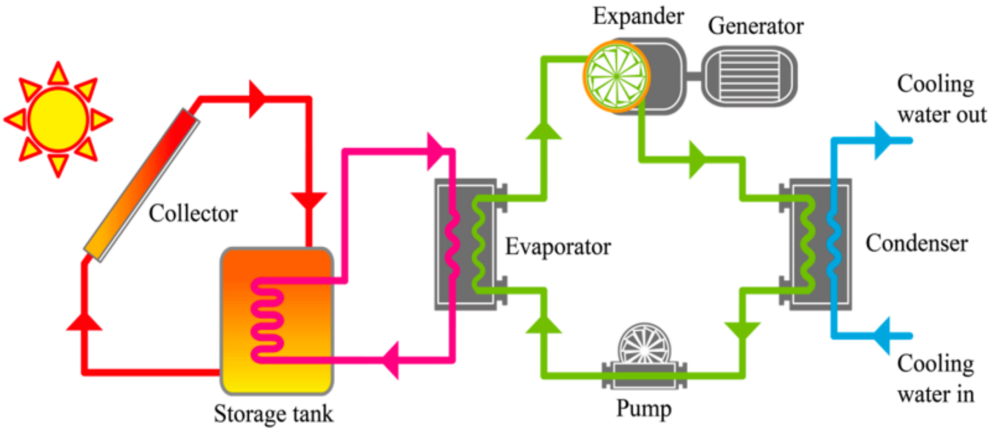

Figure 2.10. Solar ORC model [17].

The energy and thermodynamics calculations started by understanding the solar radiation available in the study case by obtaining readings for the 12 months of solar insolation in kWh/m^2/day and the daylight hours possible in every month [22]. The initial assumptions were set for the calculations as follows [17]:

1. A steady state thermodynamics
2. Adiabatic feed and expansion devices for the working fluid.
3. Pressure losses in the system are neglected.
4. The reference state for the calculations are 25ºC for the temperature and 1 bar for the pressure.

For each component of the system, a steady state energy balance is applied through equations (1) and (2) [17]:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{2.1}$$

$$\dot{Q} - \dot{W} + \sum \dot{m}_{in} \quad h_{in} - \sum \dot{m}_{out} \quad h_{out} = 0 \tag{2.2}$$

Moreover, the exergy destruction rate is calculated using equation (3) [17]:

$$\dot{E}_{d\,,k} = \dot{E}_{X_Q} - \dot{E}_{X_W} + \sum \dot{m}_{in} \; ex_{in} - \sum \dot{m}_{out} \; ex_{out} \tag{2.3}$$

Exergy transfer from heat and work is calculated as per equation (4) [17]:

$$\dot{E}_Q = \sum \left(1 - \frac{T_0}{T}\right) \dot{Q} \tag{2.4}$$

The collected energy rate is defined by equation (5) for each vacuum tubular collector [17]:

$$\dot{Q}_u = \dot{m}_c \left(C_p \, T_o - C_{pi} \, T_i\right) \tag{2.5}$$

To calculate the area of the collector, equation (6) is used [17]:

$$\dot{m}_C \, (h_0 - h_i) = G_b \; \eta_C \; A_C \tag{2.6}$$

The solar ORC efficiency is calculated by equation (7) [17]:

$$\eta_{SORC} = \eta_c \; \eta_{ORC} \tag{2.7}$$

The exergy input from the sun is calculated using equation (8) [17]:

$$E_{sun} = A_c \, G_b \, \left(1 + \frac{1}{3}\left(\frac{T_0}{T_S}\right)^4 - \frac{4}{3}\left(\frac{T_0}{T_S}\right)^4\right) \tag{2.8}$$

The net electrical exergy efficiency is calculated using the following equation:

$$\eta_{ex,el} = \frac{\dot{W}_{net}}{Ex_{in}} \tag{2.9}$$

Systems are currently presented, where an efficiency reaching to 25% can be obtained from solar ORC assemblies, covering a wide range of temperatures and yielding up to 1000 Watt per square meter [4]. Figure 2.11 below shows an efficiency versus temperature curve from one of the manufacturer's data sheet for solar ORC system. Nonetheless, the efficiency of the solar collector and ORC system have different relations to temperatures. Thus, the efficiency of the overall system is represented with a resultant graph as shown in Figure 2.12.

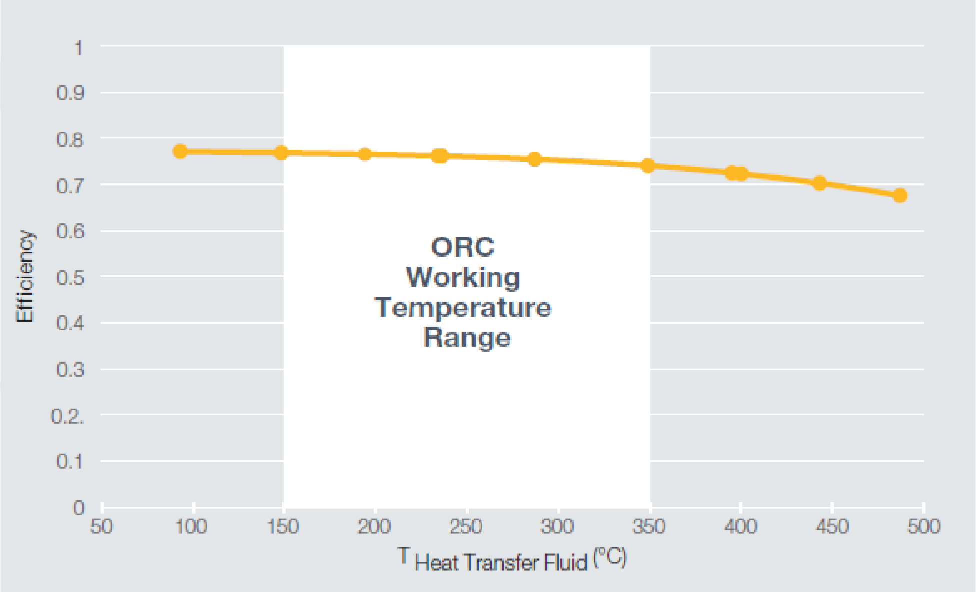

Figure 2.11. Efficiency versus Temperature curve for solar ORC from SkyFuel [4].

