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A feasibility study for utilizing waste heat to generate electrical power using organic Rankine cycle (ORC)

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Abstract- Alexandria National Refining and Petrochemicals Company (ANRPC) is a refinery in Alexandria, Egypt. A considerable amount of heat is wasted from the steam system after being utilized by different processes within the refinery. The utilized steam which can be recovered has an average flow rate of 15 Ton/hour, an average pressure of 4.5 bar, and an average temperature of 180°C~220°C. The company decides to conduct a cost-benefit analysis to assess the feasibility of a proposed Organic Rankine Cycle (ORC) system to convert this waste heat into electric power. The approach used in this study is mainly an industry perspective. It deals with the ORC unit as an investment opportunity, with its associated cost and benefits rather than its thermodynamic performance, which was discussed in several previous papers. The most two important questions to be answered are: what is the total cost of the ORC system (including the unit price, transportation, customs, installation, integration with the process, commissioning, and startup), and what are the financial benefits of the project (including the yearly energy saving, the decrease in the peak load, and the corresponding carbon dioxide (CO_2) emission reduction). This paper aims to be a guide for the decision-makers in the industry to support their decisions concerning the feasibility of installing ORC systems to recover waste heat and convert it into power. Based on the heat content of the waste heat stream and the efficiency of the evaporator (heat exchanger) of the working organic fluid, we can calculate the power that could be generated from the turbine (expander), and based on the efficiency of the generator, we can calculate the electrical power that can be generated (recovered) from the waste heat. In our case study, the expected generated electric power is 1,750 kW or equivalently, 15,000,000 kWh of electrical energy annually. Financial analysis shows that the ORC system, including the cost of the unit plus the costs of installation and integration into the process, will cost approximately 4.8 Million USD. The payback period is 4 years. The ORC unit will reduce the CO_2 emissions as a result of not generating this amount of energy using traditional methods by approximately 7,500 Ton annually. The ORC technology is an attractive solution for industries seeking for utilizing their waste heat to generate power, hence, decreasing their energy bills and contributing to reducing CO_2 emissions and combating global warming and climate change.

Keywords- Cost Benefit Analysis, Energy Efficiency, Feasibility Study, Organic Rankine Cycle (ORC), Waste Heat Recovery.

I. INTRODUCTION

A. *Waste Heat and Waste Heat Recovery (WHR)*

Industry consumes one-third of the energy worldwide [1]. About 50% of this energy is wasted as heat [2]. With increasing concerns on fuel scarcity / prices, global warming and climate change, more and more research attention has been drawn towards waste heat recovery in industrial thermal processes. Significantly, a major part of the wasted energy is identified as recoverable waste thermal energy. Thus, research on waste thermal energy utilization is urgent and imperative [3, 4].

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Waste heat can be categorized according to its temperature as low-grade (<230 °C), medium-grade (230–650°C), and high-grade (>650°C). Low-grade waste heat is especially promising because it accounts for more than 50% of industrial waste heat [5].

Facilities attempt to use waste heat inside their sites, normally in heating or preheating other processes. Alternatively, they can convert this wasted heat into power (WHP). This can be done using the traditional steam Rankine cycle (SRC) (named after its inventor, Rankine), which utilizes the heat energy to evaporate the working fluid (water or steam) and converts it to superheated steam with high pressure capable of rotating the blades of a steam turbine, thus generating a rotational mechanical power. When the steam turbine is coupled to an electrical generator, electrical energy is produced. Unfortunately, traditional steam cycles require a relatively high temperature (> 600°C) to boil the working fluid (water) and convert it to superheated steam. As a result, low-grade and medium grade waste heat are normally vented into the atmosphere with no economic usage, instead, they can contribute to the global warming and climate change, not mentioning the economic losses and decreased energy efficiency.

