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Araştırma Makalesi - Research Article

Multi-Criteria Decision- Making Modeling of *b-type* ORC-Binary Geothermal Power Plant: EATWOS Analysis

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Abstract- **In this study, taking the different parameters into account, different designs of *b-type* ORC power plant have analytically conducted. In the designs, Simav geothermal resources have been taken into consideration as the source of the plant. Then, the best design has been determined using EATWOS in the viewpoint of the working conditions. As a conclusion, the available models of *b1-type*, *b2-type* and *b3-type* were determined as Model 12, Model 10 and Model 31, respectively for energy efficiency, net yearly electricity generation and integrated-based values. *Amongst these, the best model was determined as* Model 10 with the design parameters of 353.15 K, 413.15 K, 295.15 K, 656.37 MWh and 18.08 for T_{1b}, T_{2d}, T_{2c}, E_{net} and η, respectively.**

Keywords- **EATWOS, Geothermal Energy, *B-Type* ORC**

I. INTRODUCTION

Geothermal energy is one of the prominent renewable energy sources in reducing fossil fuel consumption due to its continuity and thus reducing the emission of waste gas which causes environmental pollution. The use of geothermal energy for electricity generation is one of the indirect ways of evaluating these resources. In the use of geothermal energy for electricity generation, the most common application for the evaluation of medium enthalpy resources is the Organic Rankine Cycle (ORC) power plants. The designs of these plants are depending on several parameters such as thermophysical properties of the geothermal resources and the working parameters of plants. However, the decision on the most effective system design is a very complex problem if the number of parameters or criteria is taken into account.

The people, who need to make an individual, institutional or global decision, have to take into account multiple criteria such as cost, sustainability, time, relationships and environmental issues in each other. From this point of view, Multi-Criteria Decision-Making (MCDM) techniques is an advantageous tool since it propounds a multidimensional sight for the solution of the problem including mathematics, social issues, economics and act of operations. MCDM techniques are the techniques in which the multiple problems are optimized and the best one is chosen. So, it is widely used for problems withmulti-criteria. Data Enveloping Analysis (DEA), Efficiency Analysis Technique with Output Satisficing (EATWOS), Analytical Hierarchy Process (AHP), and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) are the commonly used MCMD techniques [1-2]. These techniques are used in many areas such as performance evaluation of corporations and universities, financial evaluations of the corporations and so on [3-7].

Energy topics and environmental topics related to energy are the complicated issues in which several purposes are mutually contradictory. So, they have a structure including more than single criteria, aim and quantity since they include maximum uncertainty, intensive investments and maximum time. For this reason, energy and environment decisions are in the scope of application of decision analysis [1, 8].

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If someone searches about the studies on decision analysis, electrical energy issues come into [8]. Beside this, the studies on renewable energy types (hydropower, solar energy, wind energy and geothermal energy) get increase in the last decade [1].

A new efficiency analysis technique, which determines the potential of recruitment of efficiency by considering satisfying levels for output amounts, was earned to literature by Peters and Zelewski (2006) [9]. This analysis technique, named EATWOS, is one of the most preferred methods of multivariate statistical analysis techniques. This technique puts on some advantages since it includes a calculation based on the weights of evaluating criteria(s). In this technique, the decision maker predicates satisfying results rather than the optimum ones [9, 10]. According to this, the decision maker avoids deceptive decisions since EATWOS allows a different grading in comparison to other techniques with its defined level of satisfying for one output at least. EATWOS is successfully used in a large area such as performance of industrial corporations, sportive players, suppliers, education, civil associations, energy systems [9-15] However in the literature, there is no or limited study on decision making of designing of energy systems such as power generation.

In this study, it is aimed to determine the best configuration of the geothermal power plant. In this purpose, conducting the different operating parameters, different designs of b-type Organic Rankine Cycle (ORC) were performed taking the properties of Simav geothermal field into account. The energy efficiencies and net power outputs of the designs were calculated by means of thermodynamic laws. Then, the optimum design parameters of the system determined with EATWOS method by using the results of the energy analysis.

II. DESIGN OF ORC-BINARY POWER PLANT

The flow diagram of the designed ORC power plant was given in Figure 1. The ORC power plant consists of separator (S), preheater (PH), evaporator (E), circulation pump (CP), condenser (C), control valve (CV) and turbine-generator (T/G) [16, 17].

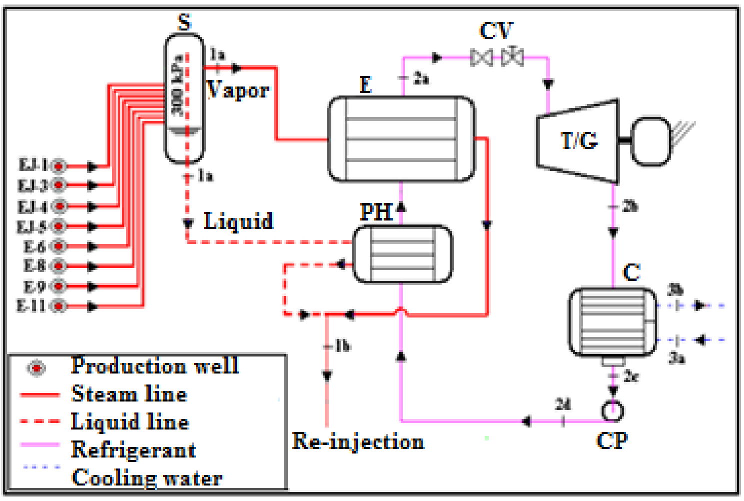


Figure 1. The flow diagram of the geothermal powered ORC-Binary power plant [16, 17]

According to Figure 1, the liquid and vapor phases of the geothermal fluid are divided into two flows in the separator. The liquid phase of the geothermal fluid enters to PH and gives its heat energy to the working fluid and vapor phase of the geothermal fluid enters to E and gives its heat energy to the preheated working fluid. At the end of these procedures both vapor and liquid phase of geothermal fluid compose and re-injected to the well. Superheated working fluid enters T/G (2a) and then expanded working fluid enters C (2b) at condensation pressure. The working fluid is compressed to the inlet pressure of the turbine at CP.

The type of working fluid is important for determining the operating conditions of the system. The thermodynamical properties of the working fluid effect the system operating parameters and the outputs of the system (net power output, energy efficiency, condensation temperature). In this study, R-134a and R-141b are used as a working fluid. *T-s* diagrams of the cycles were given in Figure 2 [16,17].