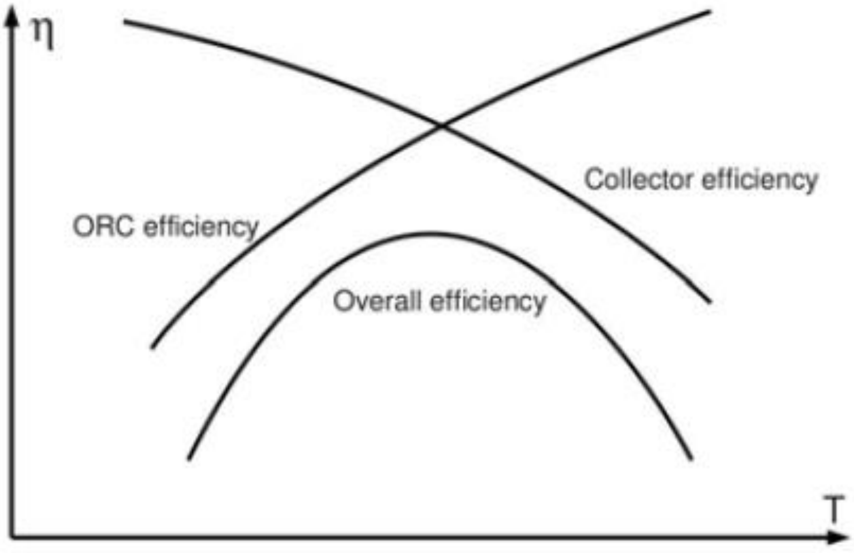

Figure 2.12. Relation between temperature and ORC / Collector efficiencies [8].

Furthermore, in the application of waste heat ORC and specifically in the cement industry, for each 1000 tons of cement produced from the plant, 1 MW of electricity is produced [23]. Table 2.2 shows an estimation of the power production from waste heat ORC in different industries.

Table 2.2: Estimated ORC electric production from waste heat in different industries [23].

Industry	Cement	Glass	Steel
Plant Capacity (ton)	2,500	500	6,000
Possible thermal power (MW)	12	5	13
Thermal power to ORC (MW)	11	4.7	13
Net ORC electric production (MW)	1.6	1	2.4
Annual electricity production (MWh/y)	12,800	8,000	19,200

2.4.2. Economic Evaluation

The economic evaluation of an ORC depends on many factors including the system design, capacity, working fluid type, and application type. Moreover, there are few costs that shall be included in the economic evaluation of ORC:

1. Initial cost, which is the amount that should be invested in order to set up the design and install the assembly.
2. Generation cost, which includes the operational and maintenance costs and usually expressed as the amount of money per kW generated.

Table 2.3 shows the calculated initial and generation costs as per different studies for different applications and capacities.

Table 2.3. Literature cost evaluations for ORC initial investment and generation cost [16,17].

ORC Application	Power Capacity	Cost type	Cost Estimation (USD)
Waste heat recovery	5 kW	Initial	2,392 to 4,771 per kW depending on working fluid
Waste heat recovery	30 to 120 kW	Initial	3,983 to 5,555 per kW
Geothermal	20 MW	Initial	3,360 per kW
Geothermal	NA	Initial	4,200 per kW for 120 ºC and 2,800 per kW for 150 ºC
Hybrid geothermal and solar	NA	Generation	104 to 135 per kW using working fluid R245fa
Solar	22.6 kW	Generation	0.28 to 0.81 per kW depending on solar source temperature

Moreover, the cost of the components of the organic Rankine cycle unit in US Dollar (C_0) can be estimated using equation (10) based on Table 2.4 [16]:

$$\log_{10} C_0 = K_1 + K_2 \log_{10}(Y) + K_3 (\log_{10}(Y))^2 \qquad (2.10)$$

Table 2.4. ORC components cost data [16].

Component	Y; unit	K_1	K_2	K_3	Y_{min}	Y_{max}
Pump	kW	3.3892	0.0536	0.1538	1	300
Heat Exchanger	m^2	4.8306	-0.8509	0.3187	10	1000
Turbine	kW	2.7051	1.4398	-0.1776	100	4000

Thereafter, the ORC total cost is calculated by multiplying the total cost of the equipment by 6.32 as per [16], which accounts for design and installation costs.

CHAPTER 3

LIBYAN ENERGY AND INDUSTIRAL SECTORS

The purpose of this chapter is the highlight the potential of the ORC system applications through the study of different case studies from the world, as well as focusing on the Libyan case. Therefore, the chapter starts with introducing two feasibility studies and reports from India and Turkey. Moreover, the Libyan current and forecasted power demands are reviewed according to official resources, in addition to reviewing Libya’s solar and waste heat potentials. Finally, a review of studies that included ORC case studies from Libya are reviewed for results and discussion.

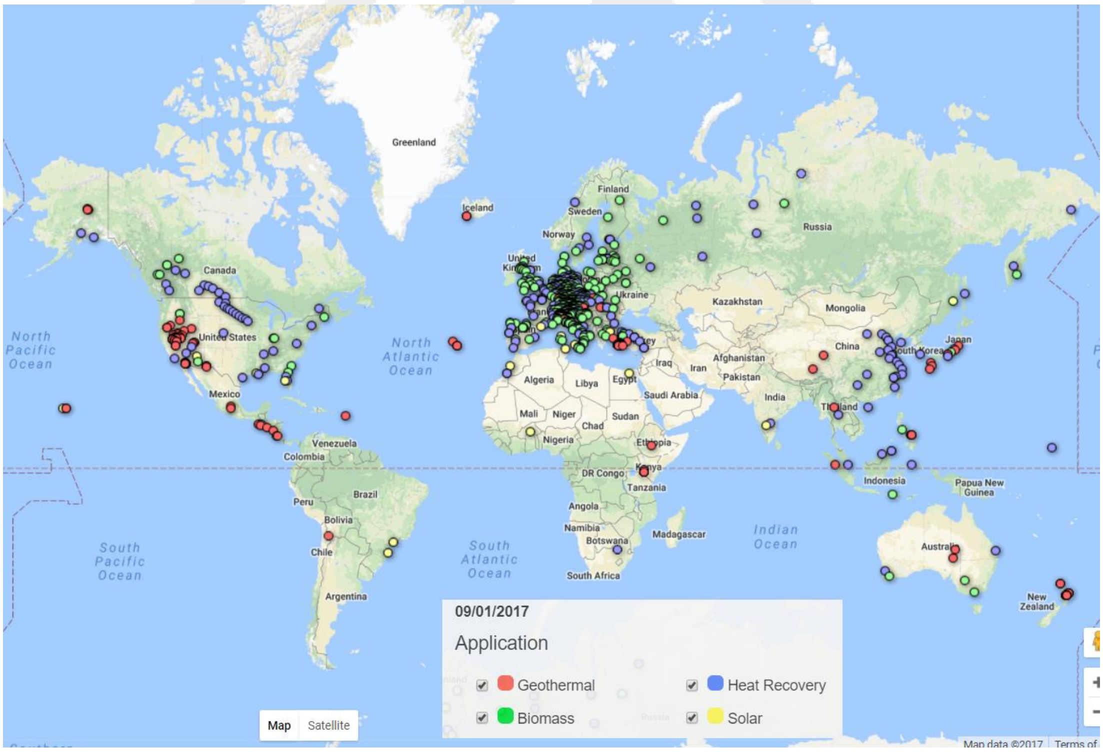

Figure 3.1. ORC World map [24].