B. Organic Rankine Cycle (ORC)

The ORC is similar to the conventional SRC but it uses an organic fluid (such as Freon) instead of water (steam) as a working fluid. The main characteristic of the organic fluid is the low boiling temperature compared to water, allowing for the use of low-grade waste heat as a heat source to evaporate the working fluid [6].

ORC technology was mainly developed for harvesting low-grade heat from geothermal [7] and solar energy sources [8], as well as in some biomass applications [9]. ORC is used in WHR in industries such as aluminum [10], cement [11, 12], steel [13, 14], glass [15], ceramic [16], pulp and paper [17], petroleum [18, 19], automotive [20], among others. ORC is used also in WHR of gas and diesel engines [21], as well as in recovering waste heat from the internal combustion (IC) engine in the transportation sector [22]. Some ORC applications involve multi or hybrid heat sources with different natures. For example, the hot stream used to evaporate the organic fluid can be a combination of waste heat and solar energy [23, 24].

The total installed capacities of the ORC units worldwide exceeds 4 GW by the end of 2020 [25]. ORC plays a major role in converting heat that was previously wasted or vented or un-utilized to energy. This is mainly due to the simple, compact, and low-cost system components with small sizing and the properties of organic fluids that can utilize low and variable temperature heat sources. It should be noted however that for many industries, the decision to implement WHR solutions (including ORC) is mainly financial [26-28].

C. Components of the ORC

A typical ORC unit consists of four components, as shown in Fig. 1 [29-32]:

1) Evaporator, containing the organic fluid (usually in liquid phase), where the organic fluid is heated by the waste heat stream and its phase is changed to the gaseous state.
2) Turbine (expander), where the heated organic fluid in a gaseous state expands and rotates the blades of the turbine to produce mechanical work. The turbine is coupled to an electric generator to convert the mechanical power into electrical power. This is the output of the ORC unit.
3) Condenser (heat exchanger), where the organic fluid is cooled using artificial cooling (with air or water) till it is condensed and its phase changes into a liquid.
4) Pump, where the organic fluid in its liquid phase is pumped again to the evaporator, and the cycle repeats itself.

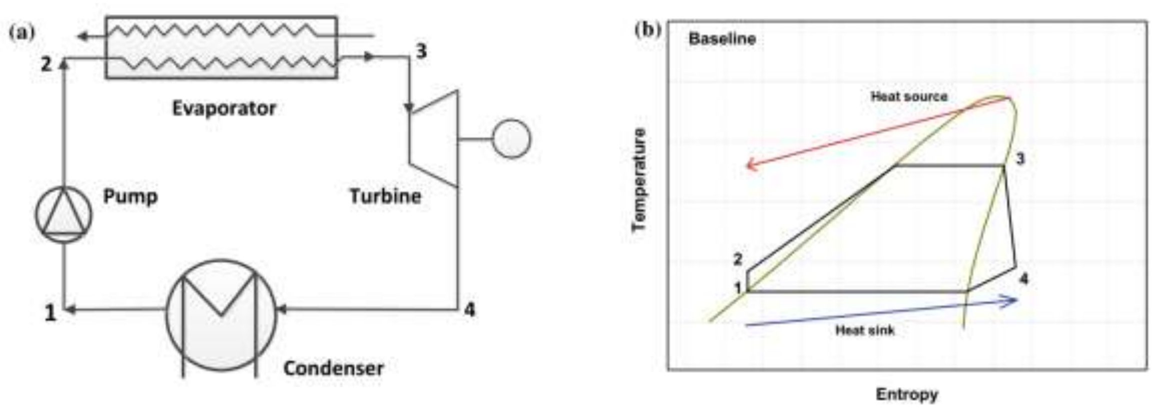

Figure 1. (a) ORC components and (b) Temperature (T) – Entropy (*s)* diagram

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In some ORC configurations, a super-heater is installed after the evaporator and before the turbine (expander) to make sure that the working fluid is not saturated or wet to avoid corrosion of the turbine. Sometimes, a re-cuperator (internal heat exchanger) is included before the condenser to capture the heat from the organic working fluid before being condensed. In some applications, especially when the outlet temperature of the turbine is relatively high, another ORC unit (cascade) may be included [33]. Some ORC units use some intermediate (or buffer) heating loop, normally thermal oil, to capture the heat content of the waste heat from several sources, and then, this heat carrier is introduced to evaporate the organic fluid.

