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Trade-off Curves and Elasticity Analysis in Multi Fuel Options System and Combined Problem

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ABSTRACT

Recent environmental concerns and policies have reformulated the traditional economic dispatch problem by including the emission impacts in the mathematical model. The combined economic and emission dispatch problem is a multi-objective non-linear optimization problem. This paper presents a method to consider the fuel costs and environmental emissions simultaneously. The ϵ-constraint method for bi-objective optimization has been used to generate Pareto front. Furthermore, trade-off curves have been developed for different types of emission. The elasticity of cost with respect to the emission (say, emission elasticity) has been estimated for all Pareto optimal points and different types of emissions that provides invaluable information for the system operator to run the system with sufficient flexibility subject to technical constraints while the operator has multi fuel options. Moreover, the emission elasticity is effective tool for competition in the electricity market. The Iranian electricity market is considered as empirical evidence.

Keywords: Combined Economic-emission Dispatch, Emission Elasticity, Iranian Electricity Market, Multi Objective Optimization Model, ϵ-constraint
JEL Classifications: C6, F64, P48, Q

1. INTRODUCTION

The economic dispatch problem determines the optimal allocation of power which is produced by different generation units. The optimal combination of units, achieved by minimizing total operation costs of production while satisfying load and operational constraints. Today, by increasing the environmental awareness and restrictions, the environmental constraints must be taken into account for modeling dispatch problems. The most important contaminants which released by fossil fuel power plants are sulfur dioxides (SO_2), nitrogen dioxides (NO_2) and carbon dioxides (CO_2).

The economic optimization and environmental dispatch problems have two different trends. While the economic dispatch reduces the operation costs of the system, the rate of environmental pollutions are increasing and reverse. Based on these reverse trends, it is necessary to model economic and emission objective functions simultaneously due to find an operating point that strikes a balance between operation costs and pollutions. The idea behind the combined economic and emission dispatch (CEED) is to compute the optimal generation for individual units of the power system by minimizing the fuel cost and emission levels simultaneously subject to various system constraints (Xuebin, 2009).

Different methods have been used to solve combined economic and environmental dispatch problem. The various approaches, which have been used to tackle the combined dispatch problem, can be classified in two main categories (Cai et al., 2010). The Lagrange multiplier methods and the multi-objective stochastic search technique. The large number of researchers use environmental cap by placing appropriate constraint on the environmental contaminate variables. In these models, the optimization run is subject to keeping the environmental variables below pre-specified values, although the result would not be efficient from economic viewpoint (Brodsky and Hahn, 1986).

In another method, multi-objective problem is converted to a single objective by linear combination of objectives as a weighted sum. The weights, are chosen based on the relative importance of objectives, which are determined by the decision maker or the expert of the system. Yalcinoz and Koksoy (2007) have mentioned that, in practice, choosing the weights appropriately is usually difficult. Thus, this approach is not widely used unless there is some unequivocal way to select the weights or unless the weights can be selected dynamically via some interactive multiple response optimization procedure. Palanichamy and Babu (2008) proposed an analytical strategy based on mathematical modeling to solve CEED problem by single equivalent objective function. Their model, represent the total generation by a quadratic equation of total load and transmission losses. Kulkarni et al. (2000) have proposed a price penalty factor to solve economic/environmental problem which blends the emission costs with the normal fuel costs. Furthermore, some modifications are proposed in a price penalty factor (Venkatesh et al., 2003).

Some researchers have proposed trade-off curves analysis method in multi-objective optimization. Geoffrion methods, used marginal rate of substitution to facilitate interactive trade-off analysis. In Geoffrion's model, the curve is determined by estimation of the marginal rates of substitution (Geoffrion et al., 1973). Yang and Li (2002), present a new explicit interactive trade-off analysis method, based on the identification of normal vector on a non-inferior frontier. The weighted min-max formulation, by regulating the relative weights of objectives in a systematic manner is used for interactive processes (Yang et al., 1990).

Several numerical optimization techniques based on evolutionary algorithms, for solving multi-objective problems, is proposed. Genetic algorithm and simulated annealing methods, have been used to solve combined economic and environmental problem. A multi-objective chaotic ant swarm optimization method, for solving the economic/environmental problem, is developed by Cai and et al. (2010). Xuebin (2009) has proposed a hybrid approach to solve the problem. First, the Pareto solutions set, is estimated through an evolutionary optimization process, then, a multi criteria decision making technique, namely TOPSIS, has been implemented to rank all the solutions to determinate the best solution in a deterministic environment. It is worth stating that, weighting mechanism has a challenging role in this structure (Balamurugan et al., 2008).

