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Analytical Analysis of Bottoming Organic Rankine Cycle (ORC) in Steam Turbine Power Station

Naser Alazemi, Abdullah M Al Tawari

***Abstract:** The utilization of the wasted energy from power plants in power generation becomes a great challenge in recent times. This investigates the feasibility of using Organic Rankine Cycle (ORC) bottoming turbine to recover the energy generated from Al Zour South Power station in Kuwait. Both of qualitative and quantitative methods of data collection were used to collect the required data for this investigation. A block diagram was built for the new proposed model in which the location of the added ORC bottoming turbine is presented. The model includes four modules and each of them has different number of turbines. The amount of power generated per month by applying the new model with using two different extraction line capacities of 10% and 20% in addition to the produced power (1000 Mw) per month for each unit were measured and plotted. As a result, the four modules generated more power as the extraction line capacity increased to 20%. More profit was gained by module four at 10% extraction and it has the lowest rate of return which was 9 years. Based on these results, module 4 is the most suitable to be installed in Al Zour South Power station in Kuwait.*

***Keywords**: Steam Turbine, Organic Rankine Cycle, Waste Heat Recovery, Steam Rankine Cycle.*

I. INTRODUCTION

One of technology oldest and most versatile prime movers utilized in drive generators or mechanical machinery are known as steam turbines [1]. Combine Heat and Power (CHP) applications popularly apply this technology while adopting specific designs for maximizing steam usage efficiency while the traditional steam turbine power plants are primarily used to produce electricity [2]. The Rankine cycle is the concerned thermodynamic cycle on which the operations of steam turbines are based on [2]. In most power generation stations, this cycle consists of a boiler or a heat source for water to high pressure (HP) steam conversion [3]. The pressure to which water is pumped into can be medium to high based on how big the unit is. At the elevated pressure water is heated, and further to the boiling point at that given pressure to vaporise it; in some power plants, this steam is heated to a temperature beyond the boiling point [4]. The HP steam is then brought down to a lower pressure by allowing it to expand while passed through multi-stage turbines. It is then led into a steam distribution system with intermediate temperature, otherwise into a condenser with vacuum exhaust conditions, to get delivered for commercial or industrial use [5]. The steam distribution systems in industries or the condenser than returns the condensate to the feed water (FW) pumps in order to continue the steam cycle [6]. In this research, the feasibility of using a system to recover this amount of waste heat and then improving the electrical efficiency and making it more environmentally friendly, will be carried out. The energy of this water can be used to increase the production of electrical power in addition to recovering the heat comes from the boiler. The steam turbine a lot of energy lost such as the water that is used to decrease the temperature in the condenser which moves back to the sea. In this research, an analysis of a selected case study will be carried out in order to utilise energy recovery in generating power. The case study selected for this project is Al Zour South Power station in Kuwait. The plant comprises a multiple-effect distillation (MED) unit which has the ability to generate about 107 million imperial gallons per day (MIGD) of drinking water which is nearly about 486,400m³ per day. This amount constitutes 20 % of Kuwait's capacity of installed water treatment.

II. LITERATURE REVIEW

Steam turbines differ from other CHP prime movers in terms of the former requiring a separate boiler or Heat Recovery Steam Generator (HRSG) to create its working fluid (steam) [7]. The power plants sometimes have a boiler to produce steam to address a heating/cooling load or some specific process, rather than use a "pressure reducing valve" for the steam pressure reduction [8]. The steam is made to run through a "back pressure steam turbine" for producing electricity [9]. An HRSG or boiler generates steam that is put through a steam turbine in CHP applications. The steam working fluid in the turbine system generates electricity, while the remainder exhaust is used for hot water or heating/cooling [10]. Rankine cycle is the process that the steam power generation is based on. Water is heated until saturation, following which it is compressed into steam. The steam is then expands over the turbine blades where the pressure drops to sub atmospheric pressures while passing through the turbine, which as a results generates electricity [11-14].