3.1. ORC POTENTIAL IN DIFFERENT COUNTRIES

There are several studies that were performed in different countries in order to show the potential or success of the ORC system in different applications. For the sake of this research two examples are reviewed from India and Turkey for a waste heat ORC and solar ORC. Goel et. al. [25], issued a report studying the potential of using Organic Rankine Cycle for a waste heat application in India. The report focuses on three key industries in the country, which are cement, glass and steel factories that have the potential to recycle the wasted heat into power. The usage of this methodology can reduce the energy consumption of the factories from the power grid or the power generated from domestic power plants.

According to the plans set by the Indo-German Energy forum, supported by the Indian and German governments, the report shows the potential power production from waste heat in the three industries. Figure 3.2 shows the current and potential power capacities from the cement industry, which is planned to produce up to 574.2 MW by 2017. Figure 3.3 illustrates the same potential power capacity for the steel industry, where the plants are planned to produce 148.4 MW by 2017. The report also investigates the potentials of biomass and solar ORC systems in India to produce 2,208 MW and 1,440 MW by 2017, as shown in Figures 3.4 and 3.5, respectively [25].

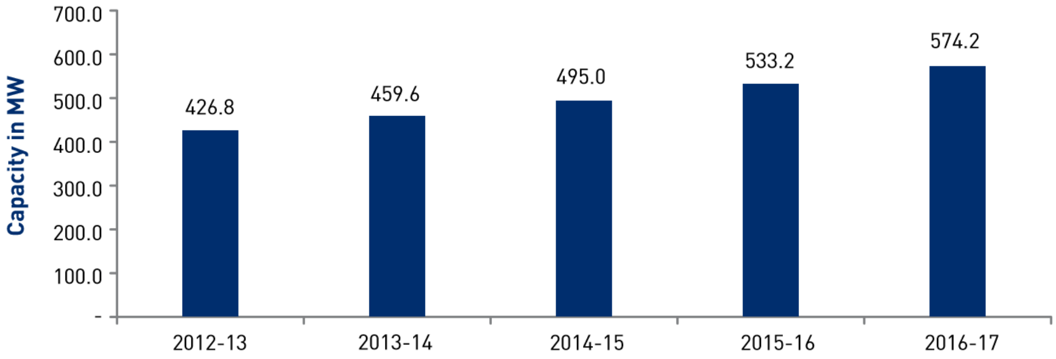

Figure 3.2. Potential power by ORC system from cement industry in India [25].

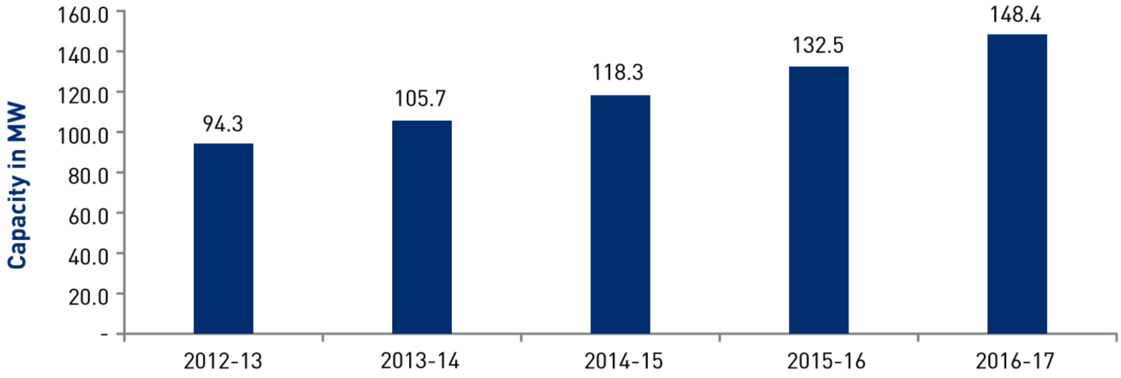

Figure 3.3. Potential power by ORC system from steel industry in India [25].

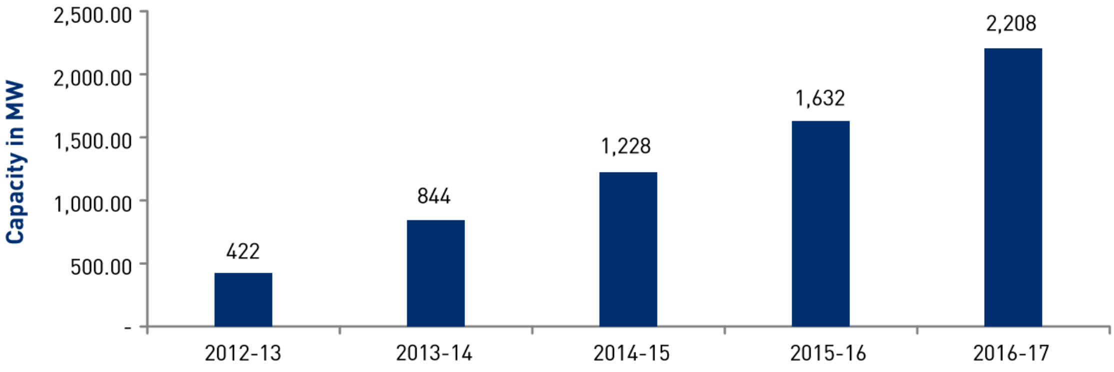

Figure 3.4. Potential power by ORC system from biomass in India [25].

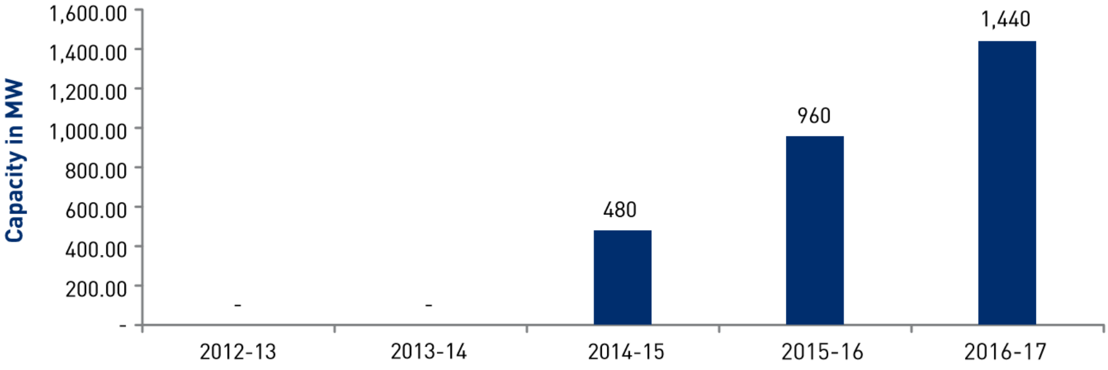

Figure 3.5. Potential power by ORC system from solar in India [25].