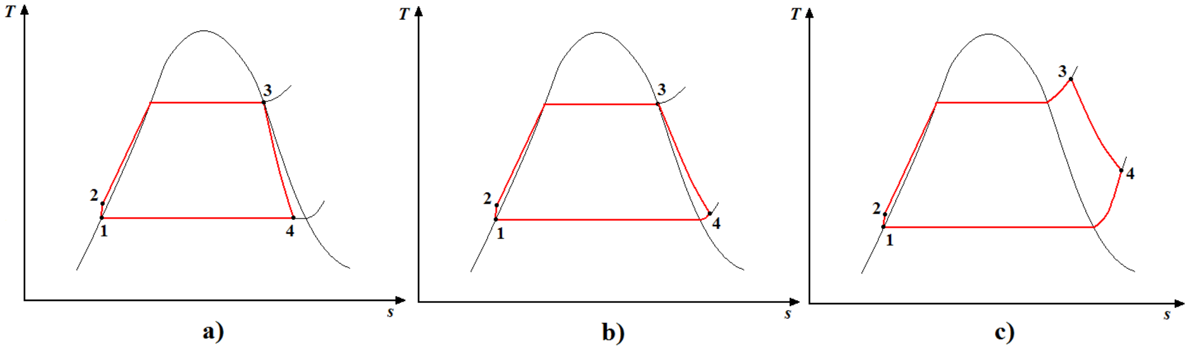


Figure 2. *T-s* diagram of *B-Type* ORC-Binary Power Plant a) *b1*-type, b) *b2*-type, c) *b3*-type [16]

According to Figure 2., the B- type cycle design consists of b1, b2 and b3 models depending on the characteristics of the working fluid at the inlet and outlet of the turbine. At the b1-type, the working fluid enters the turbine as a saturated vapor and exits the turbine as a saturated liquid-vapor mixture. The difference of type b2-type from b1-type is that the working fluid exits the turbine as a superheated vapor. At the b3-type, the working fluid enters and exits the turbine as a superheated vapor. The temperatures of the geothermal fluids at the exit of preheater (T_{1b}) and evaporator (T_{1b}), the temperature of the working fluid at the exit of condenser (T_{2c}), the pressure and the temperature of the working fluid at the exit of pump (P_{2d} and T_{2d}, respectively) are the design parameters of the power plant.

The efficiency values of the heat exchanger, turbine, generator and pump were accepted as 98%, 85%, 99% and 90%, respectively. The net power output and the energy efficiencies of the systems were calculated by using the efficiency values of these components. The detailed information about the technical data and mathematical modeling of the designed plant could be reached from the study of Ref [16-18]. The results of designed plants can be seen in App. 1-4.

III. EATWOS ANALYSIS

EATWOS is a new technique developed in 2006 in order to obtain satisfactory solutions based on output. Depending on input values, it is a technique that can be used to give relative results in outputs and to compare these results with each other and to decide the optimum result in energy system design problems. The EATWOS implementation steps are summarized below [9]. Depending on the input and output values, the input and output matrices are respectively as follows;

$$\underline{X} = \begin{bmatrix} x_{11} & \cdots & x_{1K} \\ \vdots & \ddots & \vdots \\ x_{I1} & \cdots & x_{IK} \end{bmatrix} \qquad x_{ik} \in \mathbb{R}_{\geq 0} \quad \forall_i = 1, \dots, I \quad \forall_k = 1, \dots, K \tag{1}$$

$$\underline{Y} = \begin{bmatrix} y_{11} & \cdots & y_{1J} \\ \vdots & \ddots & \vdots \\ y_{I1} & \cdots & y_{IJ} \end{bmatrix} \qquad y_{ij} \in \mathbb{R}_{\geq 0} \quad \forall_i = 1, \dots, I \quad \forall_j = 1, \dots, J \tag{2}$$

As a second step, these matrices are normalized using the following equations;

$$s_{ik} = \frac{x_{ik}}{\sqrt{\sum_{i=1}^{K} x_{ik}^2}} \tag{3}$$

$$r_{ij} = \frac{y_{ij}}{\sqrt{\sum_{i=1}^{I} y_{ik}^2}} \tag{4}$$

As the third step, the distance matrices are calculated for the input and output values. In this context, the following distance measurement expressions are used for input and output values respectively.

$$ip_{ik} = 1 + s_{ik} - s_k^* \tag{5}$$

$$op_{ik} = 1 + r_{ij} - r_j^* \tag{6}$$

s_k^* and r_j^* are normalized maximum input and output values, respectively. These values are given as follows.

$$s_k^* = \min_i\{s_k\} \tag{7}$$

$$r_j^* = \max_i\{r_j\} \tag{8}$$

The efficiency values of the designs in the decision-making mechanisms are based on the weight values of the input (w_k) and output (v_j) parameters. The last step, the efficiency values are calculated by the following equation;

$$E_i = \frac{\sum_{j=1}^{J} v_j \cdot op_{ij}}{\sum_{k=1}^{K} w_k \cdot ip_{ik}} \tag{9}$$

IV. RESULTS AND DISCUSSION

In this study, 48 designs for *b1-Type*, 48 designs for *b2-Type* and 288 designs for *b3-Type* were designed for two different working fluid (R-141b, R-134a), pressure and temperature values of the geothermal energy powered ORC cycle. T_{1b}, T_{2d} T_{2c} and P_{2d} values are the input parameters of the EATWOS analysis. Also, the output parameters of this analysis are energy efficiency (η) and the net power output values. The weights used in the modeling of inputs and outputs are calculated as the ratio of the sum of the normalized distance within each input and output to the total weight of all parameters as given in Table 1-3. The efficiency values of EATWOS analysis which were calculated according to the weight values were given in Figure 3 for *b1-type* (R-134a), Figure 4 for *b2-type* (R-141b) and Figure 5 for *b3-type* (R-134a, R-141b).

Table 1. The weights for *b1-type* models

Weight values	w_k			v_j	
	T_{1b} (K)	**T_{2d} (K)**	**T_{2c} (K)**	**W_{net} (MW)**	**η**
Parameters Total	49.086	48.385	49.555	46.641	47.125
Overall Total	147.026			93.766	
Weight	0.333863	0.329089	0.337048	0.497419	0.502581

Table 2. The weights for *b2-type* models

Weight values	w_k			v_j	
	T_{1b} (K)	**T_{2d} (K)**	**T_{2c} (K)**	**W_{net} (MW)**	**η**
Parameters Total	49.086	48.532	49.555	46.784	47.261
Overall Total	147.173			94.045	
Weight	0.333529	0.329761	0.336711	0.497469	0.502531

Table 3. The weights for *b3-type* models

R-134a						
Weight values	w_k				v_j	
	T_{1b} (K)	**T_{2d} (K)**	**T_{2c} (K)**	**P_{2d} (kPa)**	**W_{net} (MW)**	**η**
Parameters Total	145.882	144.666	146.693	145.958	139.575	140.506
Overall Total	583.198				280.082	
Weight	0.250141	0.248056	0.251532	0.250271	0.498338	0.501662
R-141b						
Weight values	w_k				v_j	
	T_{1b} (K)	**T_{2d} (K)**	**T_{2c} (K)**	**P_{2d} (kPa)**	**W_{net} (MW)**	**η**
Parameters Total	145.882	144.921	146.693	149.306	139.307	140.351
Overall Total	586.802				279.659	
Weight	0.248605	0.246968	0.249987	0.25444	0.498133	0.501867

