Chapter 66
An Analytic Hierarchy Process (AHP)-Based Multi-criteria Evaluation and Priority Analysis for Best FWH Substitution of Solar Aided Thermal Power Plant

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Abstract Utilization of solar energy in lieu of traditional feed water heating process in thermal power plants could be a milestone when the world is impending on to analyze critically the present scenario of energy consumption and liberation of greenhouse gases to the atmosphere. For it to occur, a theoretical cycle is thus proposed, which utilizes a feed water heat exchanger (FWHE) based on solar assisted system (parabolic trough), which would work in tandem to the heaters of a 210 MWe thermal power plant. Out of the listed six cases (LPH-2 to HPH-7), a congruent alternative has been proposed in this work, which relies on multi-criteria decision approach, based on analytical hierarchy process (AHP). AHP has been applied on the listed criteria, i.e., improvement in energy efficiency of plant, improvement in exergy efficiency of plant, Reduction in unit heat rate, improvement in exergy efficiency of solar field, solar contribution, and reduction in fuel consumption. After a thorough analysis, HPH-6 has been found as the most suitable alternative and the least one is LPH-2. The outcomes relied on its weightage and the relative significance/importance that have been assigned to them. Outcomes could differ with a change in the significance of various criteria, based on the necessities of the situation.

Keywords Analytic hierarchy process · Priority analysis · Solar-aided thermal power plant

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66.1 Introduction

An amalgamation of solar power with the traditional thermal power stations has an enormous potential that drives the very motive to attain a green-based power generation. With this process of combining the two, we could meet the targets of renewable energy, which in turn reduces the plant emissions and cost of fuel consumption. In this work, the motive could be achieved by using a solar-based FWHE in tandem to the traditional fossil fuel-based regenerative feed water heaters, this would in turn help us to reduce the fossil fuel consumption and its harmful emissions.

The analytic network process (ANP) and analytic hierarchy process (AHP) are multiple criteria decision-making (MCDM) methods. MCDM is a set of ideas, strategies, and procedures created to help decision-makers to settle on intricate decisions in an orderly and organized manner. A category of MCDM is multiple criteria discrete alternative problems. There are a few proposed strategies for taking care of discrete alternative problems, some of these are based on multiple attribute utility theory (MAUT) used by Keeney et al. [1], AHP/ANP by Saaty [2], other methods can be TOPSIS by Hwang et al. [3], PROMETHEE by Brans et al. [4] and ELECTRE by Roy [5]. A progressive point by point depiction of these techniques can be found in Pomerol-Barba et al. [6] and Belton Stewart et al. [7, 8] made an exhaustive bibliometric investigation on the improvement of MCDM strategies for the period 1992–2007 in both practical and theoretical situations. It is not simple to develop a mathematical model based on MCDM. Bouyssou et al. [9] said that 'there is no best model available for MCDM systems.' With its pros and cons, its application varies with the change in context. Diaz-Balteiro et al. [10], Kumar et al. [11], Shen et al. [12], and Dos Santos et al. [13] used MCDM techniques for decision making in sustainable development. Ho et al. [14] claimed that AHP is the outstanding and frequently used technique for supporting decision making among all the accessible methods, while Zhang et al. [15] mentioned that the AHP is an MCDM strategy that utilizes pair-wise examination, in the light of a numerical scale.

An AHP-TOPSIS-based framework was proposed by Choudhary et al. [16] for selecting the most efficient and suitable location for TPP. Stein EW [17] used AHP technique for ranking power generation technologies (renewable and non-renewable) on the basis of technical, financial, socio-economic, and environmental criteria. Cook et al. [18] analyzed the data of 40 power units to investigate relative operating efficiencies by using two-stage hierarchy model. AHP technique was used by Chatzimouratidis et al. [19–22] to examine ten types of renewable and non-renewable power plants. Initially, the impact of power generation by different sources on expectation for everyday comforts of nearby networks was assessed. Further, sensitivity analysis is being conducted for overall investigation of power units after considering technical, financial, and sustainability aspects. Another study is conducted on the same units for subjective and objective assessments. Pablo et al. [23] applied an AHP/ANP for selection of solar-aided TPP investment projects. Another analyst Yagmur Levent [24] had utilized another framework for by using AHP to evaluate and prioritize the equipment in a thermal power plant. Ren et al. [25] developed the MCDM framework