A Turkish study shows the current and forecasted energy production from different ORC applications from a technical and economic perspectives. The geothermal sources have the potential to generate up to 550 MW of energy, while the solar resources, Figure 3.6, is expected to produce 9000 MW due to the geographic location of Turkey in comparison to the European countries. Biomass and heat recovery are also promising in ORC applications in Turkey, according to the study. Due to the limited fossil fuels available locally in the country, the study recommends the usage of possible renewable energy sources using ORC applications, which can provide a payback on investment for an estimated 2.7 years [22].

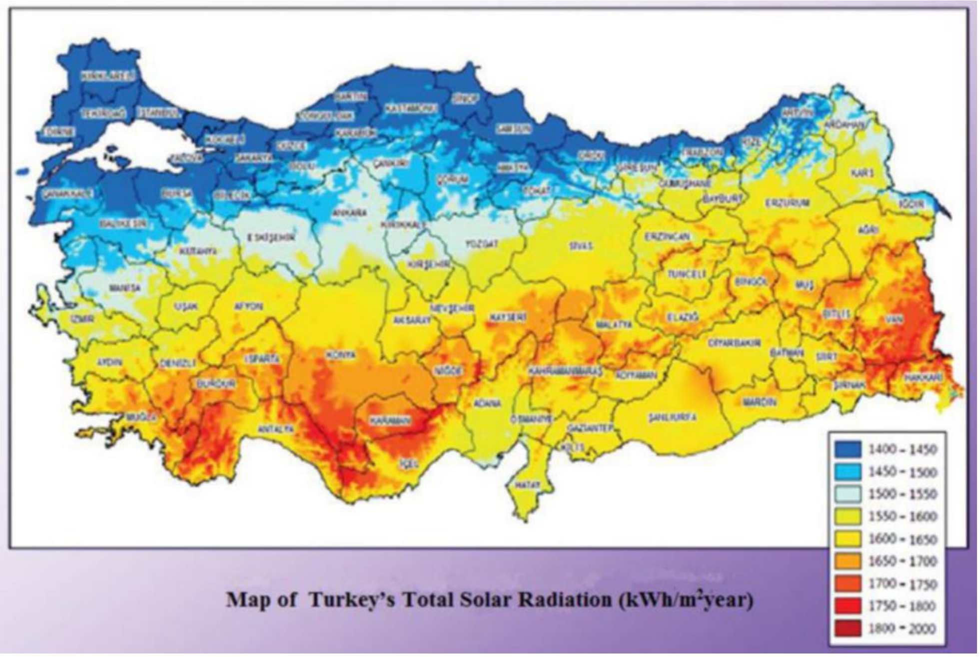

Figure 3.6. Turkey's solar radiation measured in kWh per m^2 per year.

3.2. LIBYA ENERGY DEMANDS

According to a report issued by the Tenth Arab Energy conference, the full energy demands of Libya are satisfied from fossil fuels including oil and natural gas. While the country is rich with oil reserves, there is a direction to utilize the potential of the country from renewable energy sources, especially the solar sources. In 2012, the total capacities of power generation plants in Libya are approximately 9,038 MW. The majority of the produced energy is used by the public facilities such as commercial establishments and street lighting. Figure 3.7 show the electricity the previous, current and future electricity demands in Libya until the year 2030 [26].

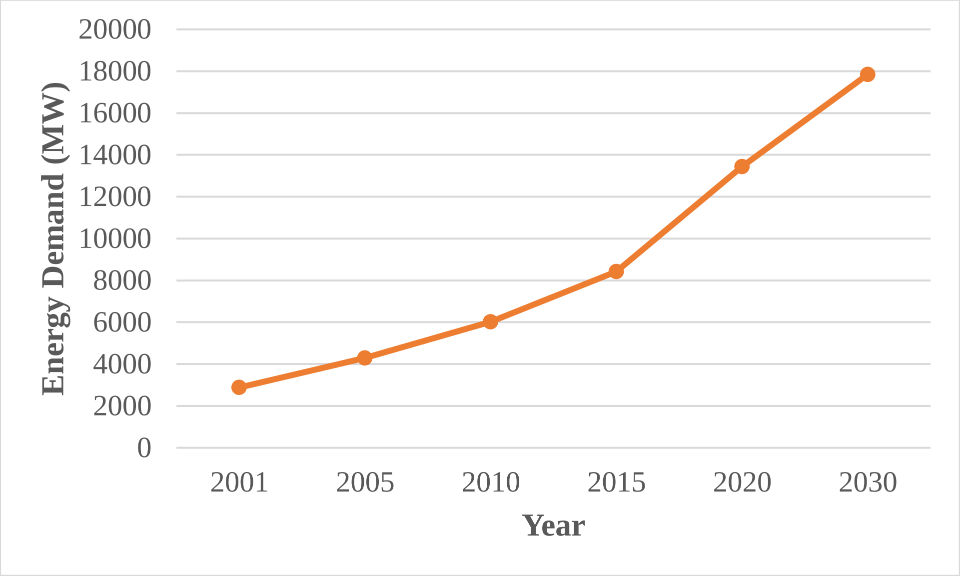

Figure 3.7. Current and future energy/ electricity demands in Libya [26].

The country's demands and production of fossil fuels shows that Libya needs to consider renewable energy sources in its energy strategy. Although Libya have shifted in the last decade to natural gas as a strategy to reduce the dependency on diesel for energy, it is expected for the country to increase its current demands by 60% by the year 2020 in order to compensate for the shortages and supply the development projects with the necessary energy. Therefore, the research into renewable energy sources is required.

3.3. LIBYAN SOLAR AND WASTE HEAT POTENTIALS

In addition to its rich oil and natural gas reserves, the geographic location of Libya grants it a high supply of solar radiance, between 15° and 35° North [27], as well as a strategic location to supply the near African and European countries with power. The country has the potential to generate approximately 140,000 TWh/ year of electricity from solar technology [28]. The direct normal irradiation map, Figure 3.8, shows that more than 95% of the geographic area can supply a minimum annual solar power of 1900 kWh/m^2, as an annual average, which provides a daily average of 7.5 kWh/m^2/day [27]. The peak of the sun radiation occurs in the summer months between May and August in the majority of the Libyan cities, as shown in Figure 3.9.

