Modeling and Economic Analysis of MED-TVC Desalination with Allam Power Plant Cycle in Kish Island

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ABSTRACT: *In this paper, a system consisting of the Allam cycle and Multi-Effect Distillation-Thermal Vapor Compression (MED-TVC) desalination was proposed to reduce the amount of carbon dioxide in the atmosphere. It uses wasted energy for the simultaneous production of freshwater and power. Firstly, analysis of the Allam cycle delineated that the heat capacity suitable for the desalination cycle is estimated to be 100 MW, the amount of heat from the outlet of the compressor. The MED-TVC desalination system, one of the most suitable and the most economical desalination systems, is used to combine the Allam cycle and desalination in Kish Island, located in the south of Iran. The results of this research indicate that the proposed cycle has a desirable economic performance, and the results of economic analysis using the Net Present Value (NPV) method and Internal Rate of Return (IROR) show the Payback period in this plan is 4.8 years.*

KEYWORDS: *Multi-effect distillation; Allam Cycle; Economic; Modeling; Simulation.*

INTRODUCTION

Due to the rapid increase in population and rapid industrialization, our planet faces several major issues such as water shortage, food, and energy crisis, and climate change. For instance, according to the United Nations Organization, nearly 1.8 billion of the world's population will experience water shortages in less than 6 years. Furthermore, due to the constant production of fossil fuel electricity, the world has experienced high levels of carbon dioxide in the upper atmosphere [1-4]. As a result, new technologies are needed to solve this problem.

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Widely-used technologies for reducing greenhouse gas emissions in fossil fuel systems have problems such as high investment costs. As the world relies heavily on fossil fuels, carbon dioxide emissions will increase dramatically in the future. Therefore, we need to accelerate the development of less costly technologies to reduce the pollution of fossil fuels. In this regard, the United Nations introduced some action plans such as Millennium Development Goals (MDGs) and Sustainable Development Goals (SDGs) to confront these issues [5-8]. Hence, researchers have proposed various methods to reduce costs and pollution.

One of the most important methods was the Net Power, which developed a new thermodynamic power cycle that burns pure oxygen and uses hydrocarbon fuels. It also captures 100% of atmospheric emissions, including carbon dioxide, and its costs can compete with the best systems that will not even absorb carbon dioxide. Net Power Co., in partnership with Toshiba, Exelon, and Kurt Schwa, commercialized the system. They designed and tested a model with a capacity of 50MW for this system. This cycle generates electricity through natural gases with 100% carbon dioxide absorption. Allam cycles have an important impact on the ability of the electric power industry to control and reduce greenhouse gas emissions [9-10]. On the other hand, due to the deterioration of fossil fuels, the issues of energy recycling in industrial and technological units have caught many researchers' attention in recent years. For this purpose, various technologies can be used for heat recycling from power plants. As the population of different regions grows, the production of freshwater becomes one of the most important industry issues. Desalination technologies are effective methods for utilizing wasted energy from power plants. Dual-purpose systems consist of two important sectors, power plants, and desalination units. The power plant is responsible for a regular supply of electrical energy and the energy needed to start the desalinating unit [11-14]. For this purpose, many studies are carried out on the simultaneous production of electrical energy and freshwater, which will be followed by studies on freshwater production systems, as well as the production of electric energy and freshwater.

Studies on freshwater systems analysis are mostly conducted to estimate the overall use of one or more specific technologies or to enhance the efficiency of freshwater systems. A group of researchers, including Ty. *Sharan et al* combined a CO_2 Brayton cycle with MED desalination to product power and freshwater. The results showed that fresh water can be produced by waste heat in the CO_2 Brayton cycle, without reduction in cycle efficiency. [11]. *Iaquaniello et al* focused on concentrating solar power, reverse osmosis, and multi-effect distillation of desalination economically [15]. *Javadi et al* combined a gas turbine with a steam turbine and focused on the Sensitivity analysis of 3E of the power plant. The results showed that gas turbine has a direct impact on cycle efficiency [16]. *Shalaby* studied osmosis desalination powered by the Rankine cycle and photovoltaic cycles for providing energy [17]. *Loutetidou* and *Arafat* investigated the technical and economical features of reverse osmosis and multi-stage flash distillation, a water desalination process, supplying their energy from thermal energy [18]. *Franz* and *Seifert* defined the coupling of a MED plant with a Clausius – Rankine cycle enriched by a solar central receiver system . They produced a steady-state model of MED plant and calculated the correlation of the Gained Output Ratio (GOR) as the steam heating system operating temperature, a certain amount of seawater, and specific desalination plant heat transfer surface [19]. *Khorshidi et al.* worked on a Multi-Effect Distillation- Thermal Vapor Compression (MED-TVC) desalination in Bandar Abbas thermal power plant in the south of Iran. They developed a mathematical model regarding the steady-state conditions. The productive algorithm was used for increasing freshwater production and decreasing the total exergy deterioration rate [20]. *Kariman et al* combined a carbon dioxide power cycle with reverse osmosis desalination to produce fresh water. Exergoeconomic analysis and optimization were used to evaluate cycle performance. Exergy analysis showed that the boiler has the highest amount of exergy destruction [21] .

