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JOINT ECONOMIC AND ENVIRONMENTAL OPTIMIZATION OF HYBRID POWER SUPPLY FOR LARGE SCALE RO-DESALINATION PLANT: WITH AND WITHOUT CO_2 SEQUESTRATION

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Abstract

In this paper, a multi- objective optimization approach is introduced to define a hybrid power supply system for a large scale RO- desalination plant. The target is to integrate a number of locally available energy resources to generate the electricity demand of the RO- desalination plant with minimizing both the electricity generation cost and the greenhouse gas emissions whereby carbon dioxide sequestration may be an option. The considered energy resources and technologies are wind turbines, solar PV, combined cycles with natural gas turbines, combined cycles with coal gasification, pulverized coal with flue gas desulfurization, and biomass combined heat and power CHP. These variable energy resources are investigated under different constraints on the renewable energy contribution. Likewise, the effect of carbon dioxide sequestration is included. Accordingly, five scenarios have been analyzed. Trade- offs between the minimum electricity generation cost and the minimum greenhouse gas emissions have been determined and represented in Pareto curves using the constraint method (ε). The results highlight that among the studied fossil fuel technologies, the integrated combined cycle natural gas turbines can provide considerable fraction of the needed power supply. Likewise, wind turbines are the most effective technology among renewable energy options. When CO_2 sequestration applied, the costs increase and significant changes in the optimum combination of renewable energy resources have been monitored. In that case, solar PV starts to appreciably compete. The optimum mix of energy resources extends to include biomass CHP as well.

Keywords: Hybrid energy system, Desalination, Optimization, CO_2 sequestration.

1. Introduction

Fresh water resources are limited in some countries. Water poverty becomes a risk that threatens many countries overall the world. To cope with this severe shortage

Nomenclatures

C	Electricity generated by combined cycle gas turbines, kWh
CCGT	Combined cycle gas turbines
CHP	Combined heat and power, cogeneration
E	Electricity generated by PV, kWe
G	GHGE,g C/ kWh
GHG	Greenhouse gas emissions
IGCC	Integrated gasification combined cycle
PF FGD	Pulverized fuel with flue gas desulfurization
PV	Solar photovoltaic cells
RO	Reverse osmosis desalination
W	Electricity generated by wind turbines, kWh

Greek Symbols

ε	The constraint Method, a method to solve multi-objective optimization problems

Abbreviations

i	Energy resource number, index

and overcomes its adverse effects, desalination of sea and brackish water has been considered intensively to a level that gulf countries become fully depending on water desalination as its water resource [1]. Worldwide, there are 16 000 desalination plants with typically 70 million m^3/day capacity [2] and it's anticipated to have more desalinated water production motivated by the relatively reduced capital cost of the desalination systems [3], but the intensive energy consumption by desalination systems is still a challenge, about 75.2 TWh per year.

Thermal desalination and reverse osmosis (RO) based desalination are two well-known and- developed technologies whereby they have been used widely. Nonetheless, typically 70% of the thermal plants globally have shifted to RO for being lower energy consuming [4] and now RO is the most used desalination technology [5]. There are other advantages of RO; these include simple operation, modular design, compact and scalable, fast installation, and easy maintenance [6,7]. Furthermore, RO is flexible as it is able to handle dynamic profile feed and throughput in terms of quantity and quality. Likewise, RO can run under different operating conditions and employ variable types of membranes which make it well fit the requirements of different sectors: industrial processes, domestic drinking water, commercial applications, etc. [8-10].

Concert efforts have been made to optimize the design, structure and operation of RO- desalination. Nonetheless, most of them directed the optimization toward the early stage- before installation. As far as the author knows, it is rare to find a study dealing with the problems countering the RO- units during the operation and define solutions. In this study, an approach is developed to address this issue as a step toward empower RO- operators to quickly overcome any emerging problems. The optimum operating conditions that favour minimizing the energy consumption and retain the productivity to its original value or the highest likely value are identified.

