COGENERATION SYSTEMS: A PROPOSAL FOR THE LEBANESE ELECTRIC GRID

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(Received 10 April 2014 - Accepted 11 August 2014)

ABSTRACT

Cogeneration systems have become an important source of energy due to their efficiency and their ability to reduce pollutant emissions. These systems could be integrated into the Lebanese electric grid. This work presents a study concerning the optimized cogeneration capacity to be installed in Lebanon by the private sector. Genetic algorithm (GA) optimization method is then used. The optimization technique takes into account the economic issue, and then the economic-environmental one. Many solutions are suggested according to environmental criteria.

Keywords: cogeneration systems, genetic algorithm, optimization

INTRODUCTION

A cogeneration system or CHP (Combined Heat and Power) is typically defined by the simultaneous production of electric power and heat. This system is formed of a prime mover, a generator, a heat recovery system and electrical interconnections. The thermal power is normally produced from the use of the heat released by the combustion of fuels present in the system.

The use of cogeneration systems increases the efficiency of energy production from 35% up to more than 80%. Then, the integration of these systems is economically viable. This has pushed the people to install these systems, knowing that the production of electricity and heat is on site. The cogeneration system may be operating from conventional fuel sources as it can operate from renewable energy (biomass, solar).

Cogeneration is normally used for distributed generation and on-site generation to take advantage of the produced heat. In fact, it is possible to invest in such systems in Lebanon because of its small geographic area, thus the power plants will be normally close to consumers. The problem of the integration of cogeneration systems is based on two topics: economy and pollution.

In this work, a general study is made to find the optimized cogeneration capacity to be installed using genetic algorithm (GA). This optimization copes with economic issue and economic-environmental issue separately.

In the next section, a general review on the Lebanese electric system is done to show the importance of installing new power plants. In the third section, the objective functions are presented as mathematical models for the integration of cogeneration systems into a grid. In the fourth section, the optimization method is presented. And in the fifth section, the optimization results are exposed to find the optimal solutions of the economic and economic-environmental problems.

GENERAL REVIEW ON THE LEBANESE ELECTRIC SYSTEM

Before the civil war, the Lebanese electric system was in good conditions. In 1974, the EDL (Électricité du Liban) produced 1700 GWh electricity, while some small utilities produced 0,296 GWh. In that year, 41.5% of the produced energy was hydroelectric (Fardoun *et al*., 2012). In general, before the civil war there was no load shedding.

During the civil war, several damages have caused to the electricity sector.

After that, the electricity sector was being rehabilitated between years 1992 and 2002. This rehabilitation was not efficient enough due to the inherited corruption, to the growth in the living standards and the level of life and to political reasons. In 2011, the plan of minister Bassil was adopted by the Lebanese government. Its execution will take a little more time than agreed because of the political conflicts and situation.

Power generation

In Lebanon, the power stations are divided into two categories: thermal and hydraulic.

EDL owns seven thermal power plants:

- Three steam turbine power plants: Zouk, Jiyeh and Al Hreesha
- Two Combined Cycle Gas Turbine (CCGT) power plants: Deir-Ammar and Zahrani
- Two Open Cycle Gas Turbine (OCGT) power plants: Baalbeck and Tyre

The total installed capacity of these plants is theoretically 2038 MW, but their current capacity is less than 1700 MW (Ghajar & Hamdan, 2011).

The hydraulic power plants are: Litani, Al-Bared, Nahr Ibrahim, Safa, Kadisha. TABLE 1 shows that the total hydraulic capacity is 270 MW and the annual hydraulic energy is about 1000 GWh.

Figure 1 shows the cumulated produced electricity in 2012. Zahrani and Deir-Ammar approximately produce 50% of the total electric energy in Lebanon.

In addition, Lebanon was purchasing electric energy from Syria (527 GWh in 2009) and Egypt (589 GWh in 2009) *via* regional interconnections. This purchased energy corresponds to nearly 7.5% of the total produced energy in 2009 (Hamdan, 2010). But because of the political circumstances in the region, the imported electric energy was no longer stable.