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* Correspondence Author

Naser Alazemi*, Faculty of Computing, Engineering and Media, De Montfort University, United Kingdom. Email: naseraltiwari@gmail.com

Abdullah M Al Tawari, High Institute of Energy/Water Resources Department, Public Authority of Applied Education, Kuwait. Email: am.altawari@paaet.edu.kw

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The low-pressure steam is condensed back to a liquid referred to as return water. It is then mixed with feed water and pumped back to the boiler [15]. The steam then approaches the turbine at where the steam pressure is decreased often to sub atmospheric pressures over the turbine blades in the condenser through the expansion process [16]. In cases where the turbine is connected with a generator, then this couple produces electricity. In the steam turbine, the steam exhausted out of the turbine is condensed and transferred to a liquid phase (water), where this water is known as a return water and when it condensed it mixed again with the new water that is feed to the steam turbine and pumped back to the boiler which is essential to repeat the working cycle in the turbine [17]. In cases when steam is required or where the available fuel can't be burnt directly in the prime mover, CHP systems find good use of such turbine systems. Steam turbines are largely suitable for large scale appliances or where the needed heat amount is much more than the power amount [18]. As mentioned above, the waste in the steam turbines is in the heat form which can be utilized for processes, cooling, space heating or it can be utilized to produce hot or chilled water. Additionally, size of steam turbines come in different where the huge sizes of them are utilized in nuclear power and large coal stations and they have average electrical efficiencies of approximately 36-38 % [19]. On the other hand, in CHP appliances, where the steam extraction minimizes their electrical output, they have normal electrical efficiencies of steam is about 11-20 % [18]. Nevertheless, the total efficiency of turbine rely on CHP system have a value ranges between 78-83 % [20]. Organic Rankin Cycle (ORC) is known as second type among the recovery processes. ORC is named for its using an organic compound of high molecular weight involving liquid-vapour phase conversion, or occurrence of boiling point at a temperature below the phase change temperature of the steam [21]. Heat recovery is allowed by the working fluid from lower temperature sources as per Rankine Cycle. Sources include biomass combustion, heat from industrial waste, geothermal heat, and solar ponds [22]. The low-temperature heat is converted into useful work that can itself be converted into electricity [23]. Its working principle is the same as that of the Rankine cycle: the working fluid is pumped to a boiler where it is evaporated, passed through an expansion device (turbine or other expander), and then through a condenser heat exchanger where it is finally re-condensed [24]. All of these features are together; allow higher turbine efficiencies compared to the steam Rankin cycle. ORC is a very suitable choice for waste heat sources with temperature as low as 145 °C which is best that is limited to heat sources of steam cycle more than 260 °C. ORCs are also used for power generation in geothermal power plants and as of more recently for in pipeline compressor heat recovery [25].

III. EXPERIMENTAL

Under the aim of reducing the amount of wasted energy generated from the station, one of the proposed solutions in this project is to install an Organic Rankine Cycle (ORC) bottoming turbine. The overall schematic diagram that represents the installed ORC turbine within the station components is given in Fig. 1. As shown in the Fig. 1, the turbine is directly connected to low pressure turbine exhaust.

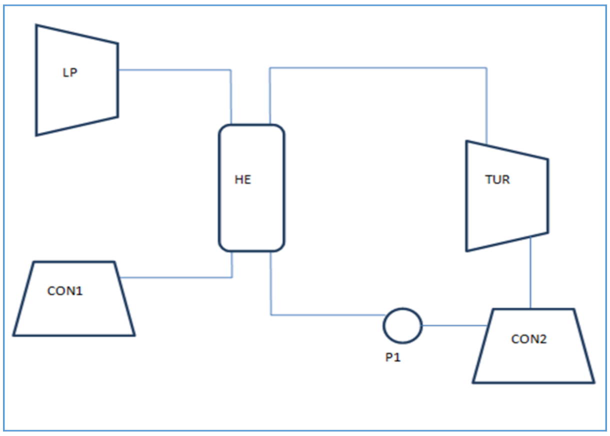

Fig. 1: The suggested layout for installing the ORC

According to Fig. 1, the outcome from the pressure turbine (LP) moves toward the heat exchanger (HE) for the purpose of organic fluid heating. After that, this fluid is discharged toward the condenser that is related to the steam cycle characterized by the symbol (CON1) in the above figure. The organic fluid that was heated is then entered the turbine and caused it to rotate, after that, this fluid is cooled down by utilizing the cycle given by the symbol (CON2). The condensed organic fluid is then pumped toward the Heat exchanger by utilizing pump (P1). For the purpose of investigating the appropriateness of utilizing organic Rankin turbine at the steam turbine bottoming, then it's essential to measure the available heat energy at the LP outlet which was measured as 2386 Kj/Kg. At this condition, the available flow rate as measured as 265185 kg/hr. To run the ORC turbine, it was proposed to take an extraction line from the LP outlet where the maximum available heat can be measured using the following equation:

$$Q_{THout} = \dot{m} * hout --- 13 \qquad (1)$$

$$Q_{THout} = \frac{\frac{265185kg}{hour}}{\frac{3600sec}{hour}} * \frac{2386kJ}{kg} \qquad (2)$$

$$Q_{THout} = 175758\ kwth \qquad (3)$$

If the extraction line capacity takes different values of (10, 20, 30...50%), then the available thermal energy is calculated at each capacity and presented in Table 1.

Table. 1 The calculated available heat at different extraction line capacities.

Extraction line capacity (%) of LP outlet	(Qth (Kw)
10	17557.8
20	35115.6
30	52673.4
40	70231.2
50	87789

IV. RESULTS

Related to the study of Khennich and Nicolas, (2012), the heat exchange type that was chosen for this design is a shell and tube heat exchanger.

In this study, a numerical model was developed for the ORC cycle performance testing. When water/ R134 used as the working fluids in the cycle, then the thermal efficiency of the heat exchanger was measured as 45 %. The overall gained heat from the shell and tube sides of the heat exchanger is presented in Fig. 2. As observed in Fig 2, more heat is gained at the shell sides at the same capacity. The possibility of ORC turbine operation at various extraction capacities for the four modulus is presented in table 2. The amount of heat that must be added to every module is 2170, 3100, 5100, and 7680 KWth, respectively.

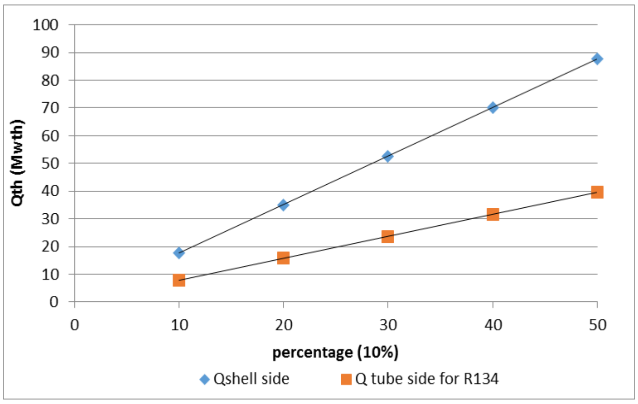

Fig. 2: The thermal energy in shell and tube sides

Table. 2 The number of turbines can be used vs. extraction line capacity.

(%) of LP outlet	Qshell side	Qtube R134	1	2	3	4
10	17557.8	7901.01	3	2	1	1
20	35115.6	15802.02	7	5	3	2
30	52673.4	23703.03	10	7	4	3
40	70231.2	31604.04	14	10	6	4
50	87789	39505.05	18	12	7	5

Data recorded in the Table 2 was taken in for one month. For the other months, the same data were recorded depend on the load conditions where these data are presented in the Fig. 3 for numbers of turbines for each module at each month. These data were measured with just taken into consideration an extraction capacity of 10% in order to minimize the influence of new turbines addition on the total performance of the steam cycle. By minimizing the extraction capacity percentage from the closed loop steam turbine pipes, then the problem of unit shutdown will be minimized.

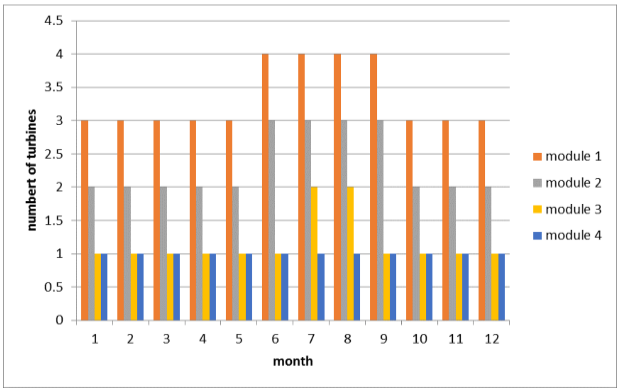

Fig. 3: The number of turbines for each month for the 4-modules with 10% extraction capacity.