The target of the model herein is to predict precisely the flow rate of water through the RO-membrane, likewise the salt rejection. There are currently a considerable number of good models; Marcovecchio et al. [11] reported that Kimura-Sourirajan model is the most used one for its validated and proved prediction accuracy. Therefore, this model is selected here to underlie the proposed optimization approach. Nonetheless, another model is needed altogether to describe the solute concentration on membrane surface, especially in view of the concentration polarization on the cross linked membrane surface. For this issue (concentration polarization prediction) Sassi and Mujtaba [12] proposed successfully applying the film theory model developed by Michaels in 1968 [13]. Kimura-Sourirajan model and the film theory act herein as the basis to build up of it the optimization model.

Many researchers have conducted studies to optimize the RO- desalination. A number of different objective functions were targeted which included minimizing the total cost [11], minimizing the specific energy [12], minimizing the total annualized cost [14-16], and maximizing the energy recovery [17].

2. Problem Definition and Objective

Renewable energy resources include hydropower, geothermal energy, solar energy, wind energy, etc. Solar energy and wind energy may be the most abundant. The availability of these two sources varies from place to place; some places are rich in both but others have some limitations. Both are intermittent resources, but solar energy is available during the morning and wind energy becomes more intense at night [18]. The worldwide distribution of solar energy and wind energy indicates the high potential to integrate both of them in favour of getting stable power supply, especially when integrated with other energy sources such as biomass, process waste heat, and fossil fuels [19-21].

Not only because of this availability feature, but there is another factor motivating this integration: the technical and environmental characteristics. Each energy source has its own advantages and disadvantages. For instance, solar PV has low capital cost relative to other energy sources, but high operating cost [22]. Table 1 lists the capital cost, operating cost of the renewable energy sources considered in this study.

The third difference distinguishing the different prime energy resources is the amount of GHG emission that may be produced. GHG emissions include CO_2, NO_x, and CH_4. In 2012, electricity and heat generation sector produced the largest share of CO_2 worldwide as shown in Fig. 1. Typically 42% of CO_2 emissions released from electricity generation plants, and that flowed by the transportation sector.

Thus concert effort has been made to reduce GHGE releasing from electricity generation plants. That target is tackled through different routes such as increasing the efficiency of the fuel utilization through replacing separate generation plants with co-generation plants [24] that have much higher efficiency. Another method is to replace fossil fuels, even partially, with renewable cleaner energies. These two approaches succeeded in reducing the GHG emissions to a considerable extent as IEA reports documented [25]. Table 2 lists how much CO_2 reductions occurred and gives objection how much is anticipated soon.

In this work, a combination of renewable energy resources and fossil fuels is investigated as a hybrid energy system for large scale RO- desalination plant. The objective is to determine the optimum energy mix suitable for a desalination plant. These plants usually exist in sunny areas, therefore solar energy is available. Other local renewable energy resources and fossil fuels may be available. Renewable energies are favoured concerning the environment, but their costs are still high. Conversely are the fossil fuels. Generalization cannot be applied here for the feasibility of using specific type of energy resources as it is a site- specific decision. Thus a suitable methodology is needed to address this problematic issue along with these opposing factors, and a systematic approach is needed to solve the problem and define the optimum hybrid energy systems.

Table 1. Costs of electricity generation from renewable energy [22].

Technology	Capacity (kWe)	Capital cost ($)	Operating Cost ($/kWe)		Life
			Fixed	Variable	
Solar - PV	<10	3910	20		33
	10- 100	3819	18		33
	100- 1000	3344	15		33
	1000-10, 000	2667	10		33
Wind	<10	7859	28		14
	10- 100	6389	38		19
	100- 1000	4019	33		16
	1000-10, 000	2644	36		20
Biomass CHP		6067	91	0.02	28

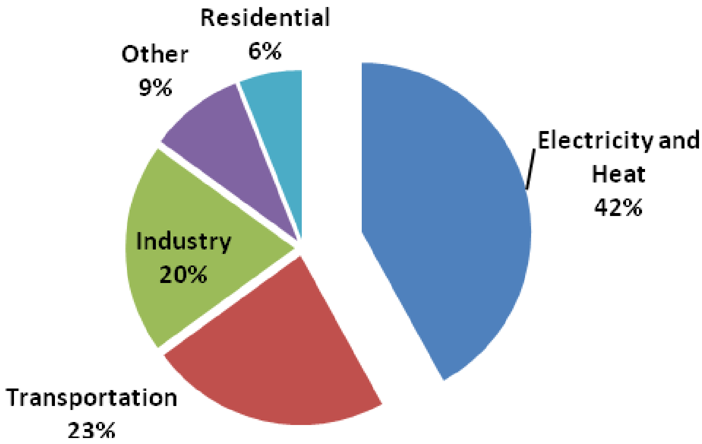

Fig. 1. CO_2 production by different sectors [23].