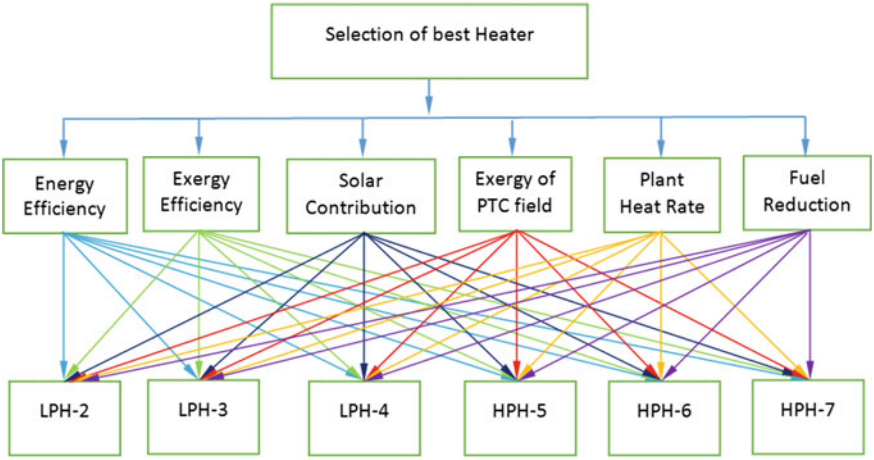

Fig. 66.1 Framework structure. *Source* Based on Saaty [2]

(nine metrics in four dimensions) for power production sustainability and security assessment, and a total of nine metrics in four dimensions including availability and security of supply, affordability and reliability, energy and economic efficiency, and environmental stewardship.

The motive behind using an ANP/AHP approach is to (i) enable decision-maker to examine complex problem by breaking a fundamental issue into less difficult and moderate sub-issues, (ii) ANP ought to be utilized, in case of interdependencies between criteria and alternatives, (iii) reliable decision making needs the elaborate study of interdependencies/priorities between criteria and alternatives. Out of numerous MCDM techniques available, AHP is used for the heater selection purpose and a framework is developed considering some specific criteria. The criteria for comparison were the main features of different heaters as shown in Fig. 66.1. Selection of best heater depends upon many factors like area of solar field, energy efficiency and exergy efficiency of the plant, solar contribution, exergy efficiency of solar field, unit heat rate (UHR), reduction in fuel consumption, ash content, CO_2 reduction, and various other factors. So the parameter selection was an important task to identify the most suitable substitution. AHP is used here with the help of Super Decision Software (open source) to rank six available cases.

66.2 Descriptions of Reference Plant

A coal-fired thermal power station with generating a capacity of 210 MWe based on Russian Technology has been selected as a reference unit for the study purpose This unit operates on sub-critical pressure, based on the Rankine cycle with reheating and regeneration. Figure 66.2 illustrates the integration of the reference unit with solar