This paper, proposed a method to develop trade-off curve for particular type of emission, namely CO_2, NO_x, and suspected particulate matter (SPM), as a major pollutants in a power system. ϵ-constraint method, has been used to generate Pareto front of combined economic and environmental problem. Meanwhile, the elasticity of cost with respect to emission, can be obtained over the non-inferior points, which is generated by multi-objective optimization model. It is an invaluable indicator in multi-objective and multi options circumstance. The operator, can compare the flexibility, trade-off expenses and cost, emission sensitivity in different fuel systems while the problem is optimized subject to both the operation costs and the environmental pollutants, to fulfill exogenous demand. Furthermore, the ratios, can provide essential information for power system's operation when both environmental and economic restrictions taken into account and multi fuel options are available. Results show that elasticity analysis, provides an accurate insight about the different quantities of cost and emissions which are available to the dispatcher, in order to serve a specific demand. In addition, operation on optimal point, needs a different strategy for different types of fuel.

The paper, is organized as follows: In section two, economic, emission and multi-objective optimization problem has been formulated. Section three analyzes trade-off curves and the elasticity of cost with respect to emission. The data which provided by the Iranian Electricity Market as well as empirical estimation of proposed model, have been considered in sections four, respectively. Last section concludes the paper.

2. ECONOMIC AND ENVIRONMENTAL PROBLEM

2.1. Economic Problem

The objective function in traditional dispatch model, is minimizing total generation costs subject to the technical constraints. The total cost of power system with N generator and M fuel options, while each generator has a cost curve of C_{ij}, is the simple sum of the operation cost of individual generators by particular fuel. The operation cost curve, is approximated by quadratic function of real power output from the generating units (Palanichamy and Babu, 2008). Therefore, the total operation cost can be formulated as follows:

$$TC_j\left(\$/h\right)=\sum\nolimits_{i=1}^{N}C_{ij}(P_{ij})=\sum\nolimits_{i=1}^{N}(a_{ij}+b_{ij}P_{ij}+C_{ij}P_{ij}^2) \quad \text{for } j=1\ldots M \qquad (1)$$

Where, TC_j is the total fuel cost, while generators use j^{th} fuel option, C_{ij} is the fuel cost of generator i in fuel option j, a_{ij}, b_{ij} and c_{ij} are cost coefficients of generator i and fuel j, and P_{ij} is amount of real power that generated by unit i and fuel j in MW.

The dispatch problem, can be defined as the following optimization problem:

$$\text{Minimize } TC_j\left(\$/h\right)=\text{Min}\sum_{i=1}^{N}(a_{ij}+b_{ij}P_{ij}+c_{ij}P_{ij}^2) \quad \text{for } j=1\ldots M \qquad (2)$$

Subject to power balance constraint and generation capacity limits,

$$P_D+P_L=\sum\nolimits_{i}^{N}P_{ij} \quad \text{for } j=1\ldots M \qquad (3)$$

$$P_{ijmin}\leq P_{ij}\leq P_{ijmax} \qquad (4)$$

Where P_D is the total system demand (MW), P_L is the total transmission network loss (MW), P_{ijmin} is the minimum power output limit of i^{th} generator (MW) while it uses j_{th} fuel and P_{ijmax} is the maximum power output limit of the i^{th} generator (MW) while it uses the j^{th} fuel. The transmission losses (P_L) can be represented as:

$$P_L=\sum\nolimits_{k=1}^{N}\sum\nolimits_{i=1}^{N}P_iB_{ik}P_k \qquad (5)$$

Where B_{ik} is transmission losses coefficient (Xuebin, 2009).

2.2. Emission Problem

The economic dispatch problem, finds the amount of power which is generated by various generating units of power system in a minimum total fuel costs. Given the increasing environmental concerns, dispatching problems have modeled emissions in several methods. The emission dispatch problem, is defined as the following optimization problem, subject to the power balance and unit capacity constraints (Muslu, 2004):

$$E_{Cj}\left(\frac{Kg}{h}\right)=\sum_{i=1}^{N}E_{Cij}\left(P_{ij}\right)=\sum_{i=1}^{N}\left(\alpha_{cij}+\beta_{cij}P_{ij}+\gamma_{cij}P_{ij}^{2}\right)$$

for j=1…M (6)

$$E_{Nj}\left(\frac{Kg}{h}\right)=\sum_{i=1}^{N}E_{Nij}\left(P_{ij}\right)=\sum_{i=1}^{N}\left(\alpha_{Nij}+\beta_{Nij}P_{ij}+\gamma_{Nij}P_{ij}^{2}\right)$$

for j=1…M (7)

$$E_{Sj}\left(\frac{Kg}{h}\right)=\sum_{i=1}^{N}E_{Sij}\left(P_{ij}\right)=\sum_{i=1}^{N}\left(\alpha_{Sij}+\beta_{Sij}P_{ij}+\gamma_{Sij}P_{ij}^{2}\right)$$

for j=1…M (8)