Table 2. GHG emissions [25].

Year	1971	1995	2000	2010	2020
Average GHGE, g C/kWh	00	158	157	151	147

3. System Description

A large scale reverse osmosis desalination plant needs electricity supply. The proposed hybrid power plant can be applicable in countries where fossil fuels and renewable energy resources may be available, for example Saudi Arabia, United Arab of Emirates, Spain, Italy, Egypt, and South Africa. A number of energy resources available locally, and it is planned to maximize the dependence on local resources. Therefore, the target is to integrate these different energy resources to attain a power supply to the desalination plant. This sought hybrid energy supply shall consider the environmental and the economic competence. These energy resources and technologies are represented in Fig. 2. These energy resources include fossil fuels as well as renewable energies, thus GHG emissions are anticipated. Each energy source and technology has distinguishing economic and environmental characteristics as given in Section 2, and more specific details will be given in Section 4. Thus, it is wanted to determine which energy sources shall be used and to which extent.

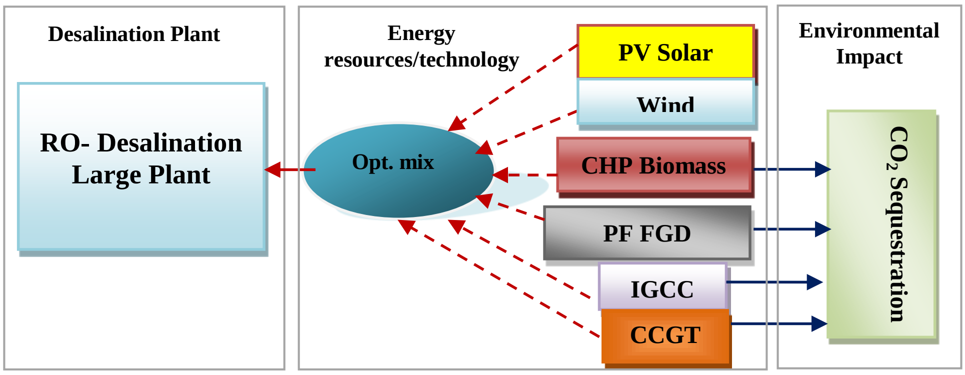

Fig. 2. Proposed hybrid energy systems for desalination plant.

PV: Solar photo voltaic; CHP: combined heat and power generation, cogeneration PF FGF: pulverized fuel with flue gas desulphurization; IGCC: integrated gasification combined cycle; CCGT: combined cycle gas turbine.

There are two- scenarios to run the hybrid energy system: with and without carbon sequestration. A trade- off exists between the economic feasibility and the environmental concerns for the cost of electricity generation can increase significantly when carbon sequestration is applied. Table 3 points to the difference in prices of the generated electricity when carbon sequestration is added to the power generation systems.

The hybrid energy system can operate with and without carbon sequestration. A trade- off exists between the economic feasibility and the environmental concerns for the cost of electricity generation can increase significantly when carbon sequestration is applied. For the two options (with and without CO_2 sequestration), there are five different scenarios have been investigated; these different cases are illustrated in the next flowchart, Fig. 3.