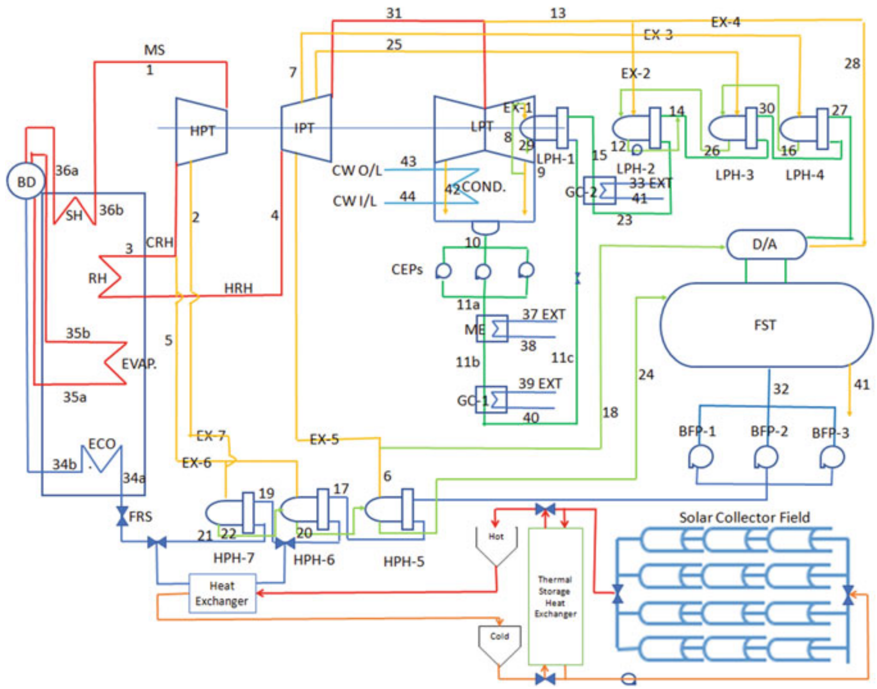

Fig. 66.2 Schematic diagram of solar integrated thermal power plant. *Source* The authors & NTPC, India

in place of high-pressure heater (HPH)-7.

All feed water heaters operate on different parameters. The data related to feedwater heaters for reference power plant has been shown in Table 66.1.

Table 66.1 Feed water heater parameters of reference unit plant

Parameter	Unit	LPH-2	LPH-3	LPH-4	HPH-5	HPH-6	HPH-7
Inlet temperature	°C	68.2	99.5	122.9	165.2	180	218.4
Outlet temperature	°C	99.5	122.9	152.1	180	218.4	239
Inlet flow	kg/s	145	145	145	190	190	190
Inlet enthalpy	kJ/kg	284.4	416.2	517.42	697	771.7	941.42
Outlet enthalpy	kJ/kg	416.2	517.42	642.30	771.7	941.42	1035.15
Solar power required	MW	19.11	14.68	18.11	14.19	32.25	17.81

Source The authors

66.3 Selection of Best Heater for Substitution

It consists of the following steps to use this tool.

66.3.1 Formulate the Model and Identify the Problem

The initial phase for utilization of the software is to build up the structure through which one can recognize the connection between various components and finalize the problem. The framework structure as demonstrated in Fig. 66.3 is created, and the issue is to select and rank the heaters from various access technologies.

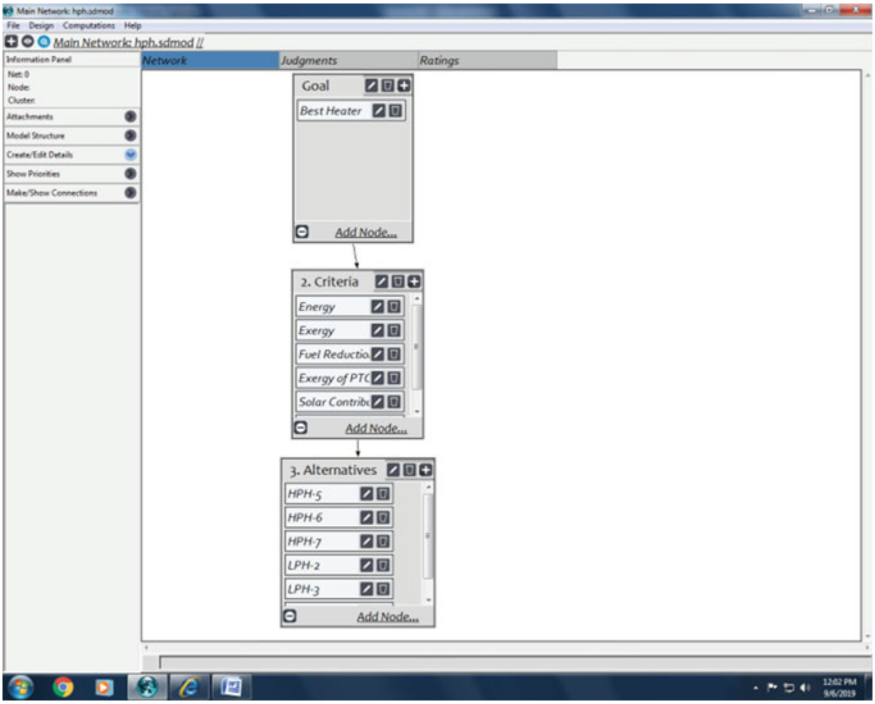

Fig. 66.3 Framework structure on software. *Source* The authors

66.3.2 Make the Framework/Matrix for the Pair-Wise Correlation Among Various Components

The subsequent step is to formulate the grid for analysis between every component/traits on which the choice depends. It helps in assigning significance to various characteristics, so that one can choose the required parameters later effortlessly for correlations. One can utilize the scale from 1 to 9, where 1 implies slightest significance and 9 implies most significant. While comparing two parameters and utilize reciprocals of these scales for reverse examinations.