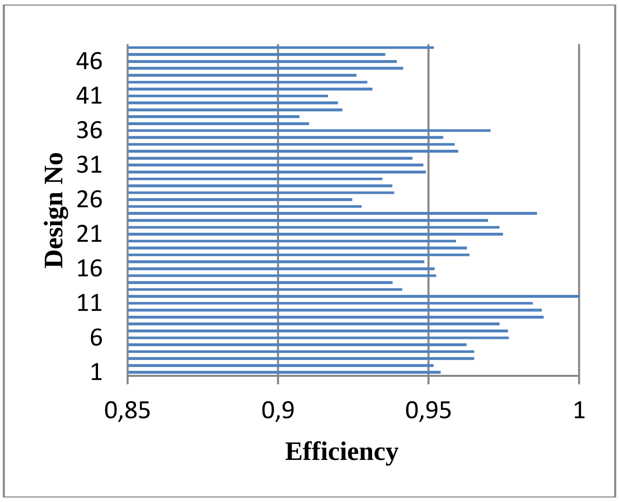


Figure 3. W_{net} based efficiency values of *b1-type* models (R-134a)

According to Figure 3, the efficiency values of the models are determined between 0.90 and 1.00. In this case, the most effective design in terms of decision-making is determined as Model 12 depending on its highest efficiency value. W_{net} based efficiency values of *b2-type* models and *b3-type* models are given in Figure 4 and Figure 5, respectively.

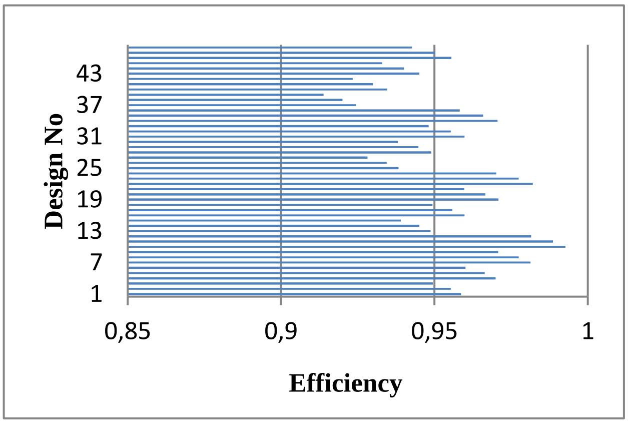
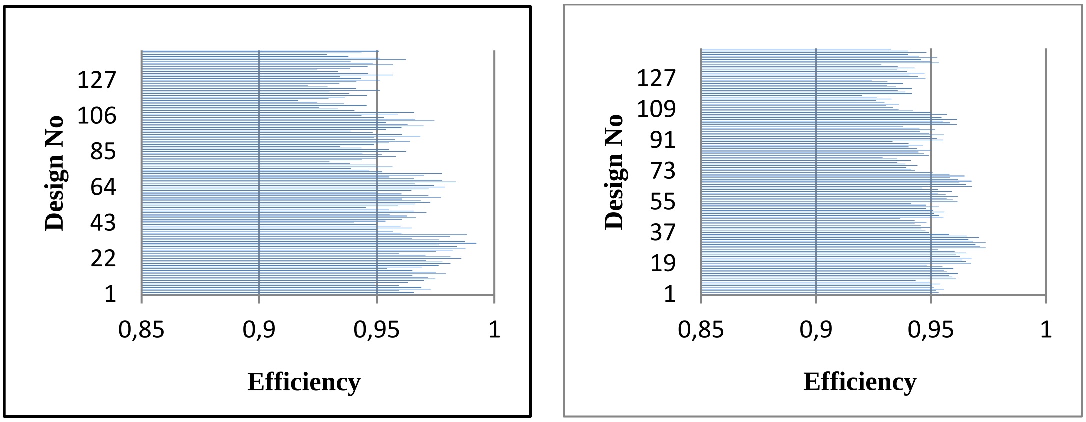


Figure 4. W_{net} based efficiency values of *b2-type* models (R-141b)



a) b)

Figure 5. W_{net} based efficiency values of *b3-type* models a) R-134a, b) R-141b

According to Figure 4 and Figure 5a, W_{net} based efficiency values of *b2-type* models and *b3-type* models for R-134a are determined between 0.91 and 0.99. The most effective design in terms of decision-making is determined as Model 10 for *b2-type* models and Model 31 for *b3-type* (R-134a). According to Figure 5b, W_{net} based efficiency values of *b3-type* models are determined between 0.92 and 0.97 for R-141b. In this case, the most effective design in terms of decision-making is determined as Model 31. η based efficiency values of *b1-type* models and *b2-type* models are given in Figure 6 and Figure 7, respectively.

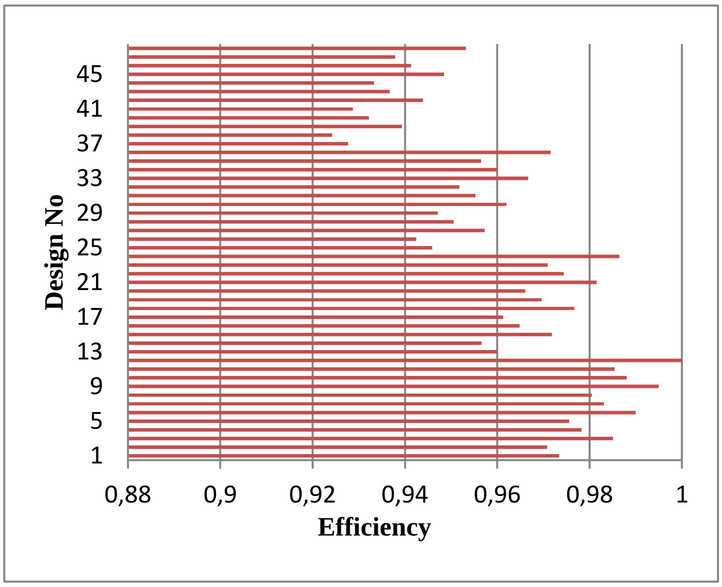


Figure 6. η based efficiency values of *b1-type* models (R-134a)