TABLE 1

Hydraulic Power Plants in Lebanon (Hamdan, 2010)

River	Installed capacity (MW)	Capacity factor (%)	Annual energy (GWh)
Kadisha	25	41	70
Nahr Ibrahim	35	35	100
Bared	20	34	50
Litani	190	50	780
Total	**270**	**43**	**1000**

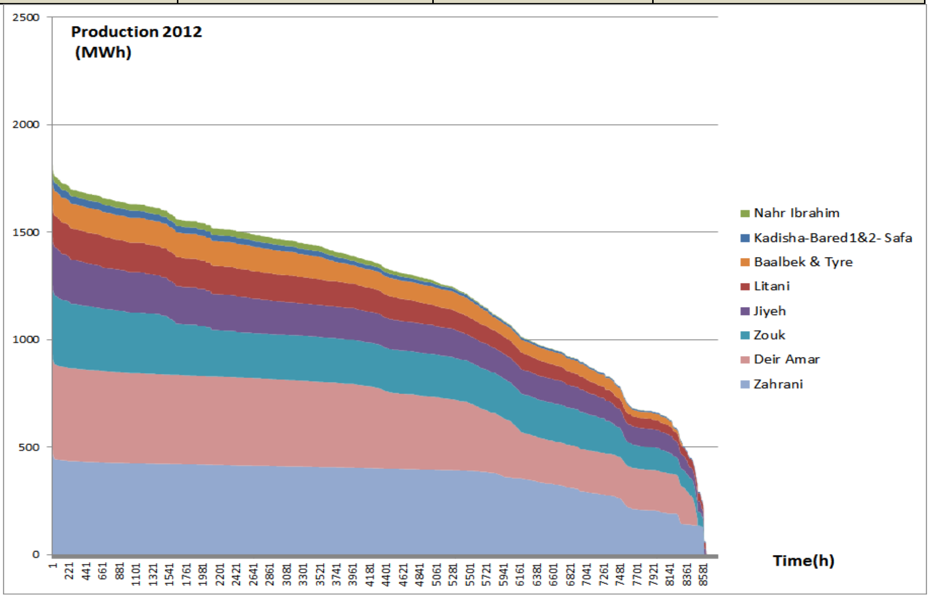

Figure 1. Cumulated produced electricity in 2012 by each power plant (Data source: EDL).

Electricity demand

The demanded electricity was 15000 GWh in 2009 and is growing about 7% per year, knowing that the power plants efficiency is decreasing about 2% per year (Ghajar & Hamdan, 2011). The produced electricity was 10406 GWh per year in 2009; it means that with the purchased energy in that year the electrical deficit was 25% of the demanded energy. Figure 2 shows the electrical deficit of the year 2010.

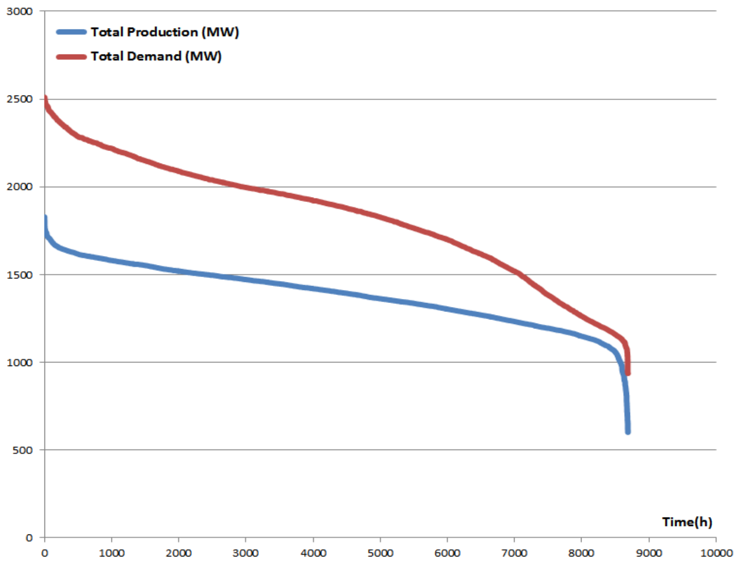

Figure 2. Production *vs* demand in 2010 (Data source: EDL).