Hoseinzadeh et al integrated a carbon dioxide power cycle with the geothermal energy source for freshwater production. The results showed that the desalination system has the highest rate in terms of the sum of capital gain and exergy deterioration cost respectively [22].

Jabboury et al's study can be mentioned as the one conducted on electricity generation and supply of energy for desalinating. *Jabboury et al*, investigated the effect of the functional variable of heat recovery boiler on the combined cycle units and desalination of seawater [23]. *Shakouri et al* combined a gas turbine with MED desalination to generate electricity and freshwater [24]. *Chacartegui et al* Commented on the economic analysis and feasibility of connecting a MED desalination unit with a combined cycle unit [25]. *Shakib et al.,* conducted a study to investigate the simulation and optimization of a cogeneration gas turbine and a desalination unit combined with a recovery boiler [26]. *Hosseini et al.* worked on optimizing the price of a combined desalination unit, along with exergy, environmental, and reliability considerations [27]. Demir and Denser have developed a hybrid system for producing electricity and freshwater, which consists of the solar thermal power plant, natural gas generator, thermoelectric generators, and Rankine cycle for power generation of desalination units[28]. Mata-Torres explored multi-purpose solar electricity and freshwater production system in Venezuela and northern Chile, where parabolic collectors and distillation desalination units were used [29].

Hoseinzadeha et al combined a solar gas power plant with a desalination unit to generate power and freshwater. The results showed that energy loss in the cycle and freshwater production will increase the efficiency of the cycle from 35% to 46%. [30]

According to the studies on the simultaneous production of freshwater and energy, achieving a balance between the production of fresh water and energy is of great importance. Nevertheless, the articles address the general aspects of the production of freshwater and energy. On the other hand, no research has investigated a reduction in the costs and pollution of electrical energy and freshwater systems. Concerning the simultaneous use of MED-TVC desalination units and Allam cycle, there is no indication in any specific study. Indeed, the gap between how these two systems are combined and economic analysis of the two are among the issues that are completely evident in the literature and this article is innovative as it shows how a MED-TVC desalination unit with Allam cycle is combined and examines the proposed cycle from an economic point of view. Combining MED-TVC desalination cycle with the Allam cycle, this study aimed at producing energy with a minimum amount of pollution for the environment, as well as producing freshwater using the energy loss in the Allam cycle. Kish Island, one of the important areas for the production of fresh water as well as electrical energy, is investigated in such a way as to determine whether the combination of these two systems has any benefits, or it is better to combine desalination with other cycles.

THEORETICAL SECTION

Modeling and simulation

Allam cycle

Allam cycle uses the Carbon Dioxide as a high-pressure fluid and a Brighton-type cycle with a low-pressure ratio that works with a unique turbine having an input pressure] of 200 - 400 bars and operating at a pressure of 6 – 12 Pa. The cycle consists of a combustion chamber that burns fuel using pure oxygen at high pressure to provide a high-pressure feed system for rotating the turbine. Fig. 1, is a schematic diagram showing the cycle. In this turbine cycle, the output gas enters the recuperator at 727 ° C and 30 bars and turns to 43 ° C and exits. This flow loses its moisture in the humidifier during the cycle before entering the compressor and reaching the temperature of 29 ° C and 17 ° C. A part of the gas compressor is removed from the cycle for sale, and the rest flows into the recuperator and then enters the turbine from two different paths. The first part of the stream flows directly into the recuperator through a circulator pump with a pressure of 310 bars. Having combined with oxygen, the other part of the stream is pumped through the oxygen pump to the desired pressure and preheated using the output stream turbine. Oxygen at the entrance of the turbine carries an autoxidation reaction, and the turbine gas enters the turbine at 1150 ° C.