D. Selection of the organic fluid

In addition to the quantity (flow) and the quality (temperature and pressure) of the waste heat, the performance of the ORC system depends mainly on the organic working fluid. There are over 100 organic fluids used worldwide. Organic fluids are classified according to their phase into dry, wet, and isentropic (mixed) [34]. Selection of the organic fluid depends on the fluid properties, including specific volume, flash point, thermal conductivity, as well as safety, cost, availability, toxicity, corrosiveness, and chemical stability at different temperatures. Moreover, the environmental factors, i.e. Ozone Depletion Potential (ODP) and Global Warming Potential (GWP) should also be considered [35, 36]. Water, the working fluid in the traditional SRC is environmentally friendly, non-flammable, non-toxic, and has zero ODP and zero GWP. ODP represents the relative amount of degradation that fluid can cause to the ozone layer relative to CFC-11 or Freon refrigerant (R11). GWP refers to the amount of global warming caused by a working fluid relative to CO_2 for 100 years. Fluids with no ODP and low GWP include benzene, propylene, toluene, propane, pentanes, butanes, and other fluids [37].

E. ORC efficiency and optimization

The efficiency of the unit is expressed in terms of its output electrical power relative to its input thermal power. The efficiency of early ORC units was normally in the range of 5~10% [38]. After a decade or more of continuous developments, the normal efficiency in nowadays ORC units is in the range of 10~20%. Theoretical models and simulated ORC units can show higher efficiency. The electrical power required by the pump is normally taken from the output (gross) power of the ORC and the resultant is the net power, leading to a net efficiency, obviously lower than the gross efficiency. Sometimes when the cooling system of the condenser is fan-cooled air, the power of the fans is taken from the output power of the ORC, and the net power is decreased once more.

F. Cost of the ORC system

A completed ORC system requires more than just the ORC unit. The ORC unit should integrate the source of waste heat from one side and the electrical grid from the other side. Therefore, the total cost of the ORC system should include both the capital or purchase cost in addition to the cost of installation and integration with the process. The purchase cost of the ORC units varies according to the size of the unit and the temperature grade of the waste heat. According to [39], the low-temperature ORC units can have an average Specific Investment Cost (SIC) from 2500 $/kW for a 50 kW unit and down to 1500 $/kW for a 250 kW unit. The SIC for the high-temperature ORC units can be as low as 1000 $/kW for a 2 MW unit. One of the European leading manufacturers of ORC units published some success stories with financial indicators in industries like cement, glass, steel, and oil & gas [40]. According to [41], the SIC of an ORC in the range of some hundred kW to some MW is in the range of 1100 ~ 2200 $/kW. According to [42], the SIC of an ORC above 500 kW is in the range of 1410 ~ 1580 $/kW.

Installation costs include transportation of the unit to the site, unloading and installing equipment (including cranes), civil work, supports, and any required permits. According to [43], installation of a 1 MW ORC unit for WHR costs approximately 32% of the cost of the ORC unit, without including the costs of integration. It was shown in [11] that the ORC unit costs about 82% of the total investment cost, whereas 18% of the total costs account for engineering, civil work, supervision, and commissioning. Integration equipment includes flanges, pipelines, valves, welding, cables, switchgear, control panel, local grid connection and protection devices, transformers (if required), adequate ventilation for the control room, and a UPS system [44].