The electrical deficit has driven the consumers to install private generators. The reason was to cover this deficit, but nowadays this becomes good investment for some people who managed small businesses which deliver power generation to EDL consumers. The average price of electricity delivered by private generators was (in 2009) 46.43 USC/kWh, knowing that the average electricity tariff by EDL is 9.58 USC/kWh which is below the cost of production (Ghajar & Hamdan, 2011).

Future scenario

If the strategic plan of minister Bassil is well executed, the installed capacity will reach 4000 MW in 2014, and 5000 MW after the year 2015 (MEW, 2010). This plan takes into account the reserve power during peak hours (15%) and the annual demand growth (7%). The plan considers also the transmission lines and the distribution.

The mentioned plan highlights the fuel supply as much as the renewable energy role in the future electricity generation. In addition, it looks forward considering the demand side management, the energy efficiency and the future electricity tariffs.

Role of the cogeneration systems in the Lebanese electric system

The Lebanese electric network needs the integration of cogeneration systems due to their continuous efficiency and their ability to reduce pollutant emissions. These systems can be adopted by the private sector and motivated by the Lebanese utility. In fact, the strategic plan of minister Bassil offers the private sector the opportunity to invest in the energy sector.

List of nomenclatures:

M: Number of cogeneration systems
N: Number of time intervals
K: Number of conventional extinct generators
P_i: Power produced by ithcogeneration system (MW)
$(P_i = P_{i\,el} + P_{i\,th})$
t_{ij}: Production time of the ithcogeneration system at jth time interval (h)
$E_{j\,load}$: Load demand at jth time interval (MWh)
$tariff$: Electricity tariff (\$/MWh)
n: Incentive or motivation factor when consumer sells the utility (usually $1 \leq n \leq 4$)
H_{bi} : Fuel enthalpy in the boiler of the ith cogeneration system (MWh)
$or\ P_i = P_{i\,thermal} + P_{i\,electrical}\ \ and\ H_{bi} = P_i * t_{ij} + Losses$
c_{ij}: Fuel cost of the ith cogeneration system at jth time interval (\$/MWh)
α_{ij}: Deterioration factor of the ith cogeneration system at jth time interval ($0 \leq \alpha_i \leq 1$; $\alpha_i =$ 0 for ideal cogeneration system and α_i=1 for damaged one)
c_{mij}: Average maintenance cost of the ithcogeneration system at jth time interval (\$)
$Inv.Cost$: Investment cost of the renewable energy system or cogeneration system (\$)
a_{jk}: Attrition cost of the kthconventional extinct generator at jth time interval due to cogeneration system integration (\$/h)
S_t: Total steam demand (Ton)
c_w: Cost of water (\$/Ton)
c_t: Transmission cost (\$/MWh)
D_{ij}: Pollution rate of fuel in the boiler of the ith system at jth time interval (kg/MWh)
Dam_{ij}: Pollution due to damaging of the ith system at jth time interval (kg)
Pol_{jk}: Pollution of the kth off-generator at jth time interval (kg/h)

OBJECTIVE FUNCTIONS

When optimizing the integration of cogeneration systems, the economic issues and the pollution one must be highlighted. The objective functions of the profit, the production cost, the total cost and the pollution are then presented.

Profit

The objective function to be maximized corresponding to the profit of the cogeneration systems integration is:

$$F_{profit} = \left(\sum_{j=1}^{N}\left(\sum_{i=1}^{M}(P_{ij} * t_{ij}) - E_{j\,load}\right) * \left[Max\left(\left(\sum_{i=1}^{M}(P_{ij} * t_{ij}) - E_{j\,load}\right), 0\right) * \left(\frac{n-1}{\left(\sum_{i=1}^{M}(P_{ij} * t_{ij}) - E_{j\,load}\right)}\right) + 1\right]\right) * tariff\ - \sum_{i=1}^{M}\sum_{j=1}^{N}(H_{bij} * c_{ij}) - \left(\sum_{i=1}^{M}\sum_{j=1}^{N}\alpha_{ij} * c_{mij}\right) - S_t * c_w$$