Through raising the percentage of extraction capacity to 20%, then the total numbers of turbines that are possible to be added to the system are presented in Fig. 4. From the figure, it's clear that increasing the extraction line capacity leads to an increase in the number of installed ORC turbines. By conducting a risk analyses, it was found that the percentage that can be supplemented by the control unit reaches 43%.

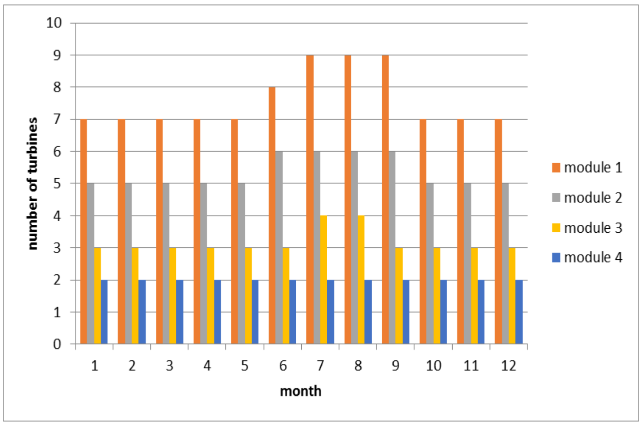

Fig. 4: The number of installed turbines per month with using 20% extraction capacity.

Fig. 5 and 6 present the amount of power generated per month from the four modules for 10% and 20% extraction capacities, respectively. When the extraction capacity is 10%, a constant power value is generated by the four modules at the first five months. A considerable increase in the generated power is observed at months 6, 7 and 8 which are the summer months. Only module 4 does not face any increase in the generated power and it generated a constant power all of the year. In the last four months of the year, the power generation amount decreased and then keeps constant till the end of the year. The same trend of the results was observed when the extraction capacity was increased to 20% but with different values as shown in Fig. 6. As increasing the extraction capacity caused an increase in the amount of power generated at each month compared with results at 10% capacity.

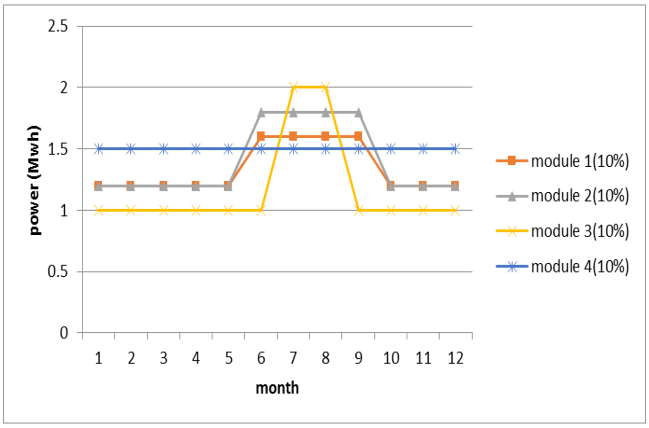

Fig. 5: The power in (Mwh) generated per month at an extraction capacity of 10%.

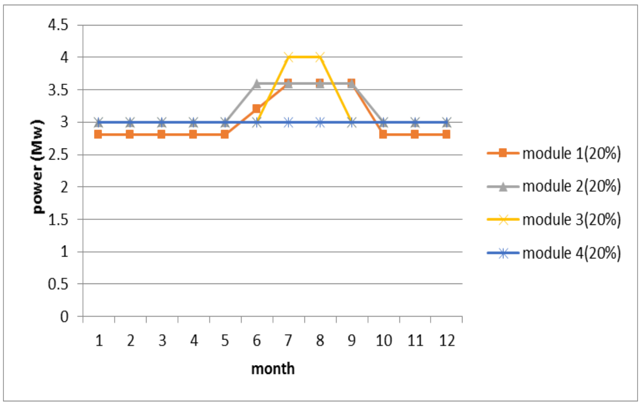

Fig. 6: The power in (Mwh) generated per month at 20% extraction capacity.

