AN INTEGRATED RESOURCE PLANNING FORMULATION USING A SIMULTANEOUS ELECTRIC/THERMAL PRODUCTION SYSTEM

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SUMMARY

An Integrated Resource Planning (IRP) formulation has been developed,it aims at identifying an optimum energy supply mix between a simultaneous electric/thermal production system (co-generation facility) at a ceramics plant and its electric utility energy supply. A technically suitable cogeneration system is selected based on the thermal/electric ratio, the process heat and type of fuel available. The optimum formulation focuses on the sizing of a co-generation system according to the electric and thermal demands of the plant and their time dependent load profiles. A performance formulation model which predicts the electric and thermal performances of all suitable generating units at site as well as part load conditions has been developed as part of the optimum sizing formulation. The introduced double edge optimal formulation satisfies: i) an overall minimum energy cost to the plant, ii) maximizing the possible profit to the utility. Two operational scenarios have been studied; a standalone and an energy exchange ones. The optimum configuration identified a gas turbine co-generation unit of an ISO capacity of 5.56 MW. This solution offered a return on investment of 27% with an energy exchange scenario between the plant and the electric utility. This corresponds to a time based energy exchange of 27% form the plant to the utility and 10% from the utility to the plant. Currently the implementation phase is under progress. Furthermore, an environment impact assessment of the optimum application was conducted. This paper provides the end-user and the electric utility with an optimum IRP/DSM tools respectively, thus facilitating the negotiation and development of competitive power exchange agreements.

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INTRODUCTION

Cogeneration improves the fuel utilization efficiency through reuse of the waste heat and consequently reducing the pollutant emissions. It increases the reliability of the power supply to the end user, and help in avoiding the transmission losses which are usually associated with the power transmitted through the utility grid (12-13% currently in Egypt). Utilities do go for cogeneration due to its impact on reducing users demands, as well as possibly providing electrical energy at a competitive price to the utility. Industries with simultaneous use of electric and thermal energies are good candidates for cogeneration applications; Cogeneration hand book (1) and Elsobki (2). A potential of possible net added capacities of cogeneration systems, in 438 industrial plants in Egypt is estimated to be more than 1,000 MW El-Salmawy (3). Ceramics industry represents an intensive user of energy, where the energy cost represents around 20% of the production cost; Energy conservation manual (4) and Brown et al (5). The specific electric and thermal energy consumptions (in kilns and dryers) are 88 kJ and 1,148 kJ per kg of product respectively (4,5). Out of the thermal loads the dryers represent a good location for heat recovery. The specific energy consumption of the dryers is 315 kJ/kg of product (4,5). This makes the recoverable thermal/electric ratio around 3.6. The selection criteria of a suitable cogeneration system for a specific application are based on the thermal to electric ratio, the process heat and type of fuel available (1-3). Applying this to the ceramics industry, where hot air is used in the spray dryers at 550^{o}C and the thermal to electric ratio is 3.6, the most suitable cogeneration system for this industry will be the gas turbine type.