Where $Max\left(\left(\sum_{i=1}^{M}\left(P_{ij}*t_{ij}\right)-E_{j\,load}\right),0\right)*\left(\frac{n-1}{\left(\sum_{i=1}^{M}\left(P_{ij}*t_{ij}\right)-E_{j\,load}\right)}\right)+1=1\ or\ n$
(if $\left(\sum_{i=1}^{M}\left(P_{ij}*t_{ij}\right)-E_{j\,load}\right)>0\ \Rightarrow n$; if $\left(\sum_{i=1}^{M}\left(P_{ij}*t_{ij}\right)-E_{j\,load}\right)<0\Longrightarrow 1$)

With: $\left(\sum_{j=1}^{N}\left(\sum_{i=1}^{M}\left(P_{ij}*t_{ij}\right)-E_{j\,load}\right)*\left[Max\left(\left(\sum_{i=1}^{M}\left(P_{ij}*t_{ij}\right)-E_{j\,load}\right),0\right)*\left(\frac{n-1}{\left(\sum_{i=1}^{M}\left(P_{ij}*t_{ij}\right)-E_{j\,load}\right)}\right)+1\right]\right)*tariff=Exchanged\ energy\ cost$

$$\sum_{i=1}^{M}\sum_{j=1}^{N}\left(H_{bij}*c_{ij}\right)=Produced\ energy\ cost$$

$$\left(\sum_{i=1}^{M}\sum_{j=1}^{N}\alpha_{ij}*c_{mij}\right)=Maintenance\ cost$$

$$S_t*c_w=Water\ cost$$

Production cost

The objective function to be minimized corresponding to the production cost of the cogeneration systems integration is:

$$F_{prod}=\sum_{i=1}^{M}\sum_{j=1}^{N}\left(H_{bij}*c_{ij}\right)-\sum_{k=0}^{K}\left(\sum_{j=1}^{N}\left(\sum_{i=1}^{M}t_{ij}\right)*a_{jk}\right)+S_t*c_w$$

With:

$$\sum_{k=0}^{K}\left(\sum_{j=1}^{N}\left(\sum_{i=1}^{M}t_{ij}\right)*a_{jk}\right)=Attrition\ cost$$

Total cost

The objective function to be minimized corresponding to the total investment cost of the cogeneration systems integration is:

$$F_{Total}=\sum_{i=1}^{M}\sum_{j=1}^{N}\left(H_{bij}*c_{ij}\right)-\sum_{k=0}^{K}\left(\sum_{j=1}^{N}\left(\sum_{i=1}^{M}t_{ij}\right)*a_{jk}\right)+\left(\sum_{i=1}^{M}\sum_{j=1}^{N}\alpha_{ij}*c_{mij}\right)$$
$$-\left(\sum_{j=1}^{N}\left(\sum_{i=1}^{M}\left(P_{ij}*t_{ij}\right)-E_{j\,load}\right)\right.$$
$$*\left[Max\left(\left(\sum_{i=1}^{M}\left(P_{ij}*t_{ij}\right)-E_{j\,load}\right),0\right)*\left(\frac{n-1}{\left(\sum_{i=1}^{M}\left(P_{ij}*t_{ij}\right)-E_{j\,load}\right)}\right)\right.$$
$$\left.\left.+1\right]\right)*tariff\ +Inv.Cost+\sum_{i=1}^{M}\sum_{j=1}^{N}\left(P_{ij}*t_{ij}\right)*c_t$$

With:

$$\sum_{i=1}^{M}\sum_{j=1}^{N}(P_{ij} * t_{ij}) * c_t = Transmission\ cost$$

Pollution

The objective function to be minimized corresponding to the pollution of the cogeneration systems integration is:

$$F_{pollution} = \sum_{i=1}^{M}\sum_{j=1}^{N}(H_{bij} * D_{ij}) + \sum_{i=1}^{M}\sum_{j=1}^{N}\alpha_{ij} * Dam_{ij} - \sum_{k=0}^{K}\left(\sum_{j=1}^{N}\left(\sum_{i=1}^{M} t_{ij}\right) * Pol_{jk}\right)$$

With:

$$\sum_{i=1}^{M}\sum_{j=1}^{N}(H_{bij} * D_{ij}) = Fuel\ pollution$$

$$\sum_{i=1}^{M}\sum_{j=1}^{N}\alpha_{ij} * Dam_{ij} = Pollution\ due\ to\ system\ deterioration$$

$$\sum_{k=0}^{K}\left(\sum_{j=1}^{N}\left(\sum_{i=1}^{M} t_{ij}\right) * Pol_{jk}\right) = Pollution\ due\ to\ conventional\ extinct\ generator$$

MULTIOBJECTIVE OPTIMIZATION

In this section, the objective functions of the previous section are solved with the genetic algorithm multiobjective optimization method in Matlab.