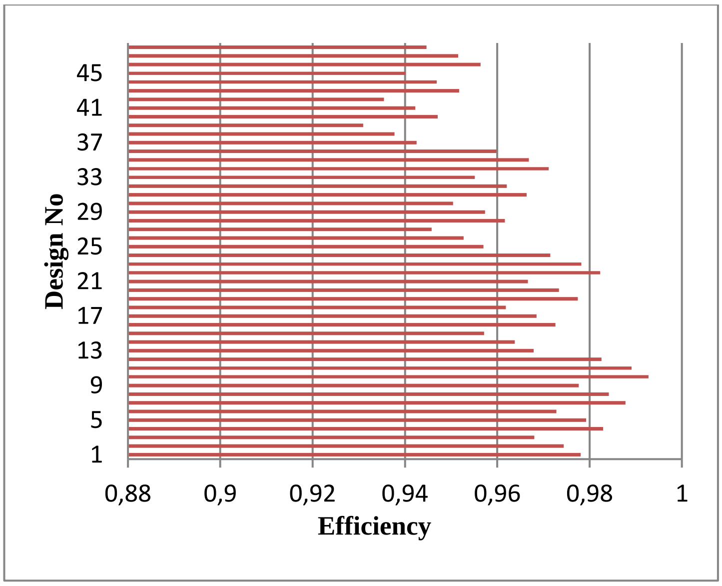
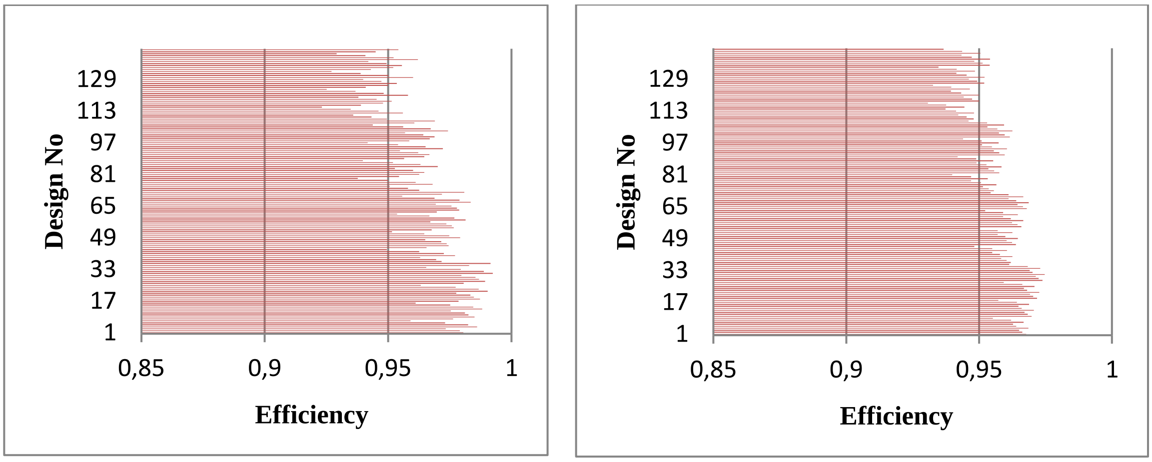


Figure 7. η based efficiency values of *b2-type* models (R-141b)

As seen in Figure 6, η based efficiency values of *b1-type* models are calculated between 0.92 and 1.00. Under the same circumstances, the most effective design in terms of decision-making is determined as model 12. According to Figure 7, η based efficiency values of b2-type models are determined between 0.93 and 0.99. In this case, the most effective design in terms of decision-making is determined as Model 10. η based efficiency values of *b3-type* models for R-134a and R-141b are given in Figure 8a and Figure 8b, respectively.



a) b)

Figure 8. η based efficiency values of *b3-type* models a) R-134a, b) R-141b

As seen in Figure 8a and Figure 8b, η based efficiency values of *b3-type* models are calculated between 0.92 and 1.00 for R-134a and 0.93 and 0.97 for R-141b. Under the same circumstances, the most effective design in terms of decision-making is determined as Model 31 for both working fluids. W_{net} and η integrated-based efficiency values of *b1-type* models and *b2-type* models are given in Figure 9 and Figure 10, respectively.

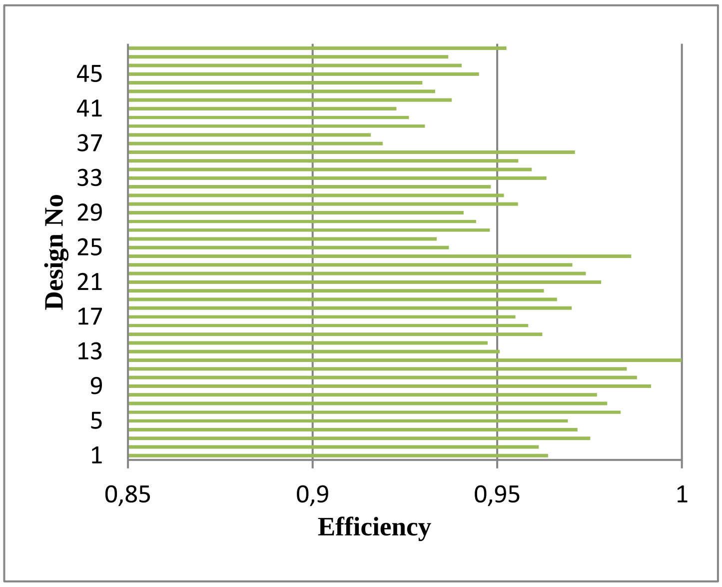


Figure 9. W_{net} and η integrated-based efficiency values of *b1-type* models (R-134a)

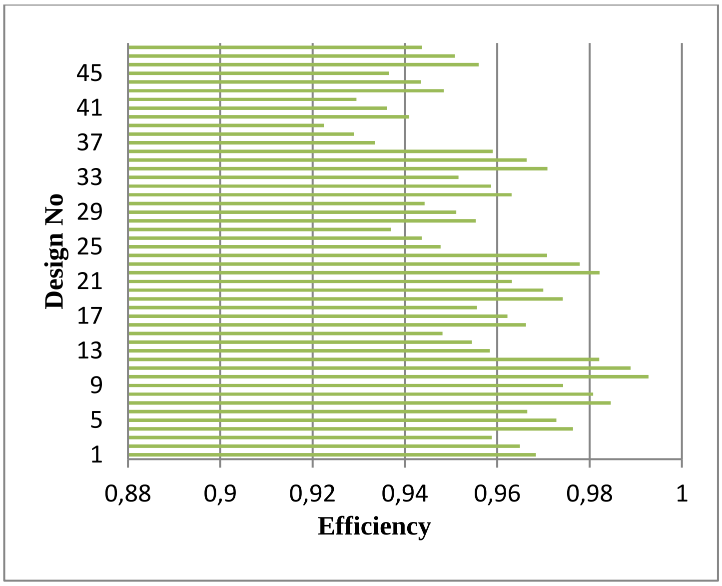
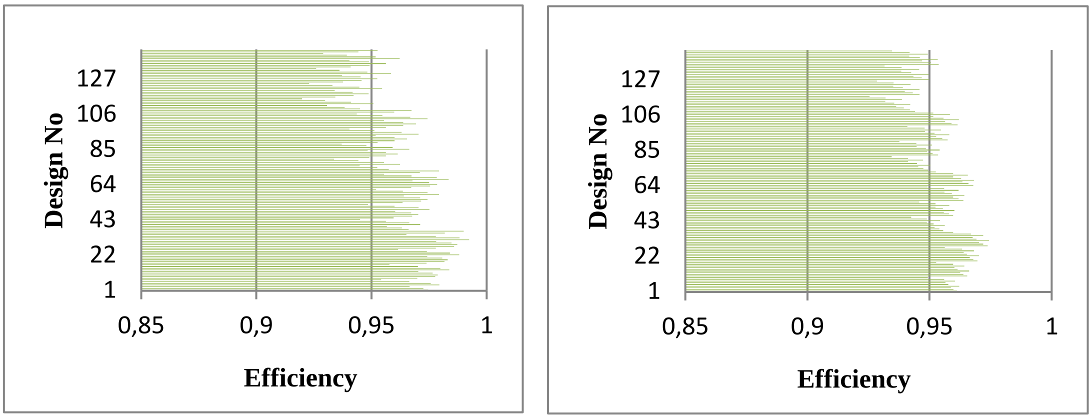