To simulate the Allam cycle, the input characteristics of the Allam cycle are first obtained. Specifications of different parts of the Allam cycle's entrance with natural gas are shown in Table 1.

The energy efficiency of the apparatus is calculated using conservation of mass-energy equations (first law). The simulation of the Allam cycle is based on the thermodynamic characteristics given in Table 1. The results of the validation are shown in Table 2.

The results of the simulation of the Allam cycle and Ref. [9] are in good agreement.

Multistage MED-TVC Desalination

In this study, the desalination unit is a multi-stage thermal type consisting of four main parts: circulator, turbocompressor, condenser, and five operators. In this system, the seawater enters the condenser first, then exchanges heat with the steam inside the condenser tube, the seawater's temperature increases, and part of it goes out of the system as the cooling water and the rest goes to the next steps. In the first step, the water

Table 1: A summary of the stream flow of a simplified commercial scale natural gas Allam Cycle [8].

Stream	Temperature (°C)	Pressure (bar)	Mass Flow (Kg/s)
1	727	30	923
2	43	29	546
3	17	29	563
4	23	100	909
5	23	100	881
6	23	100	28
7	16	100	881
8	16	100	689
9	717	312	586
10	16	100	191
11	16	100	41
12	2	99	233
13	717	310	233
14	266	330	10

Table 2: A comparison between the results obtained from the present model and the reference [9].

Cycle Attribute	Expected Value	Present Work
Net power output	303 MW	293.6 MW
Natural gas thermal input	511 MW	555 MW
Oxygen consumption	3555 MT/day	3405MT/day
Turbine outlet flow	923 Kg/s	923 Kg/s
Turbine inlet condition	T=1158 C , P=300 bar	T=1158 C , P=300 bar
Turbine outlet condition	T=727 C , P=30 bar	T=727 C , P=30 bar
Oxygen power plant	56 MW	56 MW
CO2 compression power	77 MW	86.4 MW

Is sprayed onto the evaporator pipes. As a result of the steam heating in the tubes (which has been supplied by an external source), water passes through the thermo-compressor and reaches the favorable pressure, and then enters into the first stage of evaporator pipes. Part of it evaporates and the steam formed in the first stage goes to the second stage and flows through the second stage of evaporator pipes causing the feeding water to be evaporated and the remaining steam is added as wastewater at the bottom of the evaporator. It exists and this process continues until the end. In the final stage, the produced steam enters the condenser. After increasing the temperature, the seawater that entered the condenser would be released from the outlet.

The following assumptions are considered for modeling the water desalination:

• The system is in a steady-state condition.

• The heat transfer to the environment is ignored.

• The temperature difference between the adjacent stages is considered to be the same and is defined as follows [20].

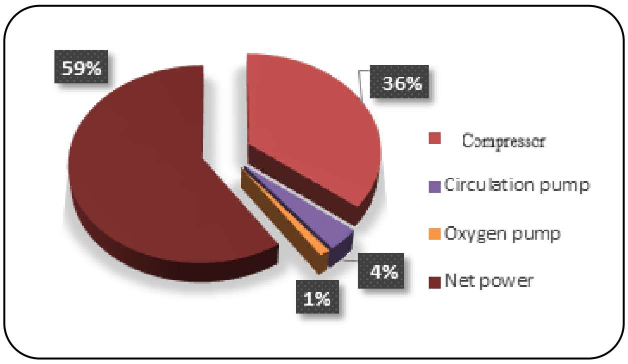

Fig. 1: The contribution of components to power generation in Allam cycle.

$$T_{i-1} - T_i = \Delta T \quad (1)$$

$$\Delta T = \frac{T_s - T_f}{n+1} \qquad T_{v,i} = T_i - BPE$$

In the above equations, T_s is the input temperature of the first evaporator in Centigrade, T_f is the feedwater temperature, and n is the number of desalination evaporators. The feedwater flow rate for each desalinization portion is obtained according to Eq. (2).