66.3.3 Standardize the Matrix/Grid and Calculate Weight for Eigenvector and the with Consistency Ratio

The following stage was to institutionalize the correlations result so that the mistakes and disarray between significances of various comparative components could be expelled effortlessly for the entire procedure to work smoothly. The eigenvector and eigenvalues for every component are computed to obtain the most extreme estimation of the eigenvector. After computing the qualities, the consistency proportion/ratio (CR) is being checked, which ought to be under 0.1. If it is lesser than this value, then it means the comparisons are good and if it is above then the correlation needs to be rechecked, and the consistency ratio needs to be enhanced.

The CR value helps to maintain the logical sequence among different attributes while correlating them. The eigenvalue and eigenvector are needed to calculate the consistency ratio if using manual calculations, but in the event of utilizing the Super Decision Software the CR can be seen directly from software as in Fig. 66.4, and correlation ratio can be altered by enhancing/reducing the parameters relation. Correlation is created after considering the parameters given in Table 66.2. Data is

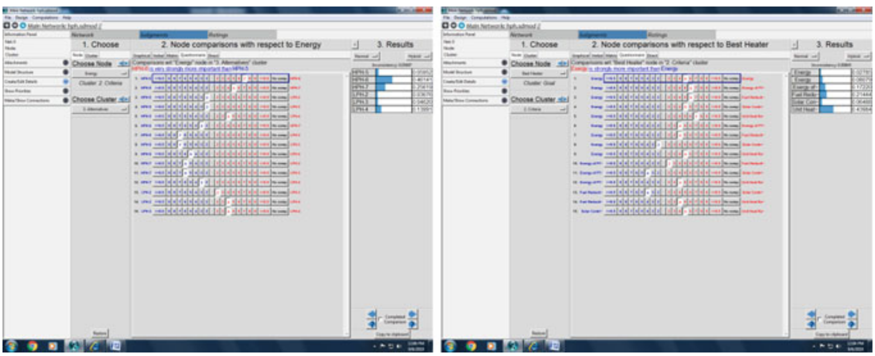

Fig. 66.4 Relative significance between criteria and alternatives with CR comparison. *Source* The authors

Table 66.2 Analysed values of criteria for AHP investigation

Parameter	Unit	HPH-7	HPH-6	HPH-5	LPH-4	LPH-3	LPH-2
Improvement in energy efficiency of plant	%	4.98	6.69	2.28	3.27	2.04	1.82
Improvement in exergy efficiency of plant	%	7.67	9.43	4.90	5.92	4.65	4.43
Reduction in unit heat rate	%	8.17	11.25	3.11	5.00	2.64	2.21
Improvement in exergy efficiency of solar field	%	9.48	9.00	8.57	7.65	6.78	5.62
Solar contribution	%	3.06	5.50	2.40	3.06	2.47	3.18
Reduction in fuel consumption	%	4.08	5.62	1.55	2.50	1.31	1.10

Source The authors

generated after a brief calculation.

66.3.4 *Super-Matrix Making, Its Analysis and Ranking the Heaters*

The correlation is being done using the software depending upon all the criteria and then super-matrix is formed as shown in Table 66.3. Afterward, the weight of various components is investigated with valid consistency ratio. Therefore, the relative significance among each of the components is generated as shown in Table 66.4, which makes the examination substantially simpler.

66.4 Results and Discussion

All the conceivable options/alternatives were assessed based on the weight of different attributes and the relative ranking among them is generated. The outcome reveals how much one heater is more advantageous in contrast with others based on the weight assigned.

As a result of the above comparison as shown in Table 66.4, HPH-6 ranked first and LPH-2 ranked last. However, the results relied on the weight criteria and the relative significance/importance assigned to them (decision-maker dependent). Different results could be acquired by changing the significance of various criteria depending upon the necessities of the situation, the ranking and selection of heater are a laborious process, and it required an in-depth knowledge of all the parameters, which impact the heater selection; however, the usage of any software tool makes the selection process substantially easier.