Where, E_{Sj}, E_{Cj} and E_{Nj} are total emission released by fuel j of SPM, CO_2 and NO_x, respectively. And α_{ij}, β_{ij} and γ_{ij} are emission coefficients of ith generating unit released by fuel j from particular pollutant. The emission dispatch problem for particular environmental pollutant can be defined as the following optimization problem:

$$\text{Minimize } E_{Cj}\left(\frac{Kg}{h}\right)=\text{Min }\sum_{i=1}^{N}\left(\alpha_{cij}+\beta_{cij}P_{ij}+\gamma_{cij}P_{ij}^{2}\right)$$

for j=1…M (9)

$$\text{Minimize } E_{Nj}\left(\frac{Kg}{h}\right)=\text{Min }\sum_{i=1}^{N}\left(\alpha_{Nij}+\beta_{Nij}P_{ij}+\gamma_{Nij}P_{ij}^{2}\right)$$

for j=1…M (10)

$$\text{Minimize } E_{Sj}\left(\frac{Kg}{h}\right)=\text{Min}\sum_{i=1}^{N}\left(\alpha_{Sij}+\beta_{Sij}P_{ij}+\gamma_{Sij}P_{ij}^{2}\right)$$

for j=1…M (11)

Subject to power balance constraint and generation capacity constraint.

2.3. Combined Economic and Emission Problem

The economic problem is significantly different from emission problem. This is because of the trade-off between these different objectives. The economic problem, reduces the operation cost at the increase rate of emission. In addition, emission problem reduces the particular emission from the system, while the operation costs are increasing (Huang et al., 2003). The combined problem can be formulated as,

Minimize F_j (TC_j, E_{Cj} or E_{Nj} or E_{Sj}) for j=1…M (12)

Subject to Equation 3 and 4.

The combined economic and emission problem, as above-mentioned, is multi-objective optimization problem. The optimization problem can be converted to a single optimization by including price penalty factor as follows:

Minimize $F_j=TC_j+hE_{Cj}$(or E_{Nj} or E_{sj}) (13)

While, h is the price penalty factor (Kumar et al., 2008). Although price penalty factor is a proper tool to convert multi-objective optimization problem into a single objective, it does not help to elicit trade-off curves. The weight factor, is another popular method in the combined objective. When the weight factor is determined, the multi-objective optimization problem is reduced to a single objective and by changing the weights, all supported non inferior points can be found (Muslu, 2004). Weights, indicate the relative importance of each objective. Thus, the challenge of implementing this method is introducing an appropriate method to determine adequate weights while different objectives cannot be evaluated under a common measure.

Here, the ϵ-constraint technique is utilized for optimization problem to obtain Pareto front (or, Pareto optimal solutions). This method, generates sub-problems, called ϵ-constraint problems, by transforming objectives into constraints. The upper bounds of these constraints are given by ϵ-vector and the Pareto front can theoretically be generated by varying the ϵ-vector.

The first step for combined problem is computing the ideal point and Nadir points that define lower and upper bounds on the value of efficient solutions, respectively. Thereby, the ideal point for economic and environmental optimization problem is obtained by:

$$TC_j^I=\text{Min }\sum_{i=1}^{N}C_{ij}\left(P_{ij}\right)\quad\text{for j=1…M}\tag{14}$$

$$E_{Nj}^I\text{or }E_{Sj}^I\text{ or }E_{Cj}^I=\text{ Min}\sum_{i=1}^{N}E_{N(S,\,C)ij}\left(P_{ij}\right)\qquad\text{for j=1… M}\tag{15}$$

And the Nadir points will be calculated through:

$$TC_j^N=\text{ Min}\left\{\,Tc_j\ \left|E_{Cj}=E_{Cj}^I\text{or }E_{Sj}=E_{Sj}^I\text{or }E_{Nj}=E_{Nj}^I\right.\right\}\tag{16}$$

$$E_{Nj}^N\text{or }E_{Sj}^N\text{or }E_{Cj}^N=\text{ Min}\left\{E_{Nj}\text{or }E_{Sj}\text{ or }E_{Cj}\ \left|TC_j=TC_j^I\right.\right\}\tag{17}$$

The Pareto front is generated through a sequence of ϵ-constraint problem. Throughout the algorithm, (that finds Pareto front) ϵ decreased by value of Δ. Based on the ϵ-constrained technique, the Pareto front obtained through the optimization that is expressed below:

$$\text{Min}\sum_{i=1}^{N}C_{ij}\left(P_{ij}\right)\text{ for j=1… M}\tag{18}$$

Subject to:

1. E_{Sj} or E_{Nj} or $E_{Cj}\leq\epsilon_{Cj}$ or ϵ_{Nj} or ϵ_{Sj} (19)

While:

$$\epsilon_{Cj}\text{or }\epsilon_{Nj}\text{ or }\epsilon_{Sj}=\ E_{Cj}^N\text{or }E_{Nj}^N\text{or }E_{Sj}^N-\Delta_j^t$$

2. $P_D+P_L=\sum_{i}^{N}P_{ij}$ for j=1…M (20)

3. $P_{ijmin}\leq P_{ij}\leq P_{ijmax}$ (21)

While, the value of Δ_j^t will increase gradually such that:

$$E_{Cj}^{I} \le \epsilon_{Cj} \le E_{Cj}^{N} \tag{22}$$

$$E_{Nj}^{I} \le \epsilon_{Nj} \le E_{Nj}^{N} \tag{23}$$

$$E_{Sj}^{I} \le \epsilon_{Sj} \le E_{Sj}^{N} \tag{24}$$

Obviously, t shows the process repeated by variation Δ_j^t to obtain different values for ϵ_{Cj}, ϵ_{Nj} and ϵ_{Sj} in the upper and lower bounds (Bérubé et al., 2009).

3. TRADE-OFF CURVES AND ELASTICITY OF COST WITH RESPECT TO EMISSION

In multi-objective optimization, trade-off analysis has an important role in decision making. Despite the fact that finding the most preferred solution is the ultimate goal of decision maker, in many cases, accessing to the set of the optimal alternatives, increases reliability and flexibility of the power system. Sometimes, the operator has several options to run the power system, namely different fuel options. In such a circumstances, obtaining the set of optimal solutions, which can show the range of variations in objectives and provide invaluable information for decision makers or even system analyzers, is crucial.

The elasticity of cost, with respect to emission, measures the percentage change in fuel costs caused by a percent change in particular emission. Mathematically, the elasticity of cost with respect to emission would be as follows:

$$\varepsilon_{Cj} = \left| \frac{\partial \ln\left(TC_j\right)}{\partial \ln(E_{Cj})} \right|, \text{ for j=1…M} \tag{25}$$

$$\varepsilon_{Nj} = \left| \frac{\partial \ln\left(TC_j\right)}{\partial \ln(E_{Nj})} \right|, \quad \text{for j=1…M} \tag{26}$$

$$\varepsilon_{Sj} = \left| \frac{\partial \ln\left(TC_j\right)}{\partial \ln(E_{Sj})} \right|, \text{ for j=1…M} \tag{27}$$

The above elasticity, is calculated over all Pareto fronts, and for different types of fuels. This elasticity, helps the decision maker to compare the flexibility and variations ranges of different fuel options. Moreover, the elasticity for an operating point can determine:

- How much is the sensitivity of the power system regarding to the changes in operating points?
- How much are the different fuel options tight or flexible against the variations?

Due to the contradiction nature of objectives in combined economic and emission problem, these information are invaluable. Meanwhile, the analysis is over optimal solutions of problem and the elasticity in different operating points clarifies the possibility of adjusting power system in different situations, particularly in uncertain circumstance.

While the operator has the trade-off curve and elasticity of cost for all fuel options, decision making in operating points among these circumstances, will be more rational and reasonable.

4. EMPIRICAL RESULTS

Here, based on the above problem formulation, the combined economic/environmental problem for regional electricity market in Iran has been implemented. Four main power plants including Isfahan, Montazeri No. 1, Montazeri No. 2 and South Isfahan Power Plant, which all located in Isfahan Electricity Market, have been chosen as a regional case study for particular day in 2013. Isfahan, Montazeri No.1 and Montazeri No. 2 power plants are steam turbine while South Isfahan Power Plant is running by gas turbine generators.

Natural gas resources of Iran, is around 29 trillion cubic meters. Iran is the second largest endowments in the world (Iran Energy Balance Sheet, 2013). Furthermore, natural gas is the main fuel in Iran and almost all heating systems are based on natural gas while 58.15% of all natural gas consumption belongs to the residential and business sector. Due to both the wide range of natural gas consumptions, and the priority of residential sector, power plants confront critical problems in accessing natural gas, particularly in autumn and winter. It is worth stating that, the demand is uncertain and as a result, the accessibility of power plants to natural gas is quite uncertain. Considering uncertainty in fuel options, the proposed model provides proper information in order to dispatch with sufficient flexibility of obtained indices.

The steam turbine power plants use both natural gas and fuel oil as fuel options. The data shows that the natural gas consumption for selected power plants in 2013 was 2437 billion cubic meters while the amount of consumed fuel oil was 2463.2 billion liters (Iran Energy Balance Sheet, 2013). The South Isfahan Power Plant is gas turbine and uses natural gas.