Figure 10. W_{net} and η integrated-based efficiency values of *b2-type* models (R-141b)

As seen in Figure 9, W_{net} and η integrated-based efficiency values of *b1-type* models are calculated between 0,91 and 1.00. Under the same circumstances, the most effective design in terms of decision-making is determined as model 12. According to Figure 10., W_{net} and η integrated-based efficiency values of *b2-type* models are determined between 0.92 and 0.99. In this case, the most effective design in terms of decision-making is determined as Model 10. W_{net} and η integrated-based efficiency values of *b3-type* models for R-134a and R-141b are given in Figure 11a and Figure 11b, respectively



a)

b)

Figure 11. W_{net} and η integrated-based efficiency values of *b3-type* models a) R-134a, b) R-141b

As seen in Figure 11a and Figure 11b, W_{net} and η integrated-based efficiency values of *b3-type* models are calculated between 0.91 and 0.99 for R-134a and 0.92 and 0.97 for R-141b. Under the same circumstances, the most effective design in terms of decision-making is determined as model 31 for both working fluids.

The efficiency values increase with the decrease of the T_{1b} and T_{2d}. With the increase of T_{2c}, the efficiency values decrease. The effect of pressure on efficiency is negative since the efficiency decrease with the increase of pressure.

V. CONCLUSION

In this study, *b-type* ORC geothermal power plants have been analytically examined considering various design parameters. Then, obtained energy efficiency and net power output values were evaluated with EATWOS multi-criteria decision-making model and the most effective design was determined.

As a result, the most effective models of *b1-type*, *b2-type* and *b3-type* were determined as Model 12, Model 10 and Model 31, respectively for energy efficiency, net yearly electricity generation and integrated-based values. The system parameters of Model 12 for *b1-type* were determined as 353.15 K. 358.15 K, 295.15 K, 410.92 MWh and 11.32 for T_{1b}, T_{2d}, T_{2c}, E_{net} and η, respectively. The system parameters of Model 10 for *b2-type* were determined as 353.15 K, 413.15 K, 295.15 K, 656.37 MWh and 18.08 for T_{1b}, T_{2d}, T_{2c}, E_{net} and η, respectively. The system parameters of Model 31 for *b3-type* (R-141b) were determined as 353.15 K, 403.15 K, 295.15 K, 1000 kPa, 601.10 MWh and 16.29 for T_{1b}, T_{2d}, T_{2c}, P_{2d}, E_{net} and η, respectively. The system parameters of model 31 for *b3-type* (R-134a) were determined as 353.15 K, 363.15 K, 295.15 K, 2750 kPa, 439.99 MWh and 11.22 for T_{1b}, T_{2d}, T_{2c}, P_{2d}, E_{net} and η, respectively.

In decision making for the optimum design, it is still needed an expert view. From this point, Model 10 seems as the best configuration taking the highest energy generation rate, relatively higher thermal efficiency and lower pressure ratios into account.

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APPENDIX

APP. 1. Design parameters of b1-type model for R-134a as a working fluid

Design No	T_{1b} (K)	T_{2d} (K)	T_{2c} (K)	E_{net} (MWh)	η	**No**	T_{1b} (K)	T_{2d} (K)	T_{2c} (K)	E_{net} (MWh)	η
1	383.15	368.15	295.15	347.58	10.85	**25**	383.15	368.15	303.15	313.29	9.78
2	383.15	363.15	295.15	335.79	10.48	**26**	383.15	363.15	303.15	299.75	9.35
3	383.15	358.15	295.15	362.62	11.32	**27**	383.15	358.15	303.15	328.17	10.24
4	373.15	368.15	295.15	363.06	10.85	**28**	373.15	368.15	303.15	327.24	9.78
5	373.15	363.15	295.15	350.75	10.48	**29**	373.15	363.15	303.15	313.10	9.35
6	373.15	358.15	295.15	378.77	11.32	**30**	373.15	358.15	303.15	342.79	10.24
7	363.15	368.15	295.15	378.49	10.85	**31**	363.15	368.15	303.15	341.14	9.78
8	363.15	363.15	295.15	365.65	10.48	**32**	363.15	363.15	303.15	326.40	9.35
9	363.15	358.15	295.15	394.86	11.32	**33**	363.15	358.15	303.15	357.35	10.24
10	353.15	368.15	295.15	393.88	10.85	**34**	353.15	368.15	303.15	355.02	9.78
11	353.15	363.15	295.15	380.52	10.48	**35**	353.15	363.15	303.15	339.67	9.35
12	353.15	358.15	295.15	410.92	11.32	**36**	353.15	358.15	303.15	371.88	10.24
13	383.15	368.15	299.15	331.57	10.35	**37**	383.15	368.15	309.15	292.01	9.11
14	383.15	363.15	299.15	317.88	9.92	**38**	383.15	363.15	309.15	278.54	8.69
15	383.15	358.15	299.15	347.16	10.83	**39**	383.15	358.15	309.15	308.06	9.61
16	373.15	368.15	299.15	346.34	10.35	**40**	373.15	368.15	309.15	305.02	9.11
17	373.15	363.15	299.15	332.03	9.92	**41**	373.15	363.15	309.15	290.94	8.69
18	373.15	358.15	299.15	362.62	10.83	**42**	373.15	358.15	309.15	321.78	9.61
19	363.15	368.15	299.15	361.05	10.35	**43**	363.15	368.15	309.15	317.98	9.11
20	363.15	363.15	299.15	346.14	9.92	**44**	363.15	363.15	309.15	303.31	8.69
21	363.15	358.15	299.15	378.02	10.83	**45**	363.15	358.15	309.15	335.46	9.61
22	353.15	368.15	299.15	375.74	10.35	**46**	353.15	368.15	309.15	330.91	9.11
23	353.15	363.15	299.15	360.22	9.92	**47**	353.15	363.15	309.15	315.64	8.69
24	353.15	358.15	299.15	393.40	10.83	**48**	353.15	358.15	309.15	349.10	9.61