The unit is normally designed to work automatically, with no or minimum personnel required. No or minimum maintenance is required (due to limited moving parts). The price of the organic fluid, which is circulated in a closed loop in the ORC unit, is considered negligible in economic studies. According to [10], an ORC unit that costs ~ 4.4 M $ and that generates ~ 830 kW of electrical energy needs about 50 kg of organic fluid, with a total price of ~ 550 $. Therefore, the Operation & Maintenance (O&M) costs are minimal for such a project.

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Table 1 shows some data of installed ORC units used in WHR with installed capacity > 100 kW. In general, when the size of the ORC unit increases and /or the temperature of the waste heat stream increases, the SIC of the unit decreases.

Table 1. SIC of WHP using ORC

Industry	**Temp. of waste heat**	**Cost ($)**	**Power (kW)**	**SIC ($/kW)**	**Reference**	**Year**
Oil & Gas	140°C	10.5 M	2,100	5000	[45]	2012
Oil & Gas	280°C	15 M	9,000	1666	[46]	2017
Oil & gas	420°C	2.6 M	2,300	1130	[47]	2014
Cement	327°C	11.5 M	3,770	3050	[48]	2020
Cement	372°C	22 M	8,000	2750	[49]	2016
Cement	480°C	8 M	4,500	1777	[50]	2021
Chemicals	84°C	3.1 M	1,000	3100	[43]	2011
Chemicals	90°C	286 K	119	2400	[51]	2013
Aluminum	180°C	4.4 M	830	5300	[10]	2022
Boiler	163°C	585 K	177	3300	[52]	2021

II. CASE STUDY

ANRPC is a refinery in Alexandria, Egypt. Its core business is to produce gasoline with octane numbers 92 & 95 that is free from lead. The refinery consists of several processes. The steam required for heating processes is generated using an in-house boiler fired by natural gas with a capacity of 100 Ton/hour. The actual loading of the boiler is 60 Ton steam/hour with a gauge pressure of 14 bar and steam temperature of about 300°C. After heating the different processes, most of the utilized steam is collected and condensed into the water to be circulated to the boiler. One stream of utilized steam can be easily recovered with a flow rate15 Ton/hour, a pressure of 4~5 bar (gauge), and a temperature of 180~220°C.

The mathematical relations that are used to calculate the evaporator capacity, the turbine power, the condenser capacity, and the pump power are given by equations (1) through (4). The net power and the net efficiency are given by equations (5) & (6). Where "$\dot{m}$" is the flow rate of the waste heat (in kg/s) and "h" denotes the enthalpy of the working fluid at different points (stages) of the cycle, regarding Figure 1 (b) [29].

Evaporator Capacity (kW)	$Q_{evap} = \dot{m}\,(h_3 - h_2)$	(1)
Turbine Power (kW)	$W_t = \dot{m}\,(h_3 - h_4)$	(2)
Condenser Capacity (kW)	$Q_{cond} = \dot{m}\,(h_4 - h_1)$	(3)
Pump Power (kW)	$W_p = \dot{m}\,(h_2 - h_1)$	(4)
Net Power Output (kW)	$W_{net} = Wt - W_p$	(5)
Net Efficiency	$\eta = W_{net} / Q_{evap}$	(6)

In this research, Benzene is selected to be the working fluid. Its boiling point (80°C) is well below the minimum waste heat stream temperature (180°C). It has zero ODP and zero GWP, it is cheap and readily available in the market. These data, together with the site-specific parameters are given in Table 2.

Table 2. Input Parameters of the ORC unit

Parameter	**Value**
Flow rate	15 Ton/hr
Pressure	4~5 Bar g
Temperature	180~220 °C
Ambient temperature	30°C
Working fluid	Benzene
Boiling point of working fluid	80°C

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III. RESULTS

The parameters of Table 3, together with the enthalpy values (from tables or charts) are substituted in equations (1) through (6) to calculate the main parameters of the proposed ORC unit. The amount of wasted heat in the excess steam is calculated, and then multiplied by 80%, the efficiency of heat exchanger between the heat source and the working fluid. Then the thermodynamic model of the organic fluid is worked out in the MATLAB software. The results are shown in Table 3. The most important number from the industry perspective is the net output power. This is approximately 10% of the average power of the refinery. That means that we can decrease the energy bill by 10% without spending a cent on fuel prices, and in addition, we can decrease the refinery's carbon footprint.