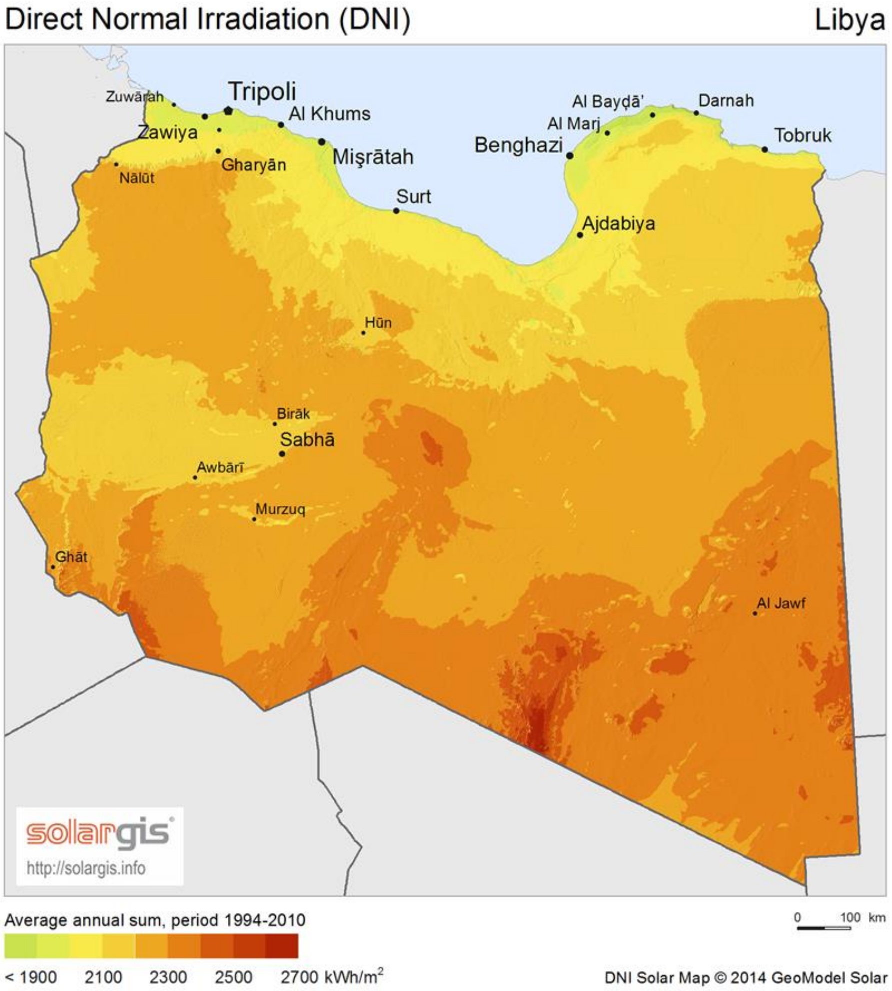

Figure 3.8. Direct normal irradiation in Libya [29].

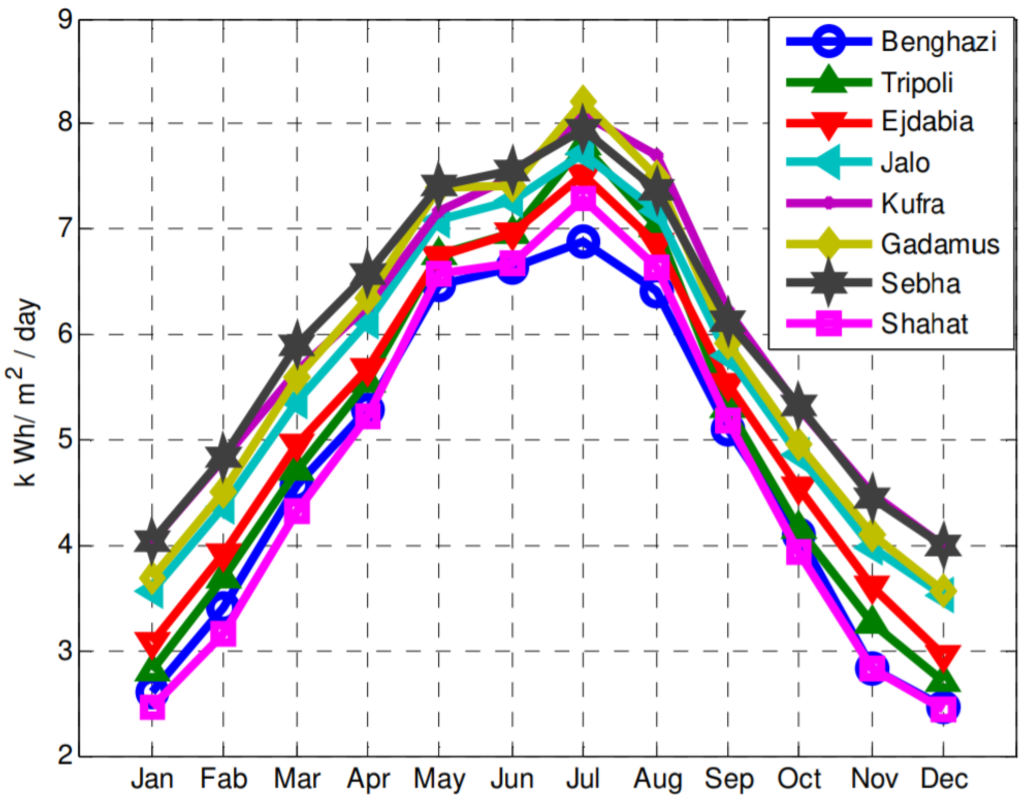

Figure 3.9. Yearly solar radiation in different areas in Libya [27].

For waste heat ORC, there are two main industries in Libya that have the potential for energy production, which are the cement and steel industry. There are seven main cement factories in Libya, five of them are around the Tripoli region while the other two are near the Benghazi area. The target production of the factories range between 300,000 tons to 1,000,000 tons per year [30]. In a USGS report in 2008, the Libyan cement facilities had a total production capacity of 8 million tons per year, with plans to increase this capacity to 15 million tons per year by the year 2011 [31]. However, due to the security and political situation of the country, those projects were put on hold. Therefore, the capacity that would be considered in this research id the original 8 million tons per year reported in 2008.

Furthermore, the iron and steel production in Libya is considered one of the key industries in the country, which enabled a total export of 680,000 metric tons of different steel products in 2008. In the same year, Libya produced 1.57 million tons of processed steel, the main two facilities are located in Misrata with 550,000 and 650,000 tons per year, and 1.14 million tons of crude iron, which are the numbers considered in this study [31]. There are other mineral industries that are operating in Libya including glass production. Nonetheless, their significance is minimal in comparison to the cement and steel sectors.

3.4. LIBYAN ORC STUDIES

The three studies investigated in this section were applied to case studies in Libya. The first case study investigated the efficiency of an ORC assembly taking into account the geographic location of Dernah in Libya with 6 kWh/m^2/day as the radiation input. The model considered for the ORC system is illustrated in Figure 3.10. The ORC system is energized using parabolic trough collectors connected to a thermal storage system, while the ORC contains the main components of evaporator, turbine, condenser and pump. The fluids used are water for the condenser and evaporator system, and oil (Therminol VP-1) for the PTC and thermal storage system [32].