The sources of data are the Iranian Power Generation and Transmission Holding Company (TAVANIR), Isfahan Regional Electricity Company, Isfahan and Montazeri Power Generation Companies. The total demand was assumed to be 1935 MW.

All thermal power plants in Iran, are fueled by natural gas and fuel oil. In this study, we use average fuel prices, which are delivered to each power plant. It is noticeable that all generators receive heavily subsidized fuel price. Therefore, there is not high variation in fuel prices.

First of all, we have estimated cost function by regression analysis based on the above formulation where the input is in MCl/h and the output is in MW. The output data indicates gross hourly production in MWh and the inputs are the amount of fuel consumption in Mega Calorie (MCl) in each hour. All data is provided by Isfahan Regional Electricity Company. Table 1 summarizes the estimated coefficients for all fuel options (Appendix 1).

Similarly, we have estimated emission function for power plants. All data have been provided by the Iranian Power Generation and Transmission holding Company (TAVANIR), Isfahan Regional Electricity Company, Isfahan and Montazeri Power Generation Companies. The output data indicates the amount of pollutant (in kilo gram or ton) released by the generator and the inputs are the amount of fuel consumption in Mega Calorie (MCl). Table 2 indicates the estimation results (Appendix 1).

We have implementing the proposed model (Equation 18) subject to Equation 19, 20, 21. Table 3 shows the Ideal and the Nadir points for optimization as described above (Appendix 1).

Trade-off curves of NO_x emission for both fuel costs, are shown in Figures 1 and 2 (Figures 5-8 in Appendix 2 shows trade-off curves for CO_2 and SPM).

Each point on a trade-off curve is a non-inferior solution and corresponds to a unique set of generator schedules. Trade-off curves, give the system operator a whole range of alternative ways of running their system. Such a non- inferior surface gives a visual and accurate picture of what range of cost and emissions are available to the operator to serve a specific load. For instance, in Figures 1 and 2, NO_X's trade-off curves for natural gas and fuel oil are presented. In each figure, there are non-inferior points which provides expected demand due to the available constraints. Decision maker can chose different combinations in different situations.

For instance, during the high air pollution period, when the government policy is reducing pollution, the operator can choose a combination which leads in higher cost and lower pollutant emissions. Consequently, the power plants will produce the optimized amount which are found from this combination and the pollution will decrease. On the other hand, comparing the graphs of natural gas and the fuel oil shows that when usage of natural gas imposes around 160,00,000 rial cost to the system, The NO_x emission will be 1630 (kg/h). However, fuel oil consumption with this cost, will emit around 4000 (kg/h) NO_x, so these results can help to better fuel choice.

Figure 1: NO_x - Natural gas

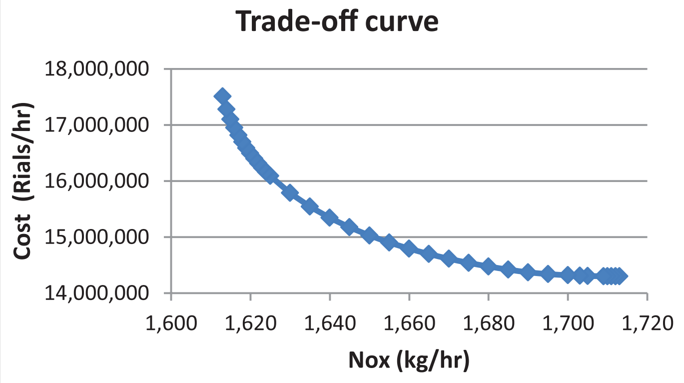
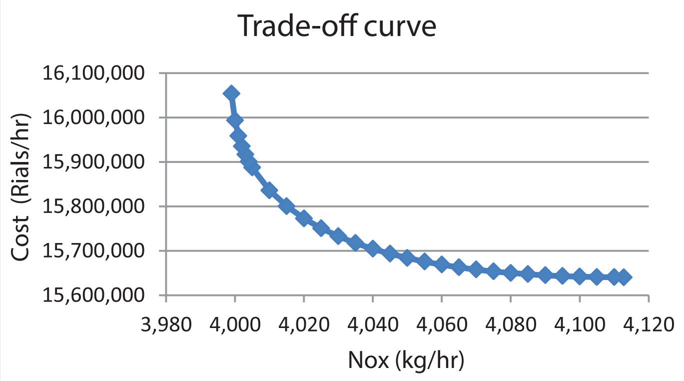


Figure 2: NO_x - Fuel oil



In addition, the slope of the trade- off curve explains the marginal rate of substitution between each unit of cost and pollutant that expresses how decrease in greenhouse gases affect production cost. Accordingly, as this amount gets higher, it means that the control cost of the specific pollutant that is under planning will become higher.