The cost of the proposed ORC unit including transportation to Alexandria seaport is 4 M$. Other costs for installation and integration are shown in the total cost breakdown of Table 4. The total ORC system costs about 4.8 M$.

The annual savings in the electricity bill of the company are shown in Table 5. Energy costs $0.08/kWh and the cost of the monthly peak load demand is $3/kW of peak demand. The ORC system can result in net annual savings in the electricity bill of the company by approximately $1.2 Million, with a ***payback time of 4 years (after a year for construction)***.

According to the energy mix in Egypt as of 2020, the CO_2 emission intensity is estimated at 500 gCO_2/kWh of energy generated [53]. This means that for every 1 kWh of electrical energy generated by the ORC in replacement of that generated by conventional sources, an equivalent 0.5 kg of CO_2 emissions will be reduced. For the proposed ORC unit, which is assumed to be in service for ~ 8600 hours yearly, the expected generated energy per year is ~ 15,000,000 kWh, which will ***reduce the CO_2 emissions by 7,500 Tons annually***, as summarized in Table 6.

Table 3. Proposed ORC Unit Parameters

Parameter	Value
Thermal power in waste heat	10,500 kW equivalent
Gross electrical power generated	1,950 kW electrical
Gross efficiency	18.5%
Cooling	Air-cooled
Power used internally in pump & fans	200 kW
Net Power Output	1,750 kW
Net Efficiency	16.66%

Table 4. ORC Project Cost Breakdown

Parameter	Value
The capital cost of the unit	$4,000,000
Transportation to site costs	$100,000
Installation & Civil Costs	$300,000
Integration Costs	$200,000
Costs of 2-year spare parts	$200,000
Total Capex	$4,800,000

Table 5. ORC Financial Savings

Parameter	Value
Net Output Power	1,750 kW
Yearly operating hours	8,600 h
Expected generated energy per year	15,000,000 kWh
Price of kWh	$ 0.08
Cost of generated energy per year	$1,200,000
Cost of reduced load demand per year	$60,000
Annual saving	$1,260,000
O & M annual costs	$60,000
Net annual savings	$1,200,000

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Table 6. Cost / Benefits of the ORC System

Parameter	Value
Total Investments	4.8 M $
Annual saving	1.2 M $
Payback Period	4 years
CO_2 Annual Reduction	7,500 Ton

IV. Discussions

Payback time is a simple financial index but we cannot rely on it alone to take decisions for projects that cost several million dollars and that have a lifetime of approximately 20 years. More accurate financial indices like Net Present Value (NPV) and Internal Rate of Return (IRR) can be used to include the time value of money. From an industry perspective, the cash flow is more important, as shown in Figure 2. The prices of electricity are supposed to rise each year by 5%. The same percentage is applied to the O&M costs. During the first year of the project, we have a minus cash flow (meaning that we spend 4.8 M$, the cost of the project). Starting from the second year, we begin to gain savings. The break-even point (when the cumulative savings are zero) comes after approximately 5 years (or 4 years from the operation of the ORC). After 10 years of operation, the cumulative savings will reach approximately 10 M$.