The ceramics company under consideration is one of the largest ceramic production complexes in Egypt, with a production capacity of twelve million square meters of ceramic tiles per year; it operates 8,400 hours per year. The manufacturing process consists of; material preparation, forming, drying, glazing, firing, cooling and finally packing and storing (4,5). Natural gas is consumed in the kilns and dryers where firing and drying processes are executed respectively. Annual gas consumption of the plant is 30,890,616 m^3. Over 80% of the gas is consumed in the kilns while the rest is consumed in the dryers. The kilns are usually divided into different heating zones where heat is recovered from one zone to another to improve the kiln thermal efficiency. On the contrary, the spray dryers that consume 18.8% of the gas in the plant represent a good chance for heat recovery. The company has two spray dryers of capacities; 80,000 m^3/hr and 39,000 m^3/hr. These spray dryers operate on average for 20 hours per day. The variation of gas consumptions over the year for the two dryers is shown in figure 1. The load duration curves of the two dryers are shown in figure 2. The average thermal demands of the large and small dryers are 8,750 and 4,265 kW respectively. The company receives its electricity through three 11 kV feeders in addition to an emergency standby feeder. Two of the main feeders provide 88.5% of the annual energy consumed by the plant, while the third provides only 11.5%. The low voltage system which operates on 380 V is composed of thirteen power distribution transformers. A simplified single line diagram of the electric supply system is shown in figure 3. The annual consumption of the plant from feeders 1&2, over one year was 30,914,320 kWh and the peak demand was 5.4 MW. The average plant load factor is 65% and its base load is 3,108 kW. Figures 4 and 5 present the annual load and the load duration curves of the plant respectively. Measurements have been carried out on feeders 1&2 for 24 hours. Their peak demands are 2.8 and 2.3 MW receptively. The coincident combined peak demand of feeders 1&2 is 5.1 MW. Figure 6 presents the daily load duration curves of feeders 1&2 and their coincident grouping. Measurements indicate the instant daily peak demand represents 94.4% of the annual peak demand. By assuming that the share of each feeder in the peak demand as well as the annual consumption will be the same as that of its daily share, the peak demand of feeders 1&2 will be 2,966 and 2,436 kW respectively. Average demand of feeders 1&2 are 1,731 and 1,483 kW respectively, while their base loads are 1,536 and 1,316 kW receptively.

PROPOSED OPTIMAL IRP FORMULATION

The developed IRP optimal formulation targets a minimum value for the simple pay back period (SPB). It is subject to a set of constraints which