The elasticity of cost with respect to the NO_x emission, for both fuel costs are shown in Figures 3 and 4 (Appendix 3 shows Figures 9-12, elasticity of cost with respect to CO_2 and SPM).

Despite the fact that the amount of NO_x emission, released from the fuel oil, is significantly more than the emission released from natural gas, as Figures 3 and 4 shows, the sensitivity of natural gas relative to variations in NO_x emission, is more than the fuel oil. As a result, when the system operator is running system by fuel oil, reducing emission, could be more preferential in a policy making. In average, 1% decrease in emission released from the natural gas, increases fuel cost by 5%, while the fuel cost in fuel oil system, increases by 1.9%.

In addition, as it is shown in Figure 3, in a notable interval of NO_x emission, cost elasticity respect to emission is varied between 0 and 5. In other words, the decrease in NO_x emission from the

Figure 3: Elasticity of cost respect to NO_x (natural gas)

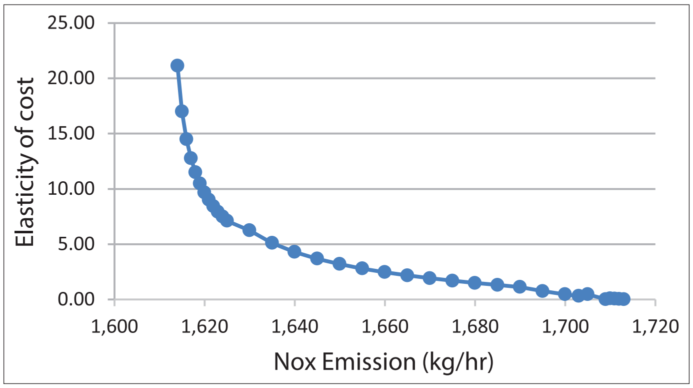
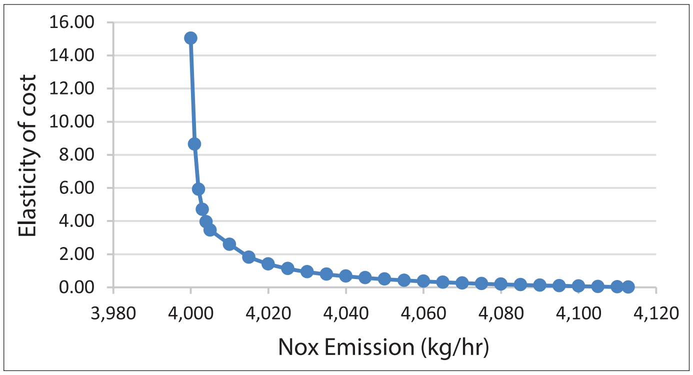


Figure 4: Elasticity of cost respect to NO_x (natural gas)



worst condition to the adequate condition, results in 5% change in cost. However, the more decrease in pollutant emission from 1630 to 1615 kg, will noticeably change the production cost. Accordingly, to find the appropriate result, the central planner can make an appropriate condition between production cost and pollutant emission based on the network conditions.

5. CONCLUSIONS

In this paper, the trade-off curves are developed by formulating combined economic and environmental problem. A ϵ-constraint technique is employed to generate Pareto optimal solutions. Moreover, the elasticity of cost with respect to emissions is estimated to evaluate the power system interactions with multi fuel option and uncertainty.

The power system operator needs particular information to compare and adjust the operation point regarding different environmental pollutants and economic considerations. The proposed model facilitates:

- System adjustment with respect to different kinds of emission
- Elicit trade-off curves while each point on a trade-off curve corresponds to unique set of generators combination
- Policy making consideration of fuel type and contamination
- Appropriate strategy adoption regarding fuel option and type of emission.

The proposed model is used for Isfahan regional electricity market including four power plants and two kinds of fuel options as a real used case. The results show that, decision maker should use two different strategies to achieve satisfactory consequences. In addition, the elasticity of cost analysis, determines the preferred solution in terms of fuels options.

The extracted figures and indices like the elasticity of the cost respect to the different types of pollutants, enables system operator to make an optimized decision which is reasonable. Accordingly, the capability of substitution of cost and different types of the pollutants and also the sensitivity in this substitution can be obtained. Thus, it is possible to adjust optimized behavior in various ranges, and substitute cost with pollution to achieve the most benefit from this substitution. In some production ranges, there is a high sensitivity in substitution of cost and pollution. However, in some production ranges, this sensitivity is in its minimum and the lowest cost substitution is possible.

Overall, extracting inflection indices, provides the possibility to determine the optimum production range based on the system's characteristics. In other words, the most important specification of the aforementioned method, will be, presenting the set of various management options in order to policy and decision making. It is notable that providing and extracting adequate indices, are effective tools in analysis and planning.