$$F_i = \frac{M_f}{n} \qquad i = 1, 2, \ldots, n \quad (2)$$

In accordance with the equations of the first law of thermodynamics and the mass-energy equivalence, the output volume of the saltwater and the output of salt concentration are obtained from equations 3a and b [18].

a) $F_i + B_{i-1} = B_i + D_i$ (3)

b) $F_i \cdot X_f + B_{i-1} \cdot X_{b(i-1)} = B_i \cdot X_{bi} + D_i \cdot X_{di} \qquad X_{di} = 0$

c) $D_{i-1} \cdot L_{i-1} + d'_{i-1} \cdot L_{i-1} = F_i \cdot C_i \cdot T_i - T_f + D_i \cdot L_i$

In Eq. (3), X_{di} represents the salt concentration of distilled steam and D_i is the amount of vapor flow that is expressed for each evaporator according to Eq. (4).

$$M_s \cdot (h_s - h_{fs}) = F_1 \cdot C_1 \cdot (T_1 - T_f) + D_1 \cdot L_1 \quad (4)$$

In Equation 4, C_l is the heat capacity characteristic of the feeding water and the salt concentration at the first evaporator. Flash produced from the floor evaporator is obtained according to the equations expressed by *Miyatake et al* [31] as follow.

$$d'_i = B_{i-1} \cdot C_{i-1} \cdot \frac{T_{i-1} - T'_i}{L_i} \quad (5)$$

$$T'_i = T_i + NEA_i \quad (6)$$

$$NEA_i = \frac{33.0\,(T_{i-1} - T_i)^{0.55}}{T_{v,i}} \quad (7)$$

In all of the above equations, T'_i is the temperature of saltwater after passing through the first evaporator and NEA_i is a non-equilibrium flash evaporation process term. The steam generated in the desalination is converted into two separate streams at a later stage, one entering the thermo-compressor(M_{ev}) and the other entering the condenser (M_c).

$$D_n = d'_n = M_c + M_{ev} \quad (8)$$

By writing the energy conservation equation for the condenser, the amount of saltwater entering the condenser is obtained according to the below equation.

$$M_c \cdot L_n = M_{sw} \cdot C_{sw} \cdot (T_f - T_{sw}) \quad (9)$$

$$M_{cw} = M_{sw} \cdot M_f \quad (10)$$

The total amount of freshwater generated by the evaporator is obtained according to the following equation.

$$D_t = \sum_{i=1}^{n} D_i + \sum_{i=2}^{n} d'_i \quad (11)$$

By writing the equilibrium energy equation in the thermo-compressor to calculate the enthalpy output in accordance with the following relation, we need to assume that the thermo-compressor is adiabatic and the entering steam is superheated. To calculate the enthalpy output of the thermo-compressor, the equilibrium energy equation is written according to the following equation for the turbocompressor. The conditions of being adiabatic for the thermo-compressor and being superheated for the input stream to the thermo-compressor are assumed.

$$M_d = M_m + M_{ev} \quad (12)$$

$$M_d \cdot h_d = M_m \cdot h_m + M_{ev} \cdot h_{ev} \quad (13)$$

The enthalpy output of the turbocompressor is obtained according to the equation below [32].

$$Ra = \frac{M_m}{M_{ev}} \quad (14)$$

$$Ra = 0.296\frac{P_d^{1.19}}{P_{ev}^{1.04}} \cdot \left[\frac{P_m}{P_{ev}}\right] \cdot \left[\frac{PCF}{TCF}\right] \quad (15)$$

$$CR = \frac{P_d}{P_{ev}} \quad (16)$$

$$ER = \frac{P_m}{P_{ev}} \quad (17)$$

In the above equations, PCF is defined as the motive steam pressure correction factor which is obtained according to Eq. (18), and TCF is defined as the suction vapor temperature correction factor obtained according to Eq. (19).

$$PCF = 3\times10^{-7}\left(P_m\right)^2 - 0.0009\left(P_m\right) + 1.16101 \quad (18)$$

$$TCF = 2\times10^{-8}\left(T_{ev}\right)^2 - 0.0006\left(P_{ev}\right) + 1.0047 \quad (19)$$

The water required to be sprayed into the boiler would change into saturated steam as the steam coming from the thermo-compressor is the superheated one. The equilibrium equations of energy and mass for the desuperheater are obtained based on the following equations.