The following Fig. 7 and 8 describe the amount of power generated (1000 Mw) per month for the two extraction capacities of 10% and 20%, respectively. Observation from Fig. 6 and 7 showed that the power generated at the first and last months of the year is somewhat constant while it increased and decreased again in the middle months between month 6 and 9. In term of numerical values, power generated with 20% is more than that generated at 10% capacity.

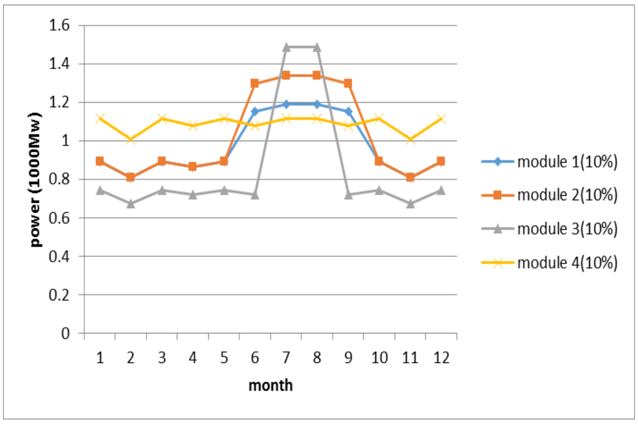

Fig. 7: The generated power (1000Mw) per month at extraction capacity of 10%.

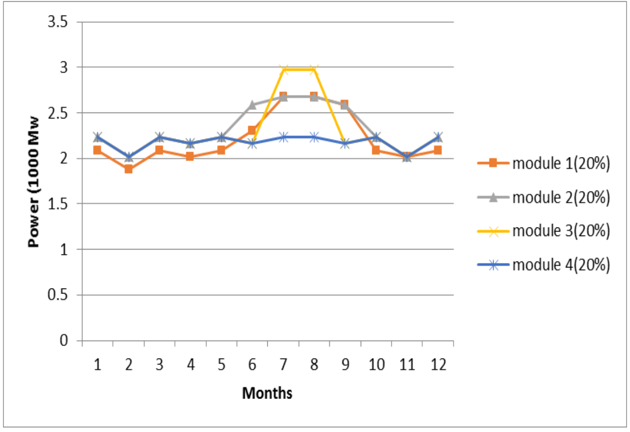

Fig. 8: The generated power (1000Mw) per month at extraction capacity of 20%.

For more clear comparison between the power generated at the two extraction capacities for the four modules, the following chart in Fig. 9 was prepared which shows that the power generated with 20% extraction capacity is two times more than that generated by 10% extraction capacity.

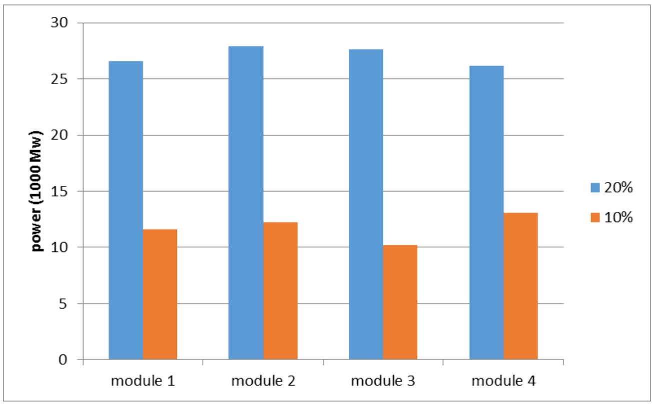

Fig. 9. The yearly generated power (1000Mw) for each module at two extraction capacities.

The obtained results in the above sections of this research were for investigating the effect of adding an ORC bottoming turbine to the components of a power station on the performance of this station. The obtained results showed that using such turbine with different extraction line capacities resulted to an increase in the amount of power generation. The following parts in the discussion showed a feasibility study of using such turbine in the station for cost analysis.