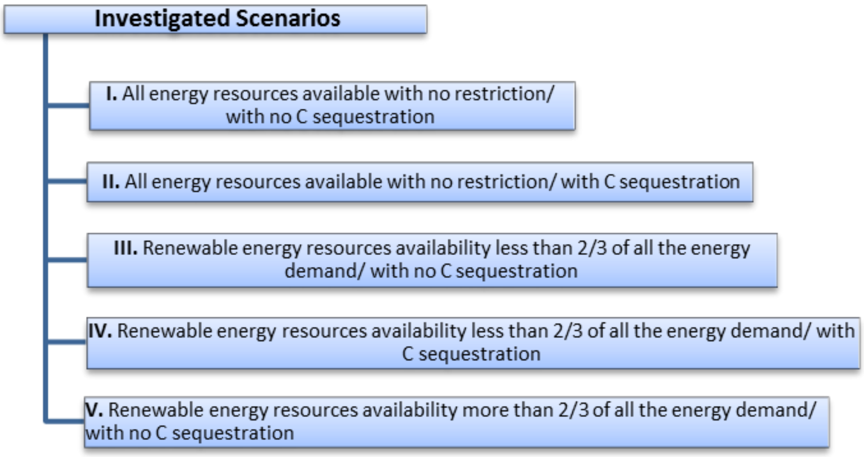

Fig. 3. The investigated scenarios.

4. Methodology and Solution Approach

4.1. Optimization methodology

The pre-scribed system and the targeted hybrid energy supply problem is mathematically formulated herein as a multi- objective optimization. This is attributed to having two contrasting objectives: minimization the electricity generation cost and minimization the greenhouse gas emissions GHGE. Most often reducing the GHGE is accompanied with padding extra expenses and consequently increases the cost of electricity generation. The optimization problem is formulated as follows:

The objective function is to minimize the electricity generation cost f_1 and the greenhouse gas emissions f_2:

$$Obj.Fun = Min\{f1(C,E) + f2(E,G)\} \tag{1}$$

where f_1 is the cost of electricity generation, and f_2 is the greenhouse gas emissions GHGE generated during the electricity generation. The symbols are as follows: C denotes the cost of electricity generation from particular energy resource in US dollars and via specific technology i; E is the electricity generated in kWh; G is the GHGE in g C/kWh. The values of these variables have been given in Table 3.

$$f_1 = \sum_{i=1}^{NE} C_i . E_i \tag{2}$$

$$f_2 = \sum_{i=1}^{NE} G_i . E_i \tag{3}$$

Subject to:

$$TE = \sum_{i=1}^{NE} E_i = Q_{RO-Des} \times \overline{E}_{RO} \tag{4}$$

$$E_i^{Lower} \leq E_i \leq E_i^{Upper} \qquad \forall i \in \{1,..NE\} \tag{5}$$

The total power demand TE is the sum of the power attained from the different energy resources and technologies is determined by capacity of the RO-desalination plant. The overall energy consumption for whole sea water RO-desalination plant is typically 3- 4 kWh/m^3, $\overline{E}_{RO}$ [26]. The term Q_{RO-Des} stands to the capacity of the RO- desalination plant, and it refers to how many cubic meters of desalinated water produced daily by the RO plant.

In order to numerically describe the different scenarios, for each scenario an extra equation is written as follows.

For scenario I all the energy resources are available, and from each energy source, the whole energy demand can be obtained if the optimization code selects that. Thus the upper limit of the energy source availability is higher than the entire energy demand:

$$E_i^{Upper} \geq ET \qquad \forall i \in \{1,..NE\} \tag{6}$$

Scenario I is similar to scenario II, except there is extra cost in scenario II. This extra expense is due to CO_2 sequestration:

For Scenario I, the cost C_i refers only to the electricity generation cost (C_g):

$$C_i = C_{gi} \qquad \forall i \in \{1,..NE\} \tag{7}$$

For Scenario II, the cost C_i consists of the electricity generation cost in addition to the cost of the CO_2 sequestration (C_{seq}):

$$C_i = C_{gi} + C_{seqi} \qquad \forall i \in \{1,..NE\} \tag{8}$$

Scenarios III and IV contain one restriction which is the availability of renewable energy resources ($E_i|RE$); this is expressed as:

$$E_i\,|_{RE} \leq \ (2/3)\ ET \qquad \forall i \in \{1,..NE\} \tag{9}$$

The difference between the two scenarios (III and IV) is whether CO_2 sequestration takes place or not.