APP. 2. Design parameters of *b2-type* model for R-141b as a working fluid

Design No	T_{1b} **(K)**	T_{2d} **(K)**	T_{2c} **(K)**	E_{net} **(MWh)**	**η**	**No**	T_{1b} **(K)**	T_{2d} **(K)**	T_{2c} **(K)**	E_{net} **(MWh)**	**η**
1	383.15	413.15	295.15	579.22	18.08	**25**	383.15	413.15	303.15	547.54	17.09
2	383.15	403.15	295.15	552.68	17.25	**26**	383.15	403.15	303.15	518.72	16.19
3	383.15	393.15	295.15	516.07	16.10	**27**	383.15	393.15	303.15	480.26	14.99
4	373.15	413.15	295.15	605.02	18.08	**28**	373.15	413.15	303.15	571.92	17.09
5	373.15	403.15	295.15	577.29	17.25	**29**	373.15	403.15	303.15	541.81	16.19
6	373.15	393.15	295.15	539.05	16.10	**30**	373.15	393.15	303.15	501.65	14.99
7	363.15	413.15	295.15	630.73	18.08	**31**	363.15	413.15	303.15	596.23	17.09
8	363.15	403.15	295.15	601.82	17.25	**32**	363.15	403.15	303.15	564.84	16.19
9	363.15	393.15	295.15	561.95	16.10	**33**	363.15	393.15	303.15	522.96	14.99
10	353.15	413.15	295.15	656.37	18.08	**34**	353.15	413.15	303.15	620.47	17.09
11	353.15	403.15	295.15	626.29	17.25	**35**	353.15	403.15	303.15	587.81	16.19
12	353.15	393.15	295.15	584.80	16.10	**36**	353.15	393.15	303.15	544.23	14.99
13	383.15	413.15	299.15	564.90	17.63	**37**	383.15	413.15	309.15	527.70	16.47
14	383.15	403.15	299.15	536.83	16.75	**38**	383.15	403.15	309.15	496.91	15.51
15	383.15	393.15	299.15	499.33	15.58	**39**	383.15	393.15	309.15	458.92	14.32
16	373.15	413.15	299.15	590.06	17.63	**40**	373.15	413.15	309.15	551.20	16.47
17	373.15	403.15	299.15	560.73	16.75	**41**	373.15	403.15	309.15	519.04	15.51
18	373.15	393.15	299.15	521.56	15.58	**42**	373.15	393.15	309.15	479.36	14.32
19	363.15	413.15	299.15	615.13	17.63	**43**	363.15	413.15	309.15	574.62	16.47
20	363.15	403.15	299.15	584.56	16.75	**44**	363.15	403.15	309.15	541.09	15.51
21	363.15	393.15	299.15	543.73	15.58	**45**	363.15	393.15	309.15	499.73	14.32
22	353.15	413.15	299.15	640.15	17.63	**46**	353.15	413.15	309.15	597.99	16.47
23	353.15	403.15	299.15	608.33	16.75	**47**	353.15	403.15	309.15	563.09	15.51
24	353.15	393.15	299.15	565.84	15.58	**48**	353.15	393.15	309.15	520.05	14.32

APP. 3. Design parameters of *b3-type* model for R-134a as a working fluid

Design No	T_{1b} (K)	T_{2d} (K)	T_{2c} (K)	P_{2d} (kPa)	E_{net} (MWh)	η
1	383.15	368.15	295.15	3000	383.16	10.97
2	383.15	368.15	295.15	2500	356.02	10.37
3	383.15	368.15	295.15	2000	315.35	9.32
4	383.15	363.15	295.15	2750	388.27	11.22
5	383.15	363.15	295.15	2500	364.18	10.61
6	383.15	363.15	295.15	2000	311.01	9.17
7	383.15	358.15	295.15	2500	281.83	8.01
8	383.15	358.15	295.15	2300	331.71	9.67
9	383.15	358.15	295.15	2000	348.51	10.33
10	373.15	368.15	295.15	3000	400.22	10.97
11	373.15	368.15	295.15	2500	371.88	10.37
12	373.15	368.15	295.15	2000	329.40	9.32
13	373.15	363.15	295.15	2750	405.56	11.22
14	373.15	363.15	295.15	2500	380.40	10.61
15	373.15	363.15	295.15	2000	324.86	9.17
16	373.15	358.15	295.15	2500	294.38	8.01
17	373.15	358.15	295.15	2300	346.48	9.67
18	373.15	358.15	295.15	2000	364.03	10.33
19	363.15	368.15	295.15	3000	417.23	10.97
20	363.15	368.15	295.15	2500	387.68	10.37
21	363.15	368.15	295.15	2000	343.39	9.32
22	363.15	363.15	295.15	2750	422.79	11.22
23	363.15	363.15	295.15	2500	396.57	10.61
24	363.15	363.15	295.15	2000	338.66	9.17
25	363.15	358.15	295.15	2500	306.89	8.01
26	363.15	358.15	295.15	2300	361.20	9.67
27	363.15	358.15	295.15	2000	379.50	10.33
28	353.15	368.15	295.15	3000	434.19	10.97
29	353.15	368.15	295.15	2500	403.44	10.37
30	353.15	368.15	295.15	2000	357.36	9.32
31	353.15	363.15	295.15	2750	439.99	11.22
32	353.15	363.15	295.15	2500	412.69	10.61
33	353.15	363.15	295.15	2000	352.43	9.17
34	353.15	358.15	295.15	2500	319.37	8.01
35	353.15	358.15	295.15	2300	375.89	9.67
36	353.15	358.15	295.15	2000	394.93	10.33
37	383.15	368.15	299.15	3000	362.47	10.32
38	383.15	368.15	299.15	2500	332.26	9.64
39	383.15	368.15	299.15	2000	289.20	8.51

APP. 3. (*continued*)

Design No	T_{1b} (K)	T_{2d} (K)	T_{2c} (K)	P_{2d} (kPa)	E_{net} (MWh)	η
40	383.15	363.15	299.15	2750	367.43	10.57
41	383.15	363.15	299.15	2500	340.09	9.86
42	383.15	363.15	299.15	2000	284.14	8.34
43	383.15	358.15	299.15	2500	258.16	7.27
44	383.15	358.15	299.15	2300	304.09	8.82
45	383.15	358.15	299.15	2000	321.88	9.51
46	373.15	368.15	299.15	3000	378.61	10.32
47	373.15	368.15	299.15	2500	347.06	9.64
48	373.15	368.15	299.15	2000	302.07	8.51
49	373.15	363.15	299.15	2750	383.79	10.57
50	373.15	363.15	299.15	2500	355.23	9.86
51	373.15	363.15	299.15	2000	296.80	8.34
52	373.15	358.15	299.15	2500	269.66	7.27
53	373.15	358.15	299.15	2300	317.63	8.82
54	373.15	358.15	299.15	2000	336.22	9.51
55	363.15	368.15	299.15	3000	394.69	10.32
56	363.15	368.15	299.15	2500	361.81	9.64
57	363.15	368.15	299.15	2000	314.91	8.51
58	363.15	363.15	299.15	2750	400.10	10.57
59	363.15	363.15	299.15	2500	370.32	9.86
60	363.15	363.15	299.15	2000	309.41	8.34
61	363.15	358.15	299.15	2500	281.12	7.27
62	363.15	358.15	299.15	2300	331.13	8.82
63	363.15	358.15	299.15	2000	350.50	9.51
64	353.15	368.15	299.15	3000	410.74	10.32
65	353.15	368.15	299.15	2500	376.52	9.64
66	353.15	368.15	299.15	2000	327.72	8.51
67	353.15	363.15	299.15	2750	416.37	10.57
68	353.15	363.15	299.15	2500	385.38	9.86
69	353.15	363.15	299.15	2000	321.99	8.34
70	353.15	358.15	299.15	2500	292.55	7.27
71	353.15	358.15	299.15	2300	344.60	8.82
72	353.15	358.15	299.15	2000	364.76	9.51
73	383.15	368.15	303.15	3000	340.69	9.64
74	383.15	368.15	303.15	2500	302.48	8.71
75	383.15	368.15	303.15	2000	255.95	7.49
76	383.15	363.15	303.15	2750	345.49	9.89
77	383.15	363.15	303.15	2500	309.80	8.92
78	383.15	363.15	303.15	2000	249.99	7.29