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APPENDIX 1

Table 1: Coefficients of cost functions

Parameters	A	B	C
Generators		Natural gas cost function	
Isfahan	1.30E+07	−27362	21.19
Montazeri 1	710686	4066.99	3.782
Montazeri 2	9105873	−16143	15.799
South Isfahan	32000	6264.7	4.087
Generators		Fuel oil cost function	
Isfahan	1207801	4406.2	2.5688
Montazeri 1	4520858	−5398	9.426
Montazeri 2	300021	6242.6	1.8928
South Isfahan	2152698	−2575	14.206

Table 2: Emission function

Generators and pollutant	Natural gas								
	NO$_x$			CO$_2$			SPM		
Coefficients	α_N	β_N	γ_N	α_C	β_C	γ_C	α_S	β_S	γ_S
Isfahan	1366	−2.856	0.0043	244124	−382.2	0.755	9.92	0.019	2.60E-05
Montazeri 1	3306.4	−7.644	0.00699	984625	−2325	1.98	62.7	−0.13	0.00013
Montazeri 2	147.7	1.663	0.00043	19144.9	424	0.076	6.408	0.033	0.00015
South Isfahan	137.7	1.178	0.0016	69020.1	213	0.433	37.59	−0.08	0.00014
	Fuel oil								
Isfahan	1366	−2.856	0.0043	244124	−382.2	0.755	9.92	0.019	2.60E-05
Montazeri1	3306.4	−7.644	0.00699	984625	−2325	1.98	62.7	−0.13	0.00013
Montazeri 2	147.7	1.663	0.00043	19144.9	424	0.076	6.408	0.033	0.00015
South Isfahan	137.7	1.178	0.0016	69020.1	213	0.433	37.59	−0.08	0.00014

SPM: Suspected particulate matter, CO$_2$: Carbon dioxides

Table 3: Ideal and nadir emission points

Fuel type	NO$_x$ (kg/h)	
	Ideal	Nadir
Natural gas	1610	1750
Fuel oil	3900	4112
Fuel type	**CO$_2$ (ton/h)**	
Natural gas	1324	1460
Fuel oil	971	991
Fuel type	**SPM (kg/h)**	
Natural gas	125.3	130.9
Fuel oil	107	108