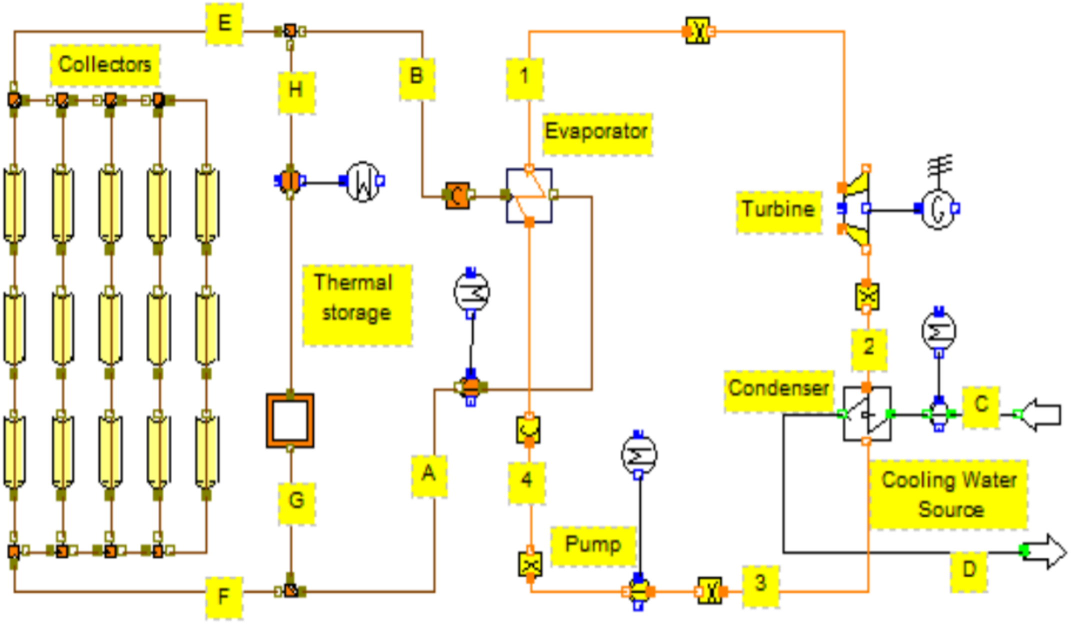

Figure 3.10. Solar ORC model [21].

The system was studied during three operational periods, which are the day, the night and the storage modes. The average efficiency for the three modes is calculated at 6.6% and the average power production is 1.5 MW for the model. The model took into consideration a solar radiation incident on the collector of 29 MW and a collector optical efficiency of 0.76 [21]. A similar system was experimented by the same institution and team, where the focus was drawn to the components of the system rather than the irradiance absorbance periods. The system was able to produce 3 MW of energy without using the heat storage system, achieving an overall efficiency of 11% for the whole system [33].

Furthermore, technical and commercial feasibilities were conducted on three models in Libya, where the direct normal irradiation differs in three areas; Tripoli, Sebha and Alkufra. The study shows that the minimum economic area for PTC for the three areas ranges between 0.271 km^2 and 0.50 km^2 depending on the geographic location, solar radiation, and implementation of a thermal storage system. The best technical and commercial performance were recorded at 3000 kWh/m^2 DNI rate, as it produced 224.5 GWh with a storage system with a payback period of 9.6 years (IRR = 9.68%). However, at that location the capital costs and operating costs were the highest with energy cost of 8.82 cents per kWh [34].

CHAPTER 4

ORC FEASIBILITY STUDY

This chapter represents the case study of the research, where ORC system characteristics are assumed based on the literature in order to facilitate the technical feasibility study. The technical feasibility estimates the possible energy production from the ORC system in Libya based on the solar and waste heat potentials. Moreover, an economic evaluation is applied in order to understand the total investment costs and running costs in such a project for Libya.

4.1. ASSUMPTIONS AND ORC MODEL

The model assumed for this research is for the solar ORC proposed by [4], Figure 4.1 and Figure 4.2. However, adjustments for the system are applied in order to adapt to the Libyan case study and apply the parameters found in previous case studies for the country, which were reviewed in chapter 3 of this thesis. Although the majority of the studies have experimented models with efficiency rates of 6.6% to 11%, the SkyFuel system claims an efficiency up to 25%. Therefore, a different efficiency rate is proposed for the case study.

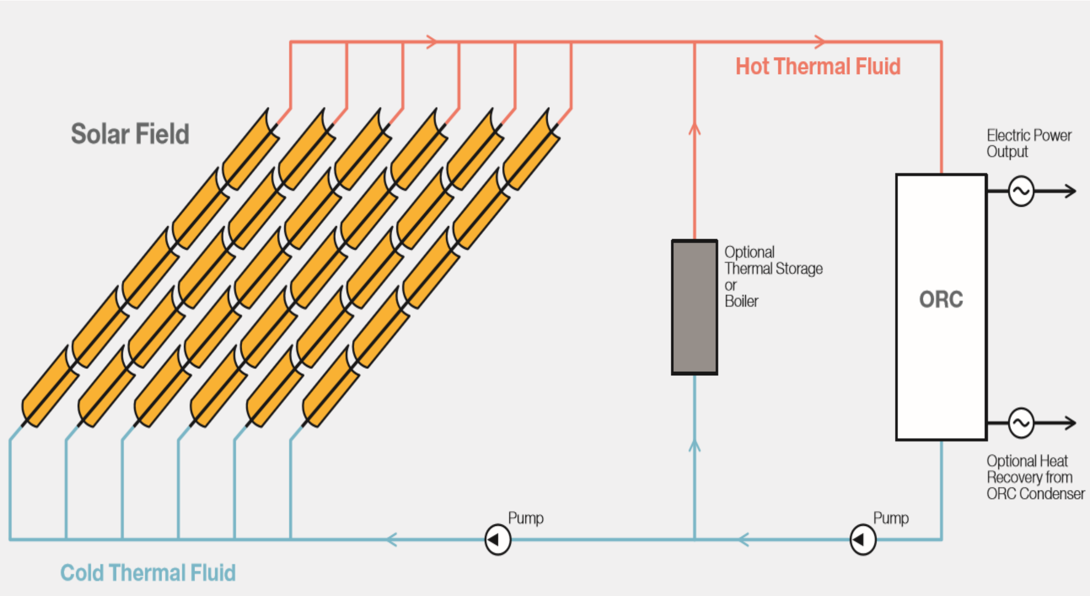

Figure 4.1. Schematic diagram of SkyFuel ORC system [4].

Figure 4.2. SkyFuel parabolic trough collectors [4].

For the waste heat ORC technical feasibility, the energy, power and efficiency rates used in [23] are applied to the case study. The extent of the study covers the current industrial capacities in Libya for the cement and the steel sectors in order to produce figures similar to [25].