An opposed case is assumed in Scenario V as the availability of renewable energy resources can be more than two thirds of the total energy demand:

$$E_i\,|_{RE} \geq \ (2/3)\ ET \qquad \forall i \in \{1,..NE\} \tag{10}$$

4.2. Solution approach

The constraint method ε is used to solve the optimization problem through three steps using LINGO software package; a screenshot of the software is given in Appendix A. This constraint method ε is selected for its simplicity. The solution is determined through three steps as follows:

- First, solve the optimization problem only considering minimizing the electricity generation cost; the results represent the maximum possible GHGE along with the minimum electricity generation cost.
- Second, solve the problem accounting for minimizing the GHGE only; the results are the maximum likely electricity generation cost and minimum GHGE.

- Third solve the problem considering minimizing the electricity generation cost with setting the GHGE at several values between the maximum and minimum values of GHGE attained in the first and second steps.
- Draw a Pareto curve for different values of ε between zero and one.

5. Results and Discussion

The problem is solved for five scenarios based on renewable energy allowed contribution. Also, these scenarios accounted for CO_2 sequestration. The model is solved for a large RO - desalination plant of 300, 000 m^3/day.

5.1. Input Data

The environmental impact of each energy source is described via CO_2 emissions in g C/kWh. The economic aspect is represented through the power generation cost in c/kWh. Both CO_2 emissions and sequestration cost have been attained from the available literature [27-30]. Accordingly, Table 3 points to the difference in prices of the generated electricity when carbon sequestration is added to the power generation systems.

Table 3. Cost of electricity generation and GHG emissions.

Energy Technology (*i*)	**Pulverized fuel**		**Integrate gasification combined cycle**		**Combined cycle gas turbine**		**CHP**		**PV**	**Wind turbines**
	With CO_2 Sequestration									
Energy source	**Coal**		**Coal**		**NG**		**Biomass**		**Solar energy**	**Wind**
Generation cost C_i c/kWh	**3.3**	**6.3**	**3.2**	**5.7**	**2.9**	**4.4**	**7**	**8.5**	**5**	**3.5**
Emissions G_i g C/kWh	**247**	**40**	**190**	**37**	**102**	**17**	**100**	**15**	**0**	**0**

5.2. Results

5.2.1. Scenario I

In this scenario, there are no restrictions put on the availability of energy resources. This is to allow the optimization program select the optimum energy mix in terms of the electricity generation cost and GHGE. There is CO_2 sequestration. The candidate energy resources include fossil fuels (combined cycle gas turbines, pulverized coal, and coal gasification combined cycle) and renewable energies (solar PV, wind, CHB biomass).

The results of scenario I, which is looking for the optimum hybrid power supply from the different energy resources given in Table 3, are represented in Fig. 4 and listed in Table 4.

In Fig. 4, the blue solid line is the Pareto curve which indicates the trade- off between the minimum electricity generation cost and the minimum GHGE. With the current conditions, minimum cost can be attained through getting 90% of the power demand from the wind turbines and 10% from combined cycle gas turbines. On the other hand, the minimum electricity generation cost can be attained when wind energy provides 100% of the power demand. Between these two extremes, many trade-offs are exist. Combined cycle gas turbines appear an appropriate technology in favours of both the cost and the environment.

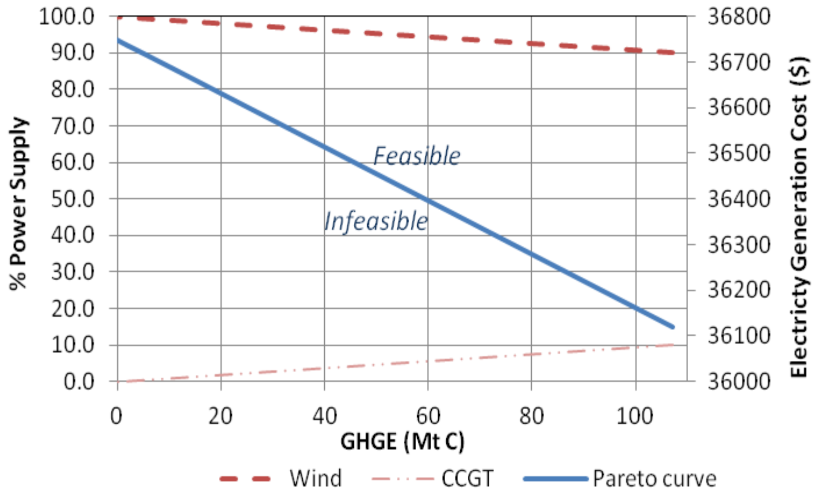

Fig. 4. Pareto curve for Scenario I.