$$M_s = M_d + M_w \quad (20)$$

$$Ms \cdot hs = M_d \cdot h_d + M_w \cdot h_w \quad (21)$$

Integration of the Allam cycle and desalination

In order to use the wasted energy in the Allam cycle to produce freshwater, the mainstream energy output of the turbine in the Allam cycle is recycled using a recuperator. On the other hand, according to the analysis of power generation in different components of the cycle, the contribution of various components to the production capacity of the cycle is shown in Fig. 3. According to Fig. 3, it is observed that the highest amount of power is produced in the compressor. Therefore, the compressor is used as a primary source of energy required for desalinating water, and the other points in the cycle have no thermal value necessary for heat recovery. The thermal value is the proper temperature for heat recovery to produce steam for desalinating. According to the design, the generated steam temperature should be 189 ° C. The output gas emitted from CO_2 and before and after the cooler has a temperature of 189 ° C which is a suitable temperature for heat recovery and use in desalination. The heat recovery site which is suitable for the desalination cycle would be the heat of the exhaust gas from the compressor which is estimated as 100 MW based on the simulation results. On the basis of the mentioned points, the proposed diagram for combining the Allam and desalination cycles is in accordance with Fig. 2.

Economic analysis

This section examines the economic analysis of the combined cycle. In order to analyze it economically, the considered economic parameters are as follows:

Duration of capital recovery

In this way, the criterion for evaluating the project is the duration of capital recovery. Plans with shorter capital returns are more attractive than plans with a longer return period. In simple calculations, the amount of initial investment is divided into annual net profit. In this method, the time value of money is not considered, and for this purpose, a modified version of this method is used in which all expenditures and incomes are discounted, such as the NPV method.

In NPV method, cash flow (income and costs) would be discounted based on the time of occurrence (income or expenditure) to the daily rate. In this way, the time value of the costs or income is also included in the cash flow. In the current NPV method, at first, all costs and revenues are discounted at the appropriate interest rate depending on when they will occur [33].

$$NPV = \sum_{t=0}^{n}\left(\frac{R_t}{(1+i)^t}\right) \quad (22)$$

In this case, (t) is the time when the cost or income is realized, (I) is the interest rate (the product of the profit rate, the rate of risk, and the predicted inflation rate), and Rt is a small amount of income or expense based on the cash flow. Then, by subtracting the costs of converted revenues from converted incomes, a pure number will be obtained which is called NPV. If this number is positive, the scheme is profitable and acceptable, and if it is negative, the plan is economically impractical and ineffective. The Internal Rate of Return (IRR) is the average rate of return on an annual business plan. In engineering economics, the internal rate of return is one of the standard methods