The optimization is executed considering the economic issues (profit, production cost and total cost) at the first step, and at the second step considering the economic issues under environmental constraints (with pollution).

According to Figure 2, the Lebanese electric system has a deficit of approximately 700 MW. For transmission reasons and to benefit from the heat produced by the system (for heating, cooling and water heating reasons), it is preferred to install at least three cogeneration systems set up in the regions with high population density (*e.g*. Beirut and its surrounding areas, Tripoli, Baalbek…). And for economic reasons, it's more practical to install three systems only. For this reason, the following constraint: $P_1 + P_2 + P_3 \leq 700\ MW$ was chosen . P_1, P_2 and P_3 are the three capacity values of the cogeneration systems to be installed. Each of these capacities has a lower bound of 50 MW and an upper bound of 300 MW. H_{bi} is replaced by $\frac{P_i * t_{ij}}{0.85}$ to simplify the calculations. In fact:

$H_{bi} = P_i * t_{ij} + Losses$. Or the efficiency of a cogeneration system is considered 85%, thus: $P_i * t_{ij} = 0.85 * H_{bi} \Longrightarrow H_{bi} = \frac{P_i * t_{ij}}{0.85}$

The motivation factor n is considered equal to 2; it means that the utility pays for the private sector which installs such systems twice the price of electricity tariff. The year's index j is set to 2.

The other factors values are treated according to their normal values.

Because the genetic algorithm (GA) is a heuristic method, the solution is not guaranteed to be optimal. The simulations number is then selected to be 1000 *(i.e.* 1000 solutions), knowing that their execution time is nearly one hour. This can lead us to get a pleasing optimal solution in a pleasing time. And because GA method only finds the minimum, the sign of the profit function was changed to find its maximum. After that, in the results the value was changed again to obtain the maximum value.

RESULTS AND DISCUSSIONS

In this section, an analysis of the optimization results will be done. The purpose is to find the optimal capacities of the cogeneration systems to be installed.

Economic mutliobjective optimization

In accordance with the economic issues, the interest is in a maximum profit and minimum total and production costs. Production cost is sometimes less dominant than the profit and the total cost because it is almost related to the system capacities (*i.e.* if system capacity is high, the production cost is normally high).

TABLE 2

Optimization Solutions of the Multiobjective Economic Functions

Profit $\times 10^8$**($)**	**Production** $\times 10^8$**($)**	**Totalcost** $\times 10^8$**($)**	P_1 **(MW)**	P_2 **(MW)**	P_3 **(MW)**
-6.28	3.1487	5.6008	246.53	299.89	53.581
-6.299	3.1442	5.6184	255.83	290.25	53.918
-6.301	3.1443	5.6208	256.02	289.5	54.474
-6.311	3.1367	5.6294	268.79	280.73	50.487
-6.313	3.1358	5.6309	270.32	279.57	50.106
-6.313	3.136	5.631	270.02	279.67	50.301

According to Table 2, the highlighted raw has the best optimal solution. It corresponds to maximum profit, minimum total cost, with a suitable production cost. Thus, the optimal solution is $P_1 = 246.53\ MW$, $P_2 = 299.89\ MW$ and $P_3 = 53.581\ MW$.

These results show that two high-capacity and one low-capacity cogeneration systems must be installed.

The high-capacity systems should be set up in the most populated big regions and the low-capacity system in a populated small region, to apply favorably the district heating process.