Table 4. Optimization results of scenario I.

GHGE	COST	F	C
107.1	36120	90.0	10.0
10.71	36687	99.0	1.0
1.071	36743	99.9	0.1
0.1071	36749	100.0	0.0
0.01071	36749	100.0	0.0
0.001071	36750	100.0	0.0
0	30450	100	0.0

F: Wind; C: combined cycle gas turbine

5.2.2. Scenario II (With CO_2 sequestration)

Scenario II is similar to scenario I, but with the potential to applying CO_2 sequestration. Therefore, it is assumed that all the considered energy resources are available with no limitations, and the generated CO_2 is treated via CO_2 sequestration. In this case, the results indicate that the global optimum will be with 100% wind energy. This will generate electricity at both the minimum cost (3,675,000) and the minimum GHGE (zero).

This may be explained by the higher generation costs due to sequestration expenses that make the renewable energy more competitive. Therefore, when CO_2 sequestration process is applied to the power plants, renewable energy systems may become more attractive and become competitive to fossil fuels. Also, wind energy has the highest potential as a competitor for the fossil fuels.

5.2.3. Scenario III (Renewable energy less than 2/3 total power supply) with no CO_2 sequestration)

In this scenario, a different case has been investigated via putting limitations on the availability of the renewable energy resources. The restriction is less than two-thirds of the power supply can be attained from renewable energy resources. This limitation is assumed for in many locations, there may be availability of either wind energy or solar energy, but not both. Also, some locations are poor in renewable energy resources and these resources may not be available adequately to reply on them as the main power supply.

Figure 5 shows the changes in the optimum hybrid power supply due to setting a restriction on the availability of renewable energy resources. For instance, Pareto curve indicates that zero GHGE is not possible in the current case. Another change is represented by the dash lines; this is the optimum combination of energy resources have been changed. In Scenario I, the optimum combination was using wind turbines along with combined cycle natural gas turbines. Nonetheless, in Scenario III, the optimum combination includes four energy resources and technologies instead of two; these four technologies are gas turbines, combined heat and power of biomass, wind turbines, and solar photovoltaic, see Table 5. It is clear that combined cycle gas turbines has a significant share in the two scenarios, and that can be illustrated by using natural gas which is the cleanest fossil fuel.

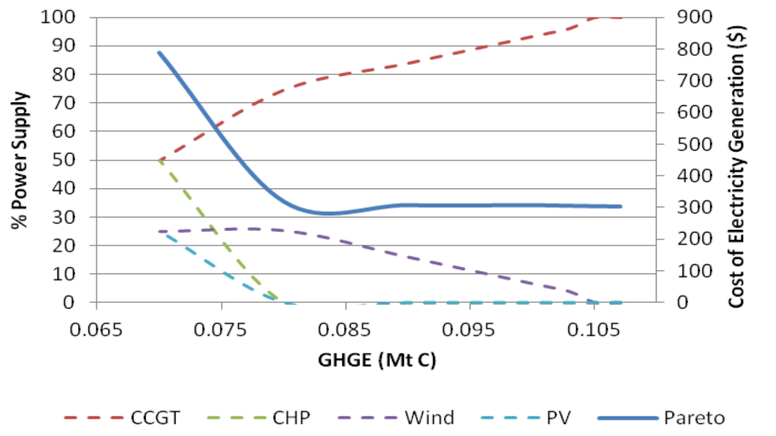

Fig. 5. Results of Scenario III.

5.2.4. Scenario IV (Renewable energy less than 2/3 total power supply) with CO_2 sequestration

This case is similar to Scenario III but with applying CO_2 sequestration. Costs of capturing, transporting, and storing CO_2 released from the fossil fuel power supply is added to the electricity generation from these resources which rises its generation cost. On the other hand, the GHGE release to atmosphere decreases. Therefore, a completely different Pareto curve is obtained as represented in Fig. 6. The most important characteristic of the new curve is the range of the cost; the cost of electricity generation becomes higher than the foregoing scenarios.