The economic feasibility compares two models for the project costs, which are presented through [16] and [34]. Average rates are produced as an estimation. Moreover, the operational costs depend on the power produced and the operational costs presented in [34]. Finally, the final rates are compared with the current costs for fossil fuels for final economic feasibility.

4.2. TECHNICAL FEASIBILITY

This section applies the assumptions of the research into the Libyan case study based on the adopted assembly. Moreover, the solar calculations are carried out separately from the waste heat calculations, which are based on different concepts. Moreover, the number of facilities are calculated based on the country's power demands' forecasts and the current industrial facilities in Libya.

4.2.1. Solar ORC

In order to have a conservative efficiency rate the average of the three efficiency rates is calculated at 14.2%. Table 4.1 shows the adjusted specifications of the system for a single unit. A thermal storage system is assumed with the assembly in order to increase the operational period of the project. According to the Libyan case study, a minimum of 1800 kWh/m^2. Therefore, the input from solar radiation is expected to raise for the system unit from 40 MW to 72 MW. Moreover, the same 0.5 MW for system operation is assumed, producing a net power output of 10.2 MW. Furthermore, according to [34], a minimum of 0.50 km^2 reflector area is needed for a feasible facility. Therefore, the parameters in Table 4.1 are adjusted accordingly and the detailed calculations are provided in Appendix A of this thesis.

Table 4.1. Adjusted SkyFuel solar ORC system for the Libyan case study.

ORC thermal to electric efficiency	14.2%
Unit reflector area	0.50 km^2
Thermal input from PTC	653 MW
Thermal to ORC power	92.7 MW
Facility power consumption	4.6 MW
Final electric output	88.1 MW

According to [26], the current energy demands of Libya are at 9,038 MW, and are expected to increase by 60% by 2020. Therefore, the final energy demands in 2020 are calculated, as follows;

Libya energy demands in 2020 (MW) = (Demand in 2014 x 60%) + Demand in 2014
Libya energy demands in 2020 = 9,038 MW x 1.6 = 14,460 MW

Energy Demand increase = Demand of 2020 – Demand of 2014
Energy Demand increase = 14,460 – 9,038 = 5,422 MW

As the country has a vision to have 25% of its energy generated from renewable energy by 2030, we assume the same percentage is generated from solar ORC;

Assumed power from solar ORC = Energy Demand Increase x 25%
Assumed power from solar ORC = 5,422 MW x 0.25 = 1355.5 MW

According to the abovementioned assumptions, the number of facilities required to bridge the energy expansion gap is calculated as the following;

$$\text{Number of Solar ORC facilities} = \frac{Assumed\ power\ from\ solar\ ORC}{Final\ Electric\ Output\ of\ one\ unit} \qquad (4.1)$$

$$\text{Number of Solar ORC facilities} = \frac{1355.5\, MW}{88.1\, MW} = 15.38 \tag{4.2}$$

Therefore, the number of solar ORC facilities needed is 16 facilities with a net power output of;

Total facilities power output = Number of Solar ORC facilities x Final Electric Output of one unit

Total facilities power output = 16 x 88.1 = 1,409.6 MW

4.2.2. Waste Heat ORC

Based on the net power outputs for waste heat ORC reviewed in [23], for a cement production facility, 1.6 MW is generated for every 2,500 ton of cement production. Moreover, 2.4 MW can be generated from steel production for every 6,000 tons of steel. According to the Libyan capacity productions for the cement and steel sectors, 8 million tons of cement and 1.2 million tons of steel are produced are produced in seven and two plants, respectively. Therefore, the ORC net power generation in a year production is calculated as the following:

Net power from WH ORC in cement facilities can be calculated with Eq. 4.3 and Eq.4.4;

$$Net\ power\ in\ cement\ facilities = \frac{Produced\ tons\ of\ cement}{2{,}500}\ x\ 1.6 \tag{4.3}$$

$$Net\ power\ \ in\ cement\ facilities = \frac{8{,}000{,}000}{2{,}500}\ x\ 1.6 = 5{,}120\ MW \tag{4.4}$$

Daily net power from WH ORC in cement facilities can be calculated with Eq. 4.5. and Eq. 4.6.

$$Daily\ net\ power\ from\ WH\ ORC\ in\ cement\ facilities = \frac{Net\ power\ from\ WH\ ORC\ in\ cement\ facilities\ for\ a\ year's\ production}{Number\ of\ days\ in\ a\ year} \tag{4.5}$$

$$Daily\ net\ power = \frac{5{,}120}{365} = 14.03\ MW \quad (4.6)$$

Net power from WH ORC in steel facilities can be calculated with Eq. 4.7. and Eq. 4.8.

$$Net\ power\ in\ steel\ facilities = \frac{Produced\ tons\ of\ steel}{6{,}000}\ x\ 2.4 \quad (4.7)$$

$$Net\ power\ in\ steel\ facilities = \frac{1{,}200{,}000}{6{,}000}\ x\ 2.4 = 480\ MW \quad (4.8.)$$

$$Daily\ net\ power\ from\ WH\ ORC\ in\ steel\ facilities = \frac{Net\ power\ from\ WH\ ORC\ in\ steel\ facilities\ for\ a\ year's\ production}{Number\ of\ days\ in\ a\ year} \quad (4.9)$$

$$Daily\ net\ power\ from\ WH\ ORC\ in\ steel\ facilities = \frac{480}{365} = 1.32\ MW \quad (4.10)$$

4.3. ECONOMIC FEASIBILITY

According to [34], a 0.5 km^2 PTC facility has facility has installation costs that includes preparation of the site, setting up the facility components, and production costs for the energy. Table 4.2 shows the calculations for the installation and production costs of the solar facility of the case study.

Table 4.2: Installation and operational costs of solar ORC facility.

Cost	Unit	Price for 88.1 MW
Site preparation	\$50 per m^2	\$ 25,000,000
Solar collectors	\$295 per m^2	\$ 147,500,000
Heat transfer system	\$80 per m^2	\$ 40,000,000
Storage system	\$100 per kWht	\$ 1,057,200 *
Generator	\$1500 per kWe	\$ 1,321,500
Capacity expense	\$70 per kW in year	\$ 16,896
Production expense	\$3 per MWh	\$ 2,315,268
Total		**\$ 217,210,864**

*. Assumed for 12-hour daily storage

Based on the above calculations, the price for each kW is calculated as the following;

$$kW\ price\ (\$) = \frac{\$\ 217{,}210{,}864}{88{,}100} = \$\ 2{,}465.5 \qquad (4.11)$$

Assuming that the investment is made over the next 3 years, the unit price for electricity production is calculated, as follows;

$$Energy\ unit\ price = \frac{\frac{\$\ 217{,}210{,}864}{3}}{88{,}100\ x\ 24\ x\ 365} = 9.38\ ¢\ per\ kWh \qquad (4.12)$$

The result of economic feasibility is compared with the results of [34], where the unit price of energy generation from solar ORC is ranging between 16.27 ¢ per kWh and 8.82 ¢ per kWh. Thus, the result of the economic feasibility is within the price range of solar ORC facilities in Libya.