SPM: Suspected particulate matter, CO$_2$: Carbon dioxides

APPENDIX 2

Figure 5: Carbon dioxides - Natural gas

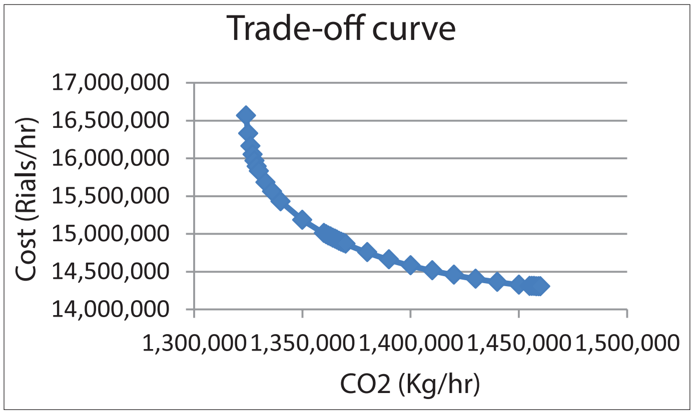


Figure 6: Carbon dioxides - Fuel oil

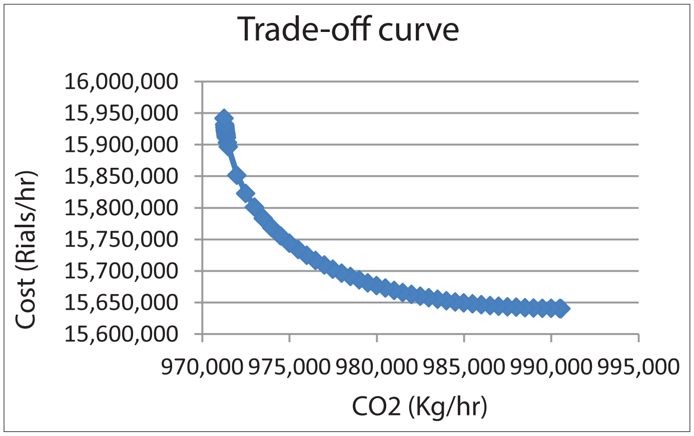


Figure 7: Suspected particulate matter - Natural gas

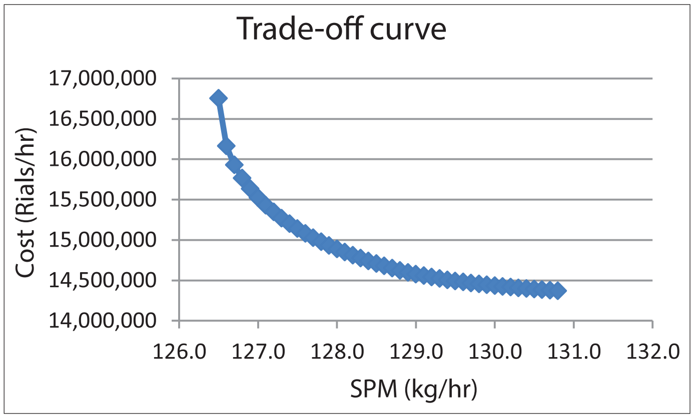
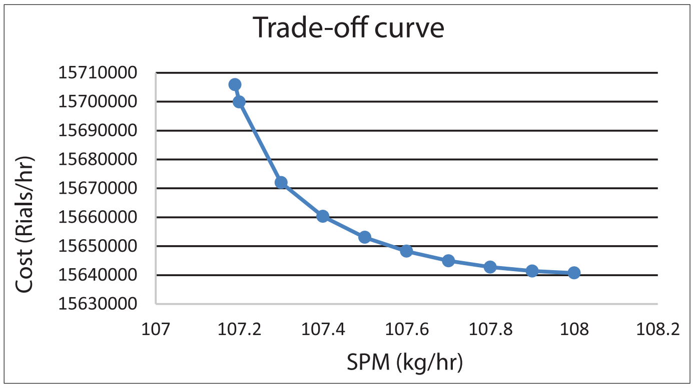


Figure 8: Suspected particulate matter - Fuel oil



APPENDIX 3

Figure 9: Elasticity of cost respect to carbon dioxides (natural gas)

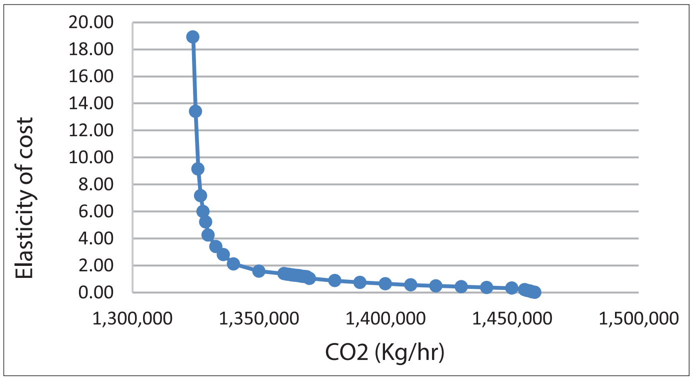


Figure 10: Elasticity of cost respect to carbon dioxides (fuel oil)

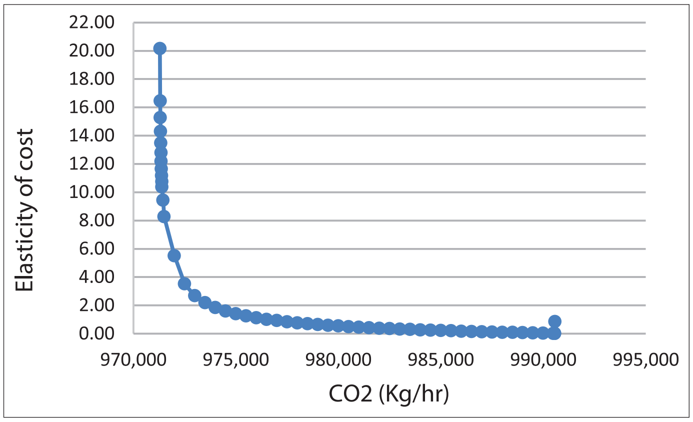


Figure 11: Elasticity of cost respect to suspected particulate matter (natural gas)

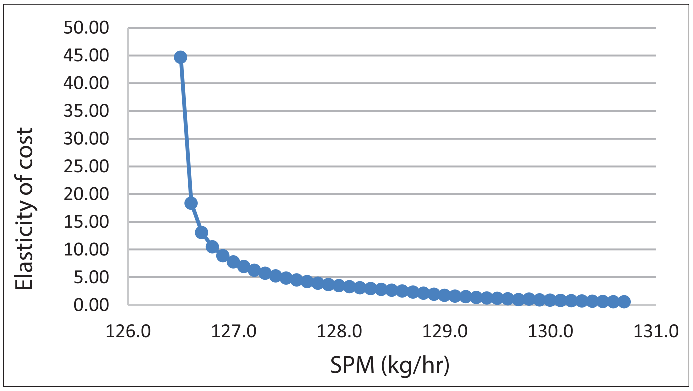


Figure 12: Elasticity of cost respect to suspected particulate matter (fuel oil)