The first parameter in the feasibility study is the cost required to install turbines in each module of the ORC bottoming cycle in addition to the yearly profit and rate of return gained from this installation. The carried-out cost analyses is similar to that provided by Rowshanzadeh (2010) [6]. Fig. 10 compares the cost required to install the four modules measured in million KWD for the two extraction capacities of 10% and 20%.

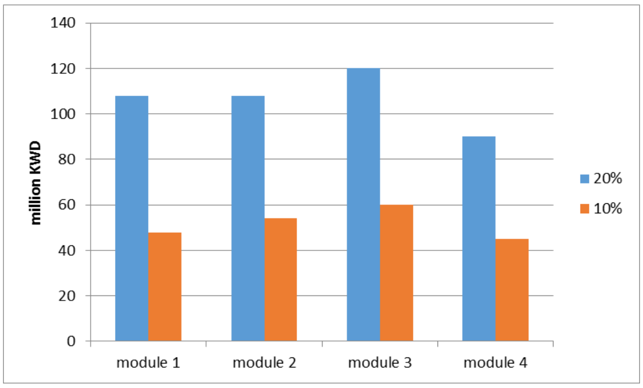

Fig. 10: The required cost of installing ORC bottoming turbines for each module at two extraction capacities.

As shown in the figure, more cost is required to install the turbines in the four modules at 20% extraction capacity and this because the number of turbines that is able to be installed at this capacity is more than that in the 10%. The maximum cost required in the two cases was observed at module 3 with a cost of 120 and 60 million KWD, respectively. Measuring the gained profit form installing turbines at each module is very essential in financial calculations and this to find the amount of gained revenue compared to the costs of expenses.

The rate of return for the first module of each extraction capacities is presented in Fig. 11. It's clearly shows the gain or loss on the installation cost of this module per months and the annual rate of return expected for both extraction capacities is 11. Fig. 12 presents the annual rate of return for module 2 at the two extraction capacities and it can be predicted that an annual rate of return of 10 was gained by 20% capacity while 12 year is required by the 10% capacity. It was observed, when a 20% extraction capacity is used, then all modules gained more profit than that gained at 10% capacity. The average amount of profit gained at 20% capacity for all modules is about 11 million KWD which is decreased to 5 million KWD as the extraction capacity reduced to 10%.

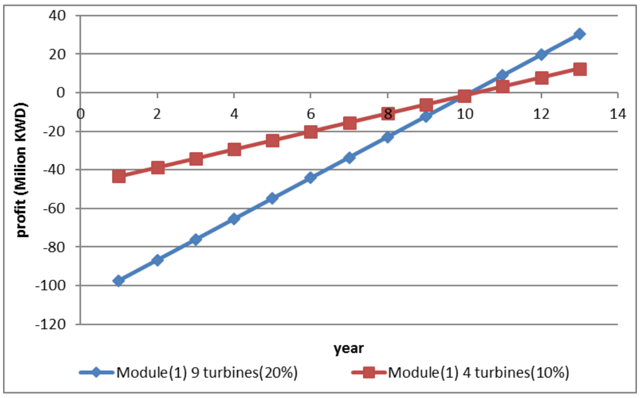

Fig. 11: The rate of return per year for the first module.

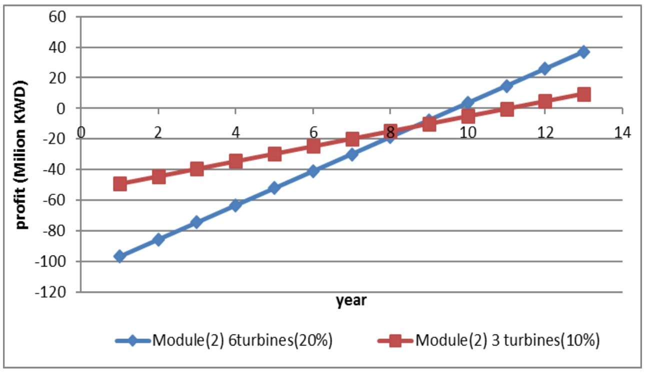

Fig. 12: The rate of return per year for the second module.