Table 5. Results of optimization of Scenario III.

COST	GHGE	C	D	F	E
305	0.1071	100	0	0	0
306	0.105	100	0	0	0
307	0.103	96.2	0	3.8	0
309	0.1	93.4	0	6.6	0
309	0.09	84.0	0	16.0	0
320	0.08	74.7	0	25.3	0
788	0.07	50	50	25	25

C: combined cycle gas turbine; D: combined heat and power; F: wind energy; E: solar photo voltaic

Another difference is the optimum energy mix. All the available wind energy is used, but no solar energy. Wind turbines and combined cycles gas turbines are certain competitor for solar energy, see Table 6.

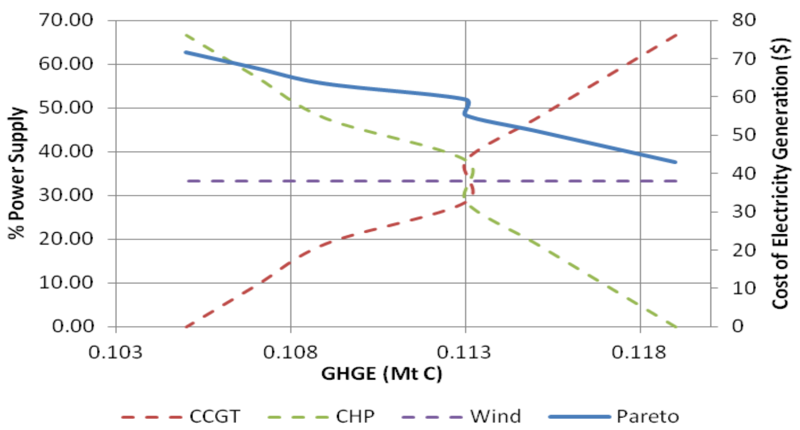

Fig. 6. Results of Scenario IV.

5.2.5. Scenario V (Renewable energy provides more than 2/3 total power supply) with CO_2 sequestration

Here there is higher contribution from renewable energy which relatively has higher electricity generation along with the extra expense of CO_2 sequestration. Thus as it is very clear from the Pareto curve, the optimum system has the highest cost, and the reduction in the cost with changing the amount of allowed GHGE is considerably small - Pareto is almost horizontal as given in Fig. 7.

Table 6. Results of Scenario IV.

Cost	GHGE	C	D	F
43.05	0.119	66.67	0	33.3
47.15	0.117	57.14	9.5	33.3
51.25	0.115	47.62	19.0	33.3
55.35	0.113	38.10	28.6	33.3
59.45	0.113	28.57	38.1	33.3
63.55	0.109	19.05	47.6	33.3
67.65	0.107	9.52	57.1	33.3
71.75	0.105	0	66.7	33.3

The dash lines referring to the employed energy resources and their contribution fraction have highly fluctuated profile; the values are listed in Table 6. This indicates that under the current scenarios, defining the optimum hybrid system has huge variety and several options. Furthermore, the solar PV line appears in all the possible trade-offs. Hence solar PV shall have higher contribution when environment protection policies such as imposing CO_2 sequestration implemented.

Table 7. Results of Scenario IV.

COST	GHGE	C	D	E	F
574	5.95	25	0	25	50
604.7	5.8	13.4	36.2	16.9	33.81643
625.25	5.7	49.5	27.5	7.7	15.38462
666.25	5.4	27.5	49.5	7.7	15.38462
686.75	5.3	36.1	13.3	16.9	33.73494
717.5	5.25	0	25	25	50

C: combined cycle gas turbine; D: combined heat and power; F: wind energy; E: solar photo voltaic