APP. 3. (*continued*)

Design No	T_{1b} (K)	T_{2d} (K)	T_{2c} (K)	P_{2d} (kPa)	E_{net} (MWh)	η
79	383.15	358.15	303.15	2500	226.73	6.30
80	383.15	358.15	303.15	2300	275.03	7.92
81	383.15	358.15	303.15	2000	290.22	8.53
82	373.15	368.15	303.15	3000	355.86	9.64
83	373.15	368.15	303.15	2500	315.95	8.71
84	373.15	368.15	303.15	2000	267.34	7.49
85	373.15	363.15	303.15	2750	360.87	9.89
86	373.15	363.15	303.15	2500	323.59	8.92
87	373.15	363.15	303.15	2000	261.12	7.29
88	373.15	358.15	303.15	2500	236.82	6.30
89	373.15	358.15	303.15	2300	287.28	7.92
90	373.15	358.15	303.15	2000	303.15	8.53
91	363.15	368.15	303.15	3000	370.98	9.64
92	363.15	368.15	303.15	2500	329.37	8.71
93	363.15	368.15	303.15	2000	278.70	7.49
94	363.15	363.15	303.15	2750	376.21	9.89
95	363.15	363.15	303.15	2500	337.34	8.92
96	363.15	363.15	303.15	2000	272.22	7.29
97	363.15	358.15	303.15	2500	246.89	6.30
98	363.15	358.15	303.15	2300	299.49	7.92
99	363.15	358.15	303.15	2000	316.03	8.53
100	353.15	368.15	303.15	3000	386.07	9.64
101	353.15	368.15	303.15	2500	342.77	8.71
102	353.15	368.15	303.15	2000	290.04	7.49
103	353.15	363.15	303.15	2750	391.50	9.89
104	353.15	363.15	303.15	2500	351.06	8.92
105	353.15	363.15	303.15	2000	283.29	7.29
106	353.15	358.15	303.15	2500	256.93	6.30
107	353.15	358.15	303.15	2300	311.66	7.92
108	353.15	358.15	303.15	2000	328.88	8.53
109	383.15	368.15	309.15	3000	309.14	8.65
110	383.15	368.15	309.15	2500	264.92	7.56
111	383.15	368.15	309.15	2000	217.97	6.34
112	383.15	363.15	309.15	2750	317.78	9.03
113	383.15	363.15	309.15	2500	271.60	7.75
114	383.15	363.15	309.15	2000	210.84	6.10
115	383.15	358.15	309.15	2500	189.69	5.16
116	383.15	358.15	309.15	2300	234.95	6.69
117	383.15	358.15	309.15	2000	252.92	7.40

APP. 3. (*continued*)

Design No	T_{1b} (K)	T_{2d} (K)	T_{2c} (K)	P_{2d} (kPa)	E_{net} (MWh)	η
118	373.15	368.15	309.15	3000	322.91	8.65
119	373.15	368.15	309.15	2500	276.71	7.56
120	373.15	368.15	309.15	2000	227.68	6.34
121	373.15	363.15	309.15	2750	331.93	9.03
122	373.15	363.15	309.15	2500	283.70	7.75
123	373.15	363.15	309.15	2000	220.23	6.10
124	373.15	358.15	309.15	2500	198.13	5.16
125	373.15	358.15	309.15	2300	245.41	6.69
126	373.15	358.15	309.15	2000	264.18	7.40
127	363.15	368.15	309.15	3000	336.63	8.65
128	363.15	368.15	309.15	2500	288.47	7.56
129	363.15	368.15	309.15	2000	237.35	6.34
130	363.15	363.15	309.15	2750	346.03	9.03
131	363.15	363.15	309.15	2500	295.75	7.75
132	363.15	363.15	309.15	2000	229.59	6.10
133	363.15	358.15	309.15	2500	206.55	5.16
134	363.15	358.15	309.15	2300	255.84	6.69
135	363.15	358.15	309.15	2000	275.41	7.40
136	353.15	368.15	309.15	3000	350.32	8.65
137	353.15	368.15	309.15	2500	300.20	7.56
138	353.15	368.15	309.15	2000	247.00	6.34
139	353.15	363.15	309.15	2750	360.10	9.03
140	353.15	363.15	309.15	2500	307.78	7.75
141	353.15	363.15	309.15	2000	238.93	6.10
142	353.15	358.15	309.15	2500	214.95	5.16
143	353.15	358.15	309.15	2300	266.24	6.69
144	353.15	358.15	309.15	2000	286.61	7.40

APP. 4. Design parameters of *b3-type* model for R-141b as a working fluid

Design No	T_{1b} (K)	T_{2d} (K)	T_{2c} (K)	P_{2d} (kPa)	E_{net} (MWh)	η
1	383.15	413.15	295.15	1300	576.57	17.65
2	383.15	413.15	295.15	1000	525.76	16.15
3	383.15	413.15	295.15	700	476.63	14.70
4	383.15	403.15	295.15	1000	530.44	16.29
5	383.15	403.15	295.15	700	462.95	14.27
6	383.15	403.15	295.15	500	427.93	13.24
7	383.15	393.15	295.15	700	469.91	14.48
8	383.15	393.15	295.15	500	416.63	12.88
9	383.15	393.15	295.15	400	365.63	11.32
10	373.15	413.15	295.15	1300	602.25	17.65
11	373.15	413.15	295.15	1000	549.17	16.15
12	373.15	413.15	295.15	700	497.85	14.70
13	373.15	403.15	295.15	1000	554.07	16.29
14	373.15	403.15	295.15	700	483.57	14.27
15	373.15	403.15	295.15	500	446.99	13.24
16	373.15	393.15	295.15	700	490.84	14.48
17	373.15	393.15	295.15	500	435.18	12.88
18	373.15	393.15	295.15	400	381.91	11.32
19	363.15	413.15	295.15	1300	627.84	17.65
20	363.15	413.15	295.15	1000	572.50	16.15
21	363.15	413.15	295.15	700	519.01	14.70
22	363.15	403.15	295.15	1000	577.61	16.29
23	363.15	403.15	295.15	700	504.11	14.27
24	363.15	403.15	295.15	500	465.98	13.24
25	363.15	393.15	295.15	700	511.69	14.48
26	363.15	393.15	295.15	500	453.67	12.88
27	363.15	393.15	295.15	400	398.14	11.32
28	353.15	413.15	295.15	1300	653.37	17.65
29	353.15	413.15	295.15	1000	595.78	16.15
30	353.15	413.15	295.15	700	540.11	14.70
31	353.15	403.15	295.15	1000	601.10	16.29
32	353.15	403.15	295.15	700	524.61	14.27
33	353.15	403.15	295.15	500	484.93	13.24
34	353.15	393.15	295.15	700	532.50	14.48
35	353.15	393.15	295.15	500	472.12	12.88
36	353.15	393.15	295.15	400	414.33	11.32
37	383.15	413.15	299.15	1300	559.88	17.12
38	383.15	413.15	299.15	1000	508.59	15.61
39	383.15	413.15	299.15	700	454.93	14.03