The rate of return was also measured for the third and fourth modules as presented in Fig. 13 and Fig. 14. The first figure shows that rate of return is 11 years for the 20% capacity and 15 years for the 10% capacity for the third module.

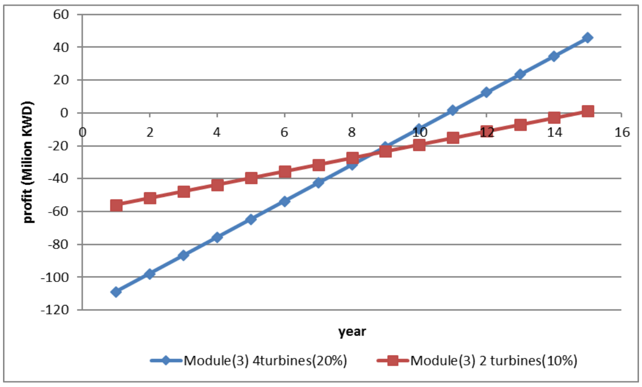

Fig. 13: The rate of return per year for the third module.

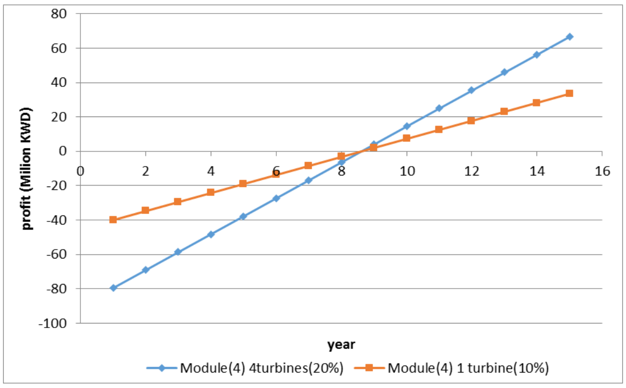

Fig. 14: The rate of return per year for the fourth module.

The numbers of turbines included in each of the four modules at the two extraction capacities are summarized in Table 3. Based on the presented results in the above table, it's clear that module 4 has the lowest rate of return period where money can be return back after 9 years.

Table. 3 The number of turbines used in each module and rate of return for each module.

Module	No. of Turbines	Rate of Return
1 at 20%	9	11
1 at 10%	4	11
2 at 20%	6	10
2 at 10%	3	12
3 at 20%	4	11
3 at 10%	2	15
4 at 20%	2	9
4 at 10%	1	9
1 at 20%	9	11

V. CONCLUSION

The viability of combining a steam turbine with a bottoming ORC cycle was examined in this study which in order to limit the amount of energy lost from exhausted steam while also gaining benefit from it. Through recovering the heat in this steam and using it to reduce waste heat from the water leaving the steam turbine, yield additional electricity and improve electric conversion efficiency. A case study in Al Zour South Power station in Kuwait was selected for this research. Different extraction lines capacities were proposed at 10, 20, 30, 40 and 50%. The available thermal energy was measured at each capacity. The type of heat exchanger was selected to be shell and tube heat exchanger and the heat that was added for each module in the system was 2170, 3100, 5100 and 7680 KWth. The results showed that all of them generated more power as the extraction line capacity increased to 20%. Then, a cost analyses were carried out to compare the required cost for installing each module and the gained profit from this installation. As a result, it was found that module 3 required higher cost to install it while module 4 needs less cost for installation. In term of gained profit, module four gained more profit at 10% extraction and this module has the lowest rate of return of 9 years so it's most suitable to be installed. Keep your text and graphic files separate until after the text has been formatted and styled.

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AUTHORS PROFILE

Naser Alazemi, received his master's from Faculty of Computing, Engineering and Media, De Montfort University, United Kingdom. He is currently an Operation Engineer at South Zour power plant and a specialist in steam turbine units. He can be reached at naseraltiwari@gmail.com.

Abdullah M Al Tawari, received his master's from Faculty of Computing, Engineering and Media, De Montfort University, United Kingdom. He is currently an instructor at the Department of Water Resources, The Higher Institute of Energy, Kuwait. He can be reached at am.altawari@paaet.edu.kw.