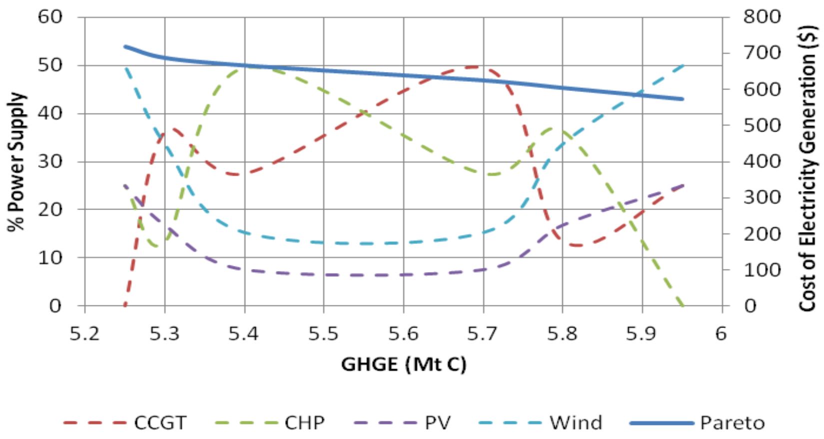

Fig. 7. Results of Scenario IV.

6. Conclusion

A hybrid power supply for a large scale RO- desalination plant is proposed and optimized considering the joint environmental and economic aspects. Several scenarios are considered based on the maximum allowed or available renewable energy resources. Likewise, the optimization is conducted with and without CO_2 sequestration. There is no unique optimum hybrid power supply for desalination system as the economic value of each energy resource is site- specific. So no generalization can be done, but there are clear trends that cannot be dismissed. When analyzing different scenarios, some particular trends appear as follows:

- Wind energy has the highest potential as energy source among the studied cases herein; this is in terms of both the cost and the impact on the environment. Integrated combined gas turbine is one of the most attractive energy systems. Solar PV will have higher contribution if fossil fuel power plants are imposed to apply CO_2 sequestration.
- Applying CO_2 sequestration will increase the electricity generation from fossil fuel plants, even the ones using cheap fuels such as coal. In this case, renewable energies especially wind turbines - followed by solar PV - will compete strongly and become competitive.
- With no CO_2 sequestration, the optimum hybrid power supply integrates the wind turbines with the natural gas turbines. With CO_2 sequestration, the optimum hybrid power supply integrates the wind turbines, the solar PV, the gas turbines, and the biomass combined heat and power. There are several combinations and trade- offs according to the allowed GHGE. All are optimum trade-offs yet which one to be applied is to be selected by the decision maker.

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Appendix A

A screenshot of the Optimization Program, LINGO.

In the present work LINGO software package has been used for the calculation of the optimum energy mix based on their economic and environmental characteristics. A screenshot of the optimization program, LINGO, is given in Fig. A-1.

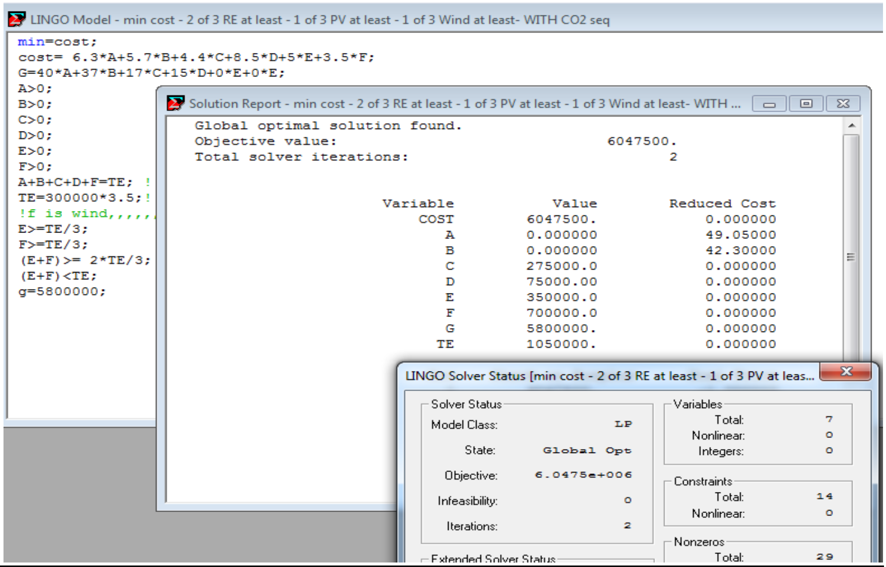

Fig. A-1. Screenshot of the Basic LINGO Program Used in this Study.