Economic-environmental multiobjective optimization

TABLE 3

Optimization Solutions of the Multiobjective Economic-Pollution Functions

Profit $\times 10^8$ **($)**	**Production** $\times 10^8$ **($)**	**Total cost** $\times 10^8$ **($)**	**Pollution** $\times 10^9$ **(kg)**	P_1 **(MW)**	P_2 **(MW)**	P_3 **(MW)**	**Total (MW)**	**Pollution / Total (kg/MW)**
-6.281	3.1486	5.6012	3.3543	246.53	299.89	53.565	599.985	5590639.766
-6.305	3.1435	5.6245	3.3503	257.86	287.45	54.691	600.001	5583824.027
-6.311	3.137	5.6295	3.345	268.39	280.9	50.711	600.001	5574990.708
-6.393	3.1174	5.707	3.3284	268.35	277.72	51.014	597.084	5574425.039
-6.41	3.1142	5.7232	3.3259	274	270.98	52.003	596.983	5571180.419
-6.413	3.1115	5.7256	3.3236	271.88	274.42	50.224	596.524	5571611.536
-6.529	3.1111	5.8399	3.3226	252.21	268.3	73.334	593.844	5595072.106
-6.55	3.0837	5.857	3.2999	270.74	266.23	55.1	592.07	5573496.377
-6.561	3.0754	5.8665	3.2927	266.29	274.37	50.096	590.756	5573705.557
-6.579	3.071	5.8838	3.2892	273.61	266.61	50.411	590.631	5568959.299
-6.589	3.0693	5.8931	3.2877	270.94	268.36	50.859	590.159	5570871.579
-6.592	3.0678	5.8963	3.2864	268.53	271.01	50.258	589.798	5572077.220
-6.621	3.0615	5.9232	3.281	269.55	268.6	50.747	588.897	5571432.695
-6.705	3.04	6.0032	3.2629	272.49	263.34	50.152	585.982	5568259.776
-14.445	2.058	13.155	0.85084	50	50	50	150	5672266.667

When having environmental constraints, the optimal solution will be dependent on the pollution criteria. This makes the solution selection more complicated.

In Table 3, the two extreme optimal solutions are presented in addition to the best optimal solutions that can be discussed according to the decision criteria. In green, the optimal solution corresponds to the best economic and worst pollution criteria. In yellow, the optimal solution corresponds to the worst economic and best pollution criteria. These two results are normally not suitable because they disparage one of the important criteria. Thus, the decision maker should follow the required criteria to select the convenient capacities.

It is remarkable that the solution corresponding to best environmental criteria corresponds to the capacities lower bound (50 MW each). The result is very normal, because the pollution is proportional to the systems capacities. And the solution corresponding to best economic criteria is approximately the same as the economic multiobjective optimization one.

The optimal solution to be selected is the one that has the minimum total and production costs, the maximum profit and the minimum polluting emissions. In fact, the cogeneration systems have a reduced pollution effect comparing to conventional power plants. But, one should select an optimal solution corresponding to good economic performance with some respect to pollution. The two selected optimal solutions in blue and orange in Table 3 are the best solutions according to the pollution: total ratio. They have close ratios, but in our opinion, it's preferred to choose the solution in blue because it has better economic performance. So the optimal solution corresponding to economic-environmental issues is $P_1 = 273.61MW$, $P_2 = 266.61\ MW$ and $P_3 = 50.411\ MW$.

These results show also that two high-capacity and one low-capacity cogeneration systems must be installed. As mentioned in the economic multiobjective optimization, the high-capacity systems should be set up in the most populated big regions and the low-capacity system in a populated small region, to apply favorably the district heating process.

CONCLUSION

This work has presented a general review on the Lebanese electric system and the need for integrating cogeneration systems into the Lebanese electric grid. Then, the genetic algorithm is used for the optimization concerning the integration of cogeneration systems. This optimization copes with the economic and economic-environmental criteria.

The study shows that the environmental issue has an important impact on the decision making of the capacities selection. The capacities to be installed are then selected taking into account the economic and the economic-environmental performances.

This work proposes a solution for the electric sector in Lebanon and gives the private sector the opportunity of positive investments. Many works could be done in the future to show the positive impact of integrating such systems on the Lebanese electric system and its economic situation.

ACKNOWLEDGMENT

The authors gratefully acknowledge the National Council for Scientific Research (CNRS) of Lebanon for the support given to the first author during his research.

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