Moreover, the total cost for the sixteen facilities planned as per this proposal is;

Total Solar ORC facilities cost = $ 217,210,864 x 16 = **$ 3,475,373,824**

CHAPTER 5

CONCLUSIONS

This chapter provides the final remarks on the study results based on the literature review and the performed case study results. Furthermore, the researcher provides his recommendations for implementation and consideration.

5.1. FINAL REMARKS

Due to the worldwide high expenditure on fossil fuels for energy, the ideas of renewable energies are becoming one of the most prioritized subjects. The main mature renewable technologies are wind and solar energies, where efficiencies make the investment reliable and the there are several technologies developed such as energy storage that made the power supplies from these technologies more feasible and reliable. Moreover, there are several industrial processes that cause energy loss through heat, which made the specialist think about ways to invest this lost energy into a form of a recycled power.

This research investigated the Organic Rankine Cycle technology and its applications for power generation through a sufficient literature review, in addition to a case study application for Libya. The main characteristic that makes the ORC feasible is its operation under low to medium temperatures. The system operates mainly through heat exchange between a heat source and an ambient source, which releases the energy into the form of power or electricity. There are several types of ORC that are operating worldwide, such as:

1. Solar ORC: collecting radiation through PTC units.
2. Biomass ORC: using biomass as a source of heat.
3. Geothermal ORC: using earth’s internal heat as an energy source.

4. Waste heat: using lost heat from industries to produce the energy needed for the cycle.

A simple ORC system consists of two cycles intersecting through an evaporator. The first loop contains the heat source, while the second source contains a cold fluid source, condenser and a generator. A heat exchanger may be used in order to increase the efficiency of the ORC system. The use of the working fluid is one of the most important factors in ORC system, which are selected based on:

1. Impact on the environment.
2. Safe use for human health.
3. Stability in order to avoid any toxic effects.
4. Providing the required pressure.
5. Availability for application.
6. Evaporating and freezing points.

In order to perform the technical and economic evaluations of the research, several studies are reviewed to set the different parameters for the case study. One of the most important parameters in ORC technical evaluation is the efficiency of transforming the heat from the source into actual power or electricity. The efficiency of the ORC system is calculated through a series of equations reviewed through [17]. Moreover, according to [23], waste heat net energy generation can be calculated through knowing the capacity of the manufacturing facility.

For the economic evaluation of the ORC system, the total energy produced is compared to the costs required for generation. The main influential parameter is the efficiency of the ORC system, where more efficient electricity is produced, the unit price of energy becomes more feasible. Furthermore, ORC system prices can be calculated through using ORC cost equation reviewed in [16].

Several studies have proven the success of ORC system in recycling lost energy from the sun or manufacturing facilities, as seen in the Indian and Turkish Case. Therefore, the Libyan case study commenced by studying the country’s current and projected demands for power. Libya currently has a demand reaching to 9,038 MW and it is expected to increase by 60% by 2020 due to the needs of the country for rebuilding and development. Therefore, possible investments can be made in the ORC systems due to the high exposure to solar energy in the country and the availability of several manufacturing facilities that can reduce the pressure on the current grid power.

Previous studies for Organic Rankine Cycle in Libya have proven the feasibility of the system from a technical and economic point of views [32-34]. Therefore, the case study adopted an ORC system with high efficiency by SkyFuel in order to check and prove the feasibility of the system in Libya. The results of the study show that building sixteen solar ORC units with the capacity of 88.1 MW over the next three years could provide Libya with 25% of the required projected power demand. This feasibility study comes in line with the country's vision to provide 25% of its power from renewable resources, which also includes other technologies.

The case study has shown that due to the significant cement and steel industries in Libya, some of the power needed for these facilities can be provided by recycling the waste heat generated; 14.03 MW from cement facilities and 1.32 MW from steel facilities. Moreover, the economic evaluation shows that a single facility generating 88.1 MW costs $ 217,210,864 with a unit price of 9.38 ¢ per kWh, which is a very feasible price in comparison with [34]. However, in the contrary to [34] the payback time is set for three years, which is reasonable for the project. The total project cost of the solar ORC is $ 3,475,373,824.

5.2. RECOMMENDATIONS

Based on the literature and the Libyan case study for the ORC system, the researcher would like to provide his recommendations as the following:

1. Based on the country's vision for the renewable energy system's implementation, further exploration for the ORC system shall be carried out such as; geothermal and biomass applications.

2. Allocations in the Libyan budget shall be made to support the vision of renewable energy utilization, and diversification of renewable energy types to include the ORC systems.
3. Implementation of modern ORC systems that has a better efficiency than the ones included in the previous studies in order to support the feasibility of the ORC system with solar and waste heat application.
4. Provide laws that encourage private sector to use ORC systems with tax reduction and environmental regulations that reduces the dependency on fossil fuels for power generation.

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APPENDIX A.

SKYFUEL SYSTEM ADJUSTMENT CALCULATIONS

ORC thermal to electric efficiency	14.2%
Unit reflector area	0.50 km^2
Thermal input from PTC	653 MW
Thermal to ORC power	92.7 MW
Facility power consumption	4.6 MW
Final electric output	88.1 MW

$$ORC\ thermal\ to\ electrical\ effeciency = \frac{\eta_1 + \eta_2 + \eta_{SF}}{3}$$

$$\eta = \frac{6.6+11+25}{3}$$

η= 14.2 %

According to [4], the reflector area required for a net power output of 9.5 MW is 55,104 m^2. The least feasible area for the Libyan Case is 0.50 km^2. Therefore;

55104 m^2 = 0.055104 km

$$\frac{0.50}{0.055104} = 9.07$$

The Skyfuel system calculations are based on 1000 W/m2, while the Libyan minimum irradiance is 1800 W/m^2. Therefore, the 40 MW output can be converted to 72 MW for the Libyan case study. Based on that the thermal energy output is calculated as the following:

Thermal energy output = 72 x 9.07 = 653 MW

Applying the efficiency rate of 14.2%,

Thermal to ORC power = 653 x 0.143 = 92.7 MW

Facility power consumption is based on the increase in reflector area rate. SkyFuel specifies 0.5 MW as a power consumption for its unit. Thus, the power consumption of the facility is calculated as follows;

Adjusted facility power consumption = 0.5 x 9.07 = 4.6 MW

Final electric power output = 92.7 MW – 4.6 MW = 88.1 MW

RESUME

Ahmed GamalAldin ALSAWAIAH was born in Dernah, Libya in 1987 and he graduated first and elementary education in this city. He completed high school education in 2007, after that, he started undergraduate program in Omar-Al-Mukhtar University Department of Engineering in 2012. Currently, he is assigned to his work in the Ministry of Interior and completing his assignment for masters in energy system from Karabük University.

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