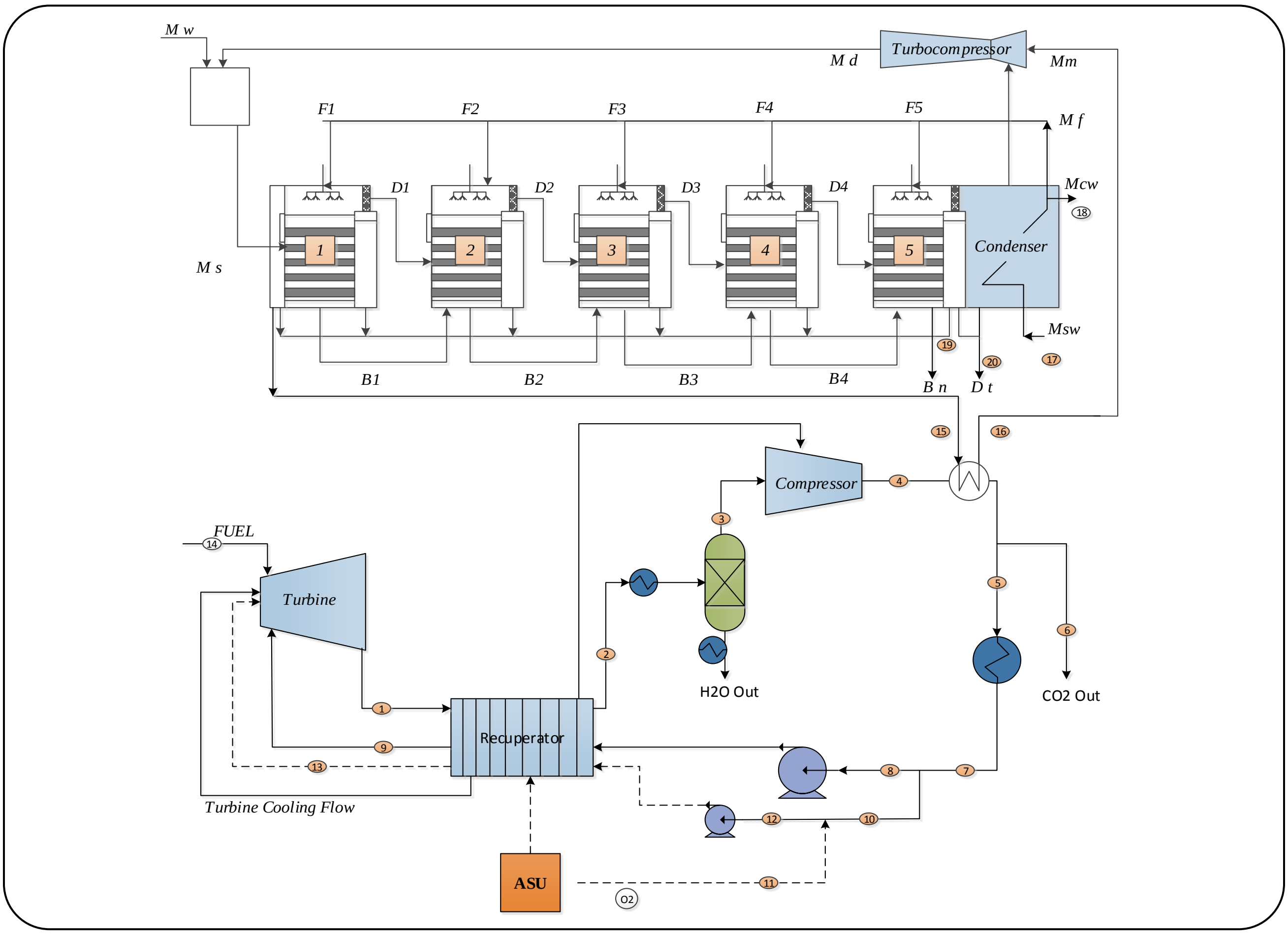

Fig. 2: General schematic diagram of Allam cycle using natural gas combined with MED-TVC desalination.

for evaluating economic plans. The internal suffix is used because the effect of environmental factors is not considered. This method aims to discount the cash flow at an unknown return rate to the current rate in a way that its pure current value approaches zero. In other words, discounted costs during the period of capital return are considered to be equal, and the unknown return rate is determined accordingly. If the rate of this return is higher than the interest rate, the scheme is profitable and applicable, and if the calculated return rate is lower than the real interest rate, the plan is unproductive.

According to the definition, the IRR's mathematical form will be as follows [33].

$$\text{if} \quad NPV\left(i^*\right) = 0 \quad \rightarrow \quad i^* = IRR \tag{23}$$

The following table shows the relationship between the economic calculations of different cycle components [33-36].

Results of Economic analysis

In this section, we will examine the results of the combined cycles of Allam and desalination. The design parameters that were used in the modeling of the cycle are shown in Table 4.

In Fig. 3, the amount of freshwater variation in steam production and consumption are shown in terms of Turbine output discharge. With regard to Fig. 3, it can be seen that as the turbine output discharge increases, the amount of produced freshwater increases too, although the consuming steam increases with increasing turbine output, the sensitivity of the freshwater production with turbine output discharge is more variable compared to steam used.

In Table 5, the effect of change in combustion efficiency on the assumption of constant input of turbine in the proposed cycle is investigated. According to Table 5, it is observed that increasing combustion efficiency, will increase the turbine's work rate, Net and gross efficiency,

Table 5: Effect of combustion efficiency on the assumption of constant turbine input temperature.

combustion efficiency	Flow rate of fuel	Net power	Turbine Power	Impure efficiency	Net efficiency
0.84	12.33	234790	393641	56.92	33.95
0.85	12.05	234427	393277	58.18	34.68
0.86	11.78	234072	392922	59.47	35.43
0.87	11.52	233725	392576	60.79	36.19
0.88	11.26	233387	392237	62.14	36.97
0.89	11	233056	391907	63.51	37.77
0.9	10.76	232733	391584	64.92	38.59
0.91	10.51	232417	391268	66.36	39.42
0.92	10.28	232108	390959	67.84	40.27
0.93	10.05	231806	390657	69.35	41.15
0.94	9.82	231511	390362	70.89	42.04