APP. 4. (*continued*)

Design No	T_{1b} **(K)**	T_{2d} **(K)**	T_{2c} **(K)**	P_{2d} **(kPa)**	E_{net} **(MWh)**	**η**
40	383.15	403.15	299.15	1000	512.77	15.74
41	383.15	403.15	299.15	700	444.56	13.70
42	383.15	403.15	299.15	500	400.92	12.39
43	383.15	393.15	299.15	700	451.00	13.89
44	383.15	393.15	299.15	500	392.84	12.14
45	383.15	393.15	299.15	400	342.94	10.61
46	373.15	413.15	299.15	1300	584.82	17.12
47	373.15	413.15	299.15	1000	531.24	15.61
48	373.15	413.15	299.15	700	475.19	14.03
49	373.15	403.15	299.15	1000	535.61	15.74
50	373.15	403.15	299.15	700	464.36	13.70
51	373.15	403.15	299.15	500	418.77	12.39
52	373.15	393.15	299.15	700	471.09	13.89
53	373.15	393.15	299.15	500	410.34	12.14
54	373.15	393.15	299.15	400	358.21	10.61
55	363.15	413.15	299.15	1300	609.67	17.12
56	363.15	413.15	299.15	1000	553.81	15.61
57	363.15	413.15	299.15	700	495.38	14.03
58	363.15	403.15	299.15	1000	558.37	15.74
59	363.15	403.15	299.15	700	484.09	13.70
60	363.15	403.15	299.15	500	436.56	12.39
61	363.15	393.15	299.15	700	491.10	13.89
62	363.15	393.15	299.15	500	427.77	12.14
63	363.15	393.15	299.15	400	373.43	10.61
64	353.15	413.15	299.15	1300	634.46	17.12
65	353.15	413.15	299.15	1000	576.33	15.61
66	353.15	413.15	299.15	700	515.52	14.03
67	353.15	403.15	299.15	1000	581.07	15.74
68	353.15	403.15	299.15	700	503.78	13.70
69	353.15	403.15	299.15	500	454.32	12.39
70	353.15	393.15	299.15	700	511.07	13.89
71	353.15	393.15	299.15	500	445.17	12.14
72	353.15	393.15	299.15	400	388.62	10.61
73	383.15	413.15	303.15	1300	540.11	16.50
74	383.15	413.15	303.15	1000	486.68	14.93
75	383.15	413.15	303.15	700	432.59	13.33
76	383.15	403.15	303.15	1000	494.56	15.17
77	383.15	403.15	303.15	700	421.32	12.97
78	383.15	403.15	303.15	500	373.09	11.53

APP. 4. (*continued*)

Design No	T_{1b} **(K)**	T_{2d} **(K)**	T_{2c} **(K)**	P_{2d} **(kPa)**	E_{net} **(MWh)**	**η**
79	383.15	393.15	303.15	700	427.05	13.14
80	383.15	393.15	303.15	500	364.81	11.26
81	383.15	393.15	303.15	400	313.46	9.69
82	373.15	413.15	303.15	1300	564.16	16.50
83	373.15	413.15	303.15	1000	508.36	14.93
84	373.15	413.15	303.15	700	451.86	13.33
85	373.15	403.15	303.15	1000	516.58	15.17
86	373.15	403.15	303.15	700	440.08	12.97
87	373.15	403.15	303.15	500	389.70	11.53
88	373.15	393.15	303.15	700	446.07	13.14
89	373.15	393.15	303.15	500	381.06	11.26
90	373.15	393.15	303.15	400	327.42	9.69
91	363.15	413.15	303.15	1300	588.13	16.50
92	363.15	413.15	303.15	1000	529.96	14.93
93	363.15	413.15	303.15	700	471.06	13.33
94	363.15	403.15	303.15	1000	538.53	15.17
95	363.15	403.15	303.15	700	458.78	12.97
96	363.15	403.15	303.15	500	406.26	11.53
97	363.15	393.15	303.15	700	465.03	13.14
98	363.15	393.15	303.15	500	397.25	11.26
99	363.15	393.15	303.15	400	341.33	9.69
100	353.15	413.15	303.15	1300	612.05	16.50
101	353.15	413.15	303.15	1000	551.51	14.93
102	353.15	413.15	303.15	700	490.21	13.33
103	353.15	403.15	303.15	1000	560.43	15.17
104	353.15	403.15	303.15	700	477.44	12.97
105	353.15	403.15	303.15	500	422.78	11.53
106	353.15	393.15	303.15	700	483.94	13.14
107	353.15	393.15	303.15	500	413.41	11.26
108	353.15	393.15	303.15	400	355.21	9.69
109	383.15	413.15	309.15	1300	520.34	15.88
110	383.15	413.15	309.15	1000	463.42	14.20
111	383.15	413.15	309.15	700	404.24	12.44
112	383.15	403.15	309.15	1000	470.67	14.42
113	383.15	403.15	309.15	700	391.72	12.05
114	383.15	403.15	309.15	500	342.78	10.58
115	383.15	393.15	309.15	700	401.10	12.34
116	383.15	393.15	309.15	500	335.93	10.37
117	383.15	393.15	309.15	400	285.34	8.82

APP. 4. (*continued*)

Design No	T_{1b} **(K)**	T_{2d} **(K)**	T_{2c} **(K)**	P_{2d} **(kPa)**	E_{net} **(MWh)**	**η**
118	373.15	413.15	309.15	1300	543.52	15.88
119	373.15	413.15	309.15	1000	484.06	14.20
120	373.15	413.15	309.15	700	422.24	12.44
121	373.15	403.15	309.15	1000	491.63	14.42
122	373.15	403.15	309.15	700	409.16	12.05
123	373.15	403.15	309.15	500	358.04	10.58
124	373.15	393.15	309.15	700	418.96	12.34
125	373.15	393.15	309.15	500	350.89	10.37
126	373.15	393.15	309.15	400	298.04	8.82
127	363.15	413.15	309.15	1300	566.61	15.88
128	363.15	413.15	309.15	1000	504.63	14.20
129	363.15	413.15	309.15	700	440.18	12.44
130	363.15	403.15	309.15	1000	512.52	14.42
131	363.15	403.15	309.15	700	426.55	12.05
132	363.15	403.15	309.15	500	373.26	10.58
133	363.15	393.15	309.15	700	436.76	12.34
134	363.15	393.15	309.15	500	365.80	10.37
135	363.15	393.15	309.15	400	310.71	8.82
136	353.15	413.15	309.15	1300	589.65	15.88
137	353.15	413.15	309.15	1000	525.14	14.20
138	353.15	413.15	309.15	700	458.08	12.44
139	353.15	403.15	309.15	1000	533.36	14.42
140	353.15	403.15	309.15	700	443.89	12.05
141	353.15	403.15	309.15	500	388.43	10.58
142	353.15	393.15	309.15	700	454.52	12.34
143	353.15	393.15	309.15	500	380.68	10.37
144	353.15	393.15	309.15	400	323.34	8.82