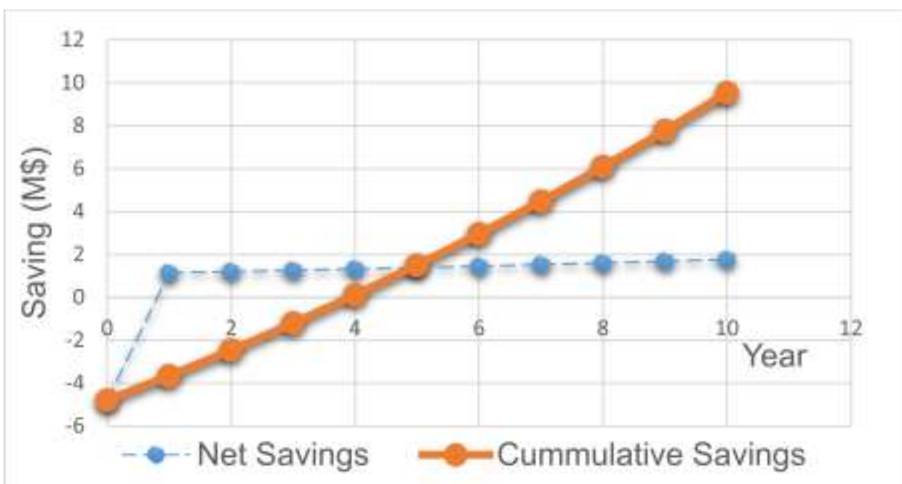

Figure 2. Cash flow of the ORC project

The COVID-19 pandemic decelerates the efforts toward energy efficiency. Lockdowns and problems with the supply chains worldwide are serious issues concerning any technical support or spare parts. The Egyptian government issued a decree to reduce energy costs for the industrial sector during the pandemic by 10%. The annual savings from the quoted ORC unit ($1.2 M) is approximately 10% of the annual electricity bill of the company, which is equal to the reduction in the bill during the pandemic. In general, energy efficiency projects will not be feasible if the energy costs are subsidized.

Governments should launch a batch of incentives/mechanisms to expedite energy efficiency in industries, including WHR methods. One recommendation is that each industry has to utilize a certain share (e.g. 20%) of its energy consumption from renewable / WHR systems. Industries that exceed this share can have their bills with corresponding reductions/bonuses.

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One important note to be discussed with the ORC manufacturer is the possibility of the ORC unit operating in part load mode if the flow rate decreases. The part load can be as low as 10% of the design values, a great advantage of ORC units compared to conventional generating methods. If something is going wrong or there is no flow, the unit will fail safely using an automated shutdown procedure.

As the unit is proposed to be installed in a petroleum refinery, the area required by the unit (about 100 m^2) should be investigated very well to be a “Safe” or “Non-hazardous” area. Classified or hazardous areas need special explosive-proof (Ex) equipment that can work safely in such explosive atmospheres. The costs of the Ex equipment may be 10~20 times the cost of the normal equipment. Therefore, the location of the unit should be as near as possible to the waste heat stream AND in a safe, non-classified area. If the ORC unit has to be installed in a classified area, the project will be unfeasible from a financial viewpoint.

V. CONCLUSION

Energy efficiency is a requirement of today and the future. High and rising energy costs and the requirement to reduce CO_2 emissions are the main drivers for investing in waste heat recovery systems. Electricity generation from waste heat means electricity for free (no additional fuel consumption), providing a secure extra revenue. ORC is a well-proven technology that allows converting waste heat into useful power. Compared to conventional power production technologies, ORC is flexible, accepting partial loads, able to utilize waste heat sources at relatively low temperatures, and requires very little O&M. The reasonable payback time for an ORC power plant, combined with positive environmental effects should attract investors and plant owners to fully utilize this technology.

In our study, the suggested ORC system will utilize the hot stream of the excess steam in a refinery, with an average temperature of 180°C, an average pressure of 4.5 bars, and an average flow of 15 Tons/hour. The unit costs about $4.8 Million and it paybacks its investment in 4 years. The unit will result in a CO_2 emission reduction of 7,500 Tons annually.

Relatively high investment costs, together with medium-term payback time, along with subsidized energy costs may turn this solution to be unattractive to industries. Here, the government should interfere with a batch of incentives/mechanisms to facilitate the transformation to a lower-carbon and more efficient industry.

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