Table 66.3 Weighted super matrix

Clusters	RPEn	RPEx	Ex(PTC)	FR	SC	UHC	HPH-5	HPH-6	HPH-7	LPH-2	LPH-3	LPH-4	Best heater
RPE_n	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.02785
RPE_x	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.08079
E_x(PTC)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.17220
FR	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.21444
SC	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.06488
UHR	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.43984
HPH-5	0.05952	0.08057	0.17798	0.05588	0.05345	0.05441	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
HPH-6	0.46141	0.42923	0.26421	0.48675	0.50721	0.48900	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
HPH-7	0.25619	0.23165	0.33383	0.25623	0.10814	0.25872	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
LPH-2	0.03676	0.05565	0.03516	0.03066	0.13658	0.03000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
LPH-3	0.04620	0.05948	0.07179	0.03802	0.05894	0.04058	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
LPH-4	0.13991	0.14341	0.11703	0.13245	0.13569	0.12730	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Best heater	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000

Source The authors

Table 66.4 Alternative ranking

Graphic	Alternatives	Total	Normal	Ideal	Rank
	HPH-5	0.0391	0.0782	0.1756	4
	HPH-6	0.2227	0.4454	1.0000	1
	HPH-7	0.1295	0.2591	0.5817	2
	LPH-2	0.0201	0.0402	0.0903	6
	LPH-3	0.0241	0.0483	0.1084	5
	LPH-4	0.0644	0.1288	0.2893	3

Source The authors

66.5 Conclusion

This study intends to assess a priority investigation of feed water heaters used in a TPP after solar substitution. The technique proposed in this work contributes theoretically and methodologically to better comprehend the complex decision-making process. Conclusion, hereby, sees a lot varying range of solar power requirement by heaters from 14 to 33 MW for the pre-existing thermal power plants, mandating an aperture area of 3–7 ha. (Source: the authors). With such a huge variation, it is not possible to select the best possible regenerative feed water heater along with the solar integration. AHP framework proposed by Saaty [2] is being used to prioritized the substitution by using six criteria (improvement in energy efficiency of plant, improvement in exergy efficiency of plant, reduction in unit heat rate, improvement in exergy efficiency of solar field solar contribution, and reduction in fuel consumption) and six alternatives (all six heaters) Super Decision Software is attributed toward defining the correlation and finding the respective weightages between criteria's and alternatives. Finally, the relative significance is generated, which is lowest for LPH-2 (0.0201) and highest for HPH-6 (0.2227). After normalizing, it is found that there is the difference of 41.83% in relative significance between first and second ranking alternatives, whereas 90.97% in first and last alternative. HPH-6 has been selected as the first alternative along with solar-based FWHE to satisfy the technical parameters and challenges for a very motive toward green power cogeneration.

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References

1. Keeney, R.L., Raiffa, H.: Decisions with multiple objectives: preferences and value trade-offs. IEEE Trans. Syst. Man. Cybern. **9**, 403 (1979). https://doi.org/10.1109/tsmc.1979.4310245
2. Saaty, T.L., Vargas, L.G.: Decision Making With the Analytic Process Network Process. Springer Science and Business Media, New York, NY (2008)