Table 6: The cost of components.

price of MED-TVC Desalination	432500000	$
Turbine cost	49410000	$
Compressor cost	16190000	$
Cost of pump circulation	3119000	$
Cost of oxygen pump	1392000	$
Installation cost	251305500	$
Investment cost	753916500	$
Annual maintenance cost	37695825	$/year
Total cost	1.5455e+09	$

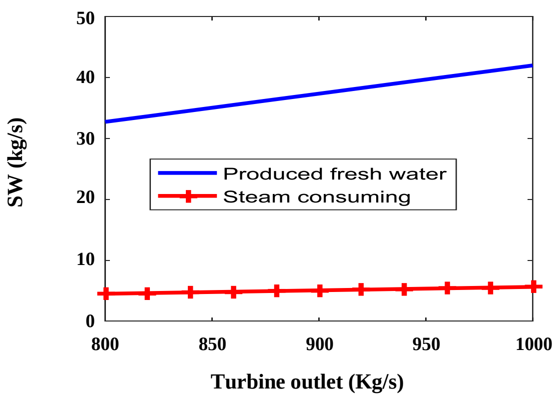

Fig. 3: Changes in freshwater production and steam consumption in terms of turbine discharge

and decrease in the fuel discharge rate. The turbine's work rate, Net, and gross efficiency increase, while the fuel discharge rate decreases with increasing combustion efficiency.

Table 6 shows the costs of the proposed cycle and the costs of different cycle components. According to Table 6, it is observed that the highest amount of cost is for the desalination unit and the lowest amount is related to the oxygen pump.

Table 7 shows the amount of generated power, the amount of generated freshwater, sales revenue, and other costs as well as the return on the capital. The Payback period in the proposed cycle is estimated as four years and eight months, indicating that the proposed cycle plan has a good performance in terms of return on capital as well as the amount of power, fresh water, and electricity generated. According to Table 7, the amount of fresh water produced is 35 liters per second and the amount of annual water revenue and annual electricity sales revenue for a year is 110376 m^3/year and 193268376 $/year respectively.

In table 8, the estimated price of water and electricity over the years is shown in which the price of water has been fixed at $ 1. Table 8 shows the annual amount of generated electricity and water, as well as the Annual Revenue and NPV.

According to Table 8, it is observed that NPV has a positive number in all analyzed years that indicates t he efficient performance of the proposed cycle from an economic perspective.

Table 7: Specifications of the proposed cycle from an economic perspective.

Power Generation	231750	KW
Produced fresh water	110376	m^3/year
Annual electricity sales revenue	193268376	$/year
Annual Water Revenue	110376	$/year
Annual maintenance cost	37695825	$/year
Net annual income	155682927	$/year
Payback period	4.8	year

Table 8: Estimated Income of the proposed cycle based on the price of freshwater and electricity generated

year	Lifetime of the project	Discount rate	Electricity price$	water price $	Annual Revenue $	Net present value (NPV)
2018	1	0.132	10.34	1	211548842	6.06E+08
2019	2	0.132	10.53	1	215521705	4.78E+08
2020	3	0.132	10.65	1	217960358	3.82E+08
2021	4	0.132	10.82	1	221324162	2.97E+08
2022	5	0.132	11.04	1	225867004	1.87E+08
2023	6	0.132	11.26	1	230210305	1.30E+08
2024	7	0.132	11.48	1	234737150	49204011

CONCLUSIONS

In this paper, a hybrid cycle consisting of the MED-TVC desalination and Allam cycle is proposed for freshwater and energy generation in Kish Island, located in southern Iran. Allam cycles are needed for electricity generation as well as for providing energy for the desalination plant. The results of the analysis carried out in this research showed that the highest amount of wasted energy is in the compressor. Therefore, the compressor is applied to provide the required energy for the desalination unit. The performance of the proposed cycle is analyzed in terms of energy, and economy. The results show that by using the wasted energy from the Allam cycle, 110376 m^3 fresh water can be produced and 231750 kW of electricity will be generated within a year. In addition, the capital return of the scheme is estimated to be 4.8 years and the lifetime of the proposed project has a positive NPV during the first seven years.

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