3. Hwang, C.L., Yoon, K.: Multiple Attribute Decision Making Methods and Applications: A State-of-the-Art Survey. Springer-Verlag, Berlin Heidelb, New York (1981)
4. Brans, J.P., Vincke, P., Mareschal, B.: How to select and how to rank projects : the PROMETHEE method. Eur. J. Oper. Res. **24**, 228–238 (1986). https://doi.org/10.1016/0377-2217(86)90044-5
5. Roy, B.: The outranking approach and the foundations of ELECTRE methods. Theory Decis. **31**, 49–73 (1991). https://doi.org/10.1007/978-3-642-75935-2_8
6. Pomerol, J., Barba-Romero, S.: Multicriterion Decision in Management: Principles and Practice. Kluwer Academic Publishers, New York (2000)
7. Belton, V., Stewart, T.: Multiple Criteria Desicion Analysis: An Integrated Approach. Kluwer Academic Publishers, London (2002)
8. Wallenius, J., Dyer, J.S., Fishburn, P.C., Steuer, R.E., Zionts, S., Deb, K.: Multiple criteria decision making, multiattribute utility theory: recent accomplishments and what lies ahead. Manage. Sci. **54**, 1336–1349 (2008). https://doi.org/10.1287/mnsc.1070.0838
9. Bouyssou, D., Marchant, T., Pirlot, M., Perny, P., Tsoukias, A., Vincke, P.: Evaluation and Decision Models: A Critical Perspective. Kluwer Academic Publishers, London, Dordrecht (2000)
10. Diaz-Balteiro, L., González-Pachón, J., Romero, C.: Measuring systems sustainability with multi-criteria methods: a critical review. Eur. J. Oper. Res. **258**, 607–616 (2017). https://doi.org/10.1016/j.ejor.2016.08.075
11. Kumar, D., Garg, C.P., Evaluating sustainable supply chain indicators using fuzzy AHP: case of Indian automotive industry. Benchmarking **24**, 1742–1766 (2017). https://doi.org/10.1108/bij-11-2015-0111
12. Shen, K.Y., Tzeng, G.H.: Advances in multiple criteria decision making for sustainability: modeling and applications. Sustainability **10**, 1–7 (2018). https://doi.org/10.3390/su10051600
13. Dos Santos, P.H., Neves, S.M., Sant'Anna, D.O., Oliveira, C.H. de, Carvalho, H.D.: The analytic hierarchy process supporting decision making for sustainable development: an overview of applications. J. Clean. Prod. **212**, 119–138 (2019). https://doi.org/10.1016/j.jclepro.2018.11.270
14. Ho, W., Ma, X.: The state-of-the-art integrations and applications of the analytic hierarchy process. Eur. J. Oper. Res. **267**, 399–414 (2018). https://doi.org/10.1016/j.ejor.2017.09.007
15. Zhang, Y., Mohsen, J.P.: A Project-based sustainability rating tool for pavement maintenance. Engineering **4**, 200–208 (2018). https://doi.org/10.1016/j.eng.2018.03.001
16. Choudhary, D., Shankar, R.: An STEEP-fuzzy AHP-TOPSIS framework for evaluation and selection of thermal power plant location: a case study from India. Energy **42**, 510–521 (2012). https://doi.org/10.1016/j.energy.2012.03.010
17. Stein, E.W.: A comprehensive multi-criteria model to rank electric energy production technologies. Renew. Sustain. Energy Rev. **22**, 640–654 (2013). https://doi.org/10.1016/j.rser.2013.02.001
18. Cook, W.D., Green, R.H.: Evaluating power plant efficiency: a hierarchical model. Comput. Oper. Res. **32**, 813–823 (2005). https://doi.org/10.1016/j.cor.2003.08.019
19. Chatzimouratidis, A.I., Pilavachi, P.A.: Multicriteria evaluation of power plants impact on the living standard using the analytic hierarchy process. Energy Policy **36**, 1074–1089 (2008). https://doi.org/10.1016/j.enpol.2007.11.028
20. Chatzimouratidis, A.I., Pilavachi, P.A.: Sensitivity analysis of technological, economic and sustainability evaluation of power plants using the analytic hierarchy process. Energy Policy **37**, 788–798 (2009). https://doi.org/10.1016/j.enpol.2008.10.009
21. Chatzimouratidis, A.I., Pilavachi, P.A.: Sensitivity analysis of the evaluation of power plants impact on the living standard using the analytic hierarchy process. Energy Convers. Manag. **49**, 3599–3611 (2008). https://doi.org/10.1016/j.enconman. 2008.07.009
22. Chatzimouratidis, A.I., Pilavachi, P.A.: Technological, economic and sustainability evaluation of power plants using the analytic hierarchy process. Energy Policy **37**, 778–787 (2009) https://doi.org/10.1016/j.enpol.2008.10.009
23. Aragonés-Beltrán, P., Chaparro-González, F., Pastor-Ferrando, J.-P., Pla-Rubio, A.: An AHP (analytic hierarchy process)/ANP (analytic network process)-based multi-criteria decision

approach for the selection of solar-thermal power plant investment projects. Energy **66**, 222–238 (2014). https://doi.org/10.1016/j.energy.2013.12.016
24. Yagmur, L.: Multi-criteria evaluation and priority analysis for localization equipment in a thermal power plant using the AHP. Energy **94**, 476–482 (2016). https://doi.org/10.1016/j.energy.2015.11.011
25. Ren, J., Dong, L.: Evaluation of electricity supply sustainability and security: Multi-criteria decision analysis approach. J. Clean. Prod. **172**, 438–453 (2018). https://doi.org/10.1016/j.jclepro.2017.10.167