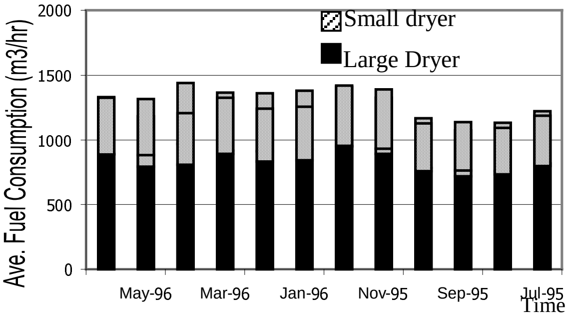

Fig. 1: Average Fuel Consumption of the Two Dryers

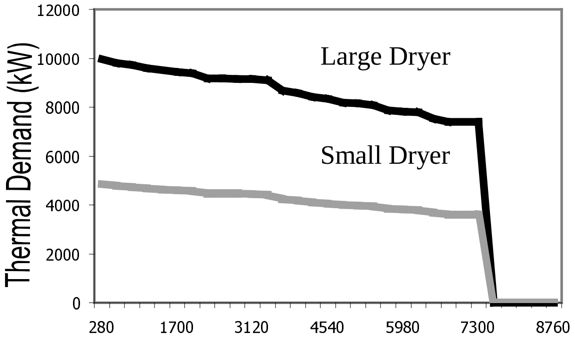

Fig. 2: Annual Thermal Load Duration Curve of the Large and Small Dryers

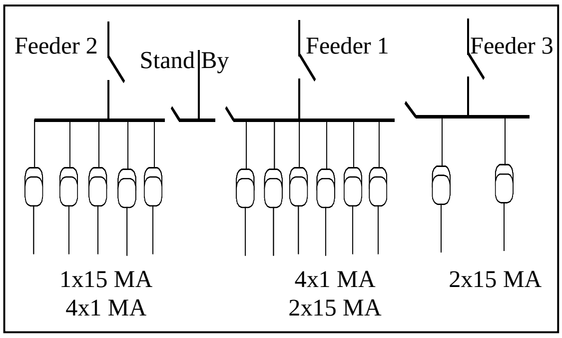

Fig. 3: Main Single Line Diagram of the Company

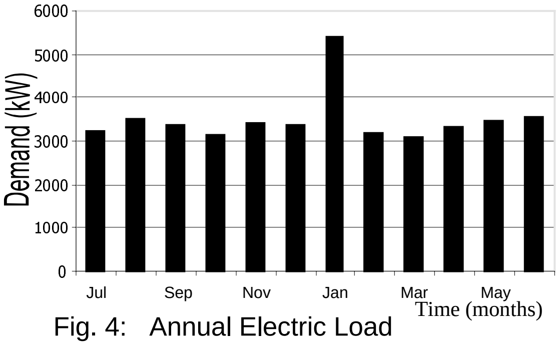

Fig. 4: Annual Electric Load Curve of the Plant

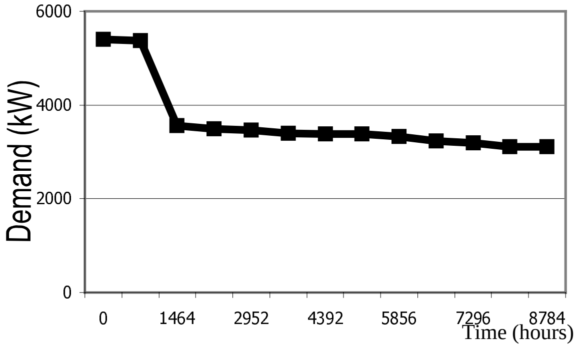

Fig. 5: Annual Load Duration Curve of the Plant

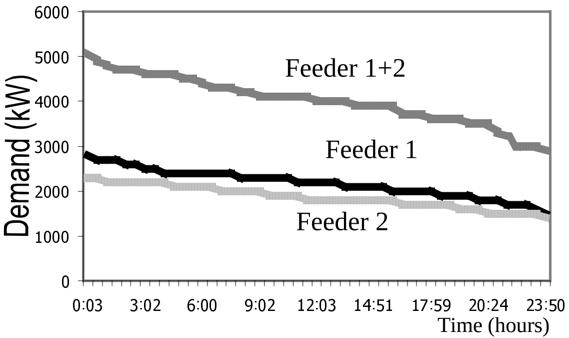

Fig. 6: Daily Load Duration Curve of the Two Feeders and their Combination

reflect maximum electric loading conditions for the cogeneration unit, covering the total connected base load, maximum utilization efficiency for the cogeneration unit, maximum size for the cogeneration unit without exceeding the thermal demand of the plant, thermal and electric energy balance among the plant, cogeneration unit and electric utility, minimum energy cost for the thermal and electric energy productions form the cogeneration unit to the plant as compared to the utility electric price and cost of running the dryers, lower value for the price of electricity from the cogeneration unit to the utility. The optimization formulation utilizes as its state variables the time dependent electric and thermal demands, the electric thermal parameters of the cogeneration unit that are obtained form a developed electric-thermodynamic model in addition to a techno-economical scheme. The control variables of the optimal formulation are the electric and thermal energy prices (kWh & fuel), the electric and thermal demands and their associated durations and investment costs. The IRP optimal formulation is expressed as:

$$Minimize\ SPB = Min.\ (IC/TNS), \qquad (1)$$

Subject to:

$$(LF_{c.\ load} = 0.65) \leq LF_{cog} \leq 1.0 \qquad (2)$$
$$R_{cog} \geq Connected\ base\ load \qquad (3)$$
$$T/E_{cog} \leq T/E_{plant} \qquad (4)$$
$$RH_{cog} \leq TE_{dryer} \qquad (5)$$
$$\sum (TE_{cog} - TE_{plant}) = TE_{supp.} \qquad (6)$$
$$\sum (EE_{cog} - EE_{plant}) = EE_{exchange} \qquad (7)$$
$$EEC_{cog\text{-}plant}/kWh < EEC_{ut\text{-}plant}/kWh \qquad (8)$$
$$EEC_{grid\text{-}ut} \geq EEC_{cog\text{-}ut} \qquad (9)$$

Regarding the unit cost, it is affected by many factors such as; unit size, efficiency and any additional accessories. Also the cost may change significantly depending on the scope of the application and the market prevailing conditions. However prices based on real quotations have been stated in (1) for unit sizes between 1 MW up to 13 MW. A curve fitting has been developed for these prices. The following equation provides the cost per kW as a function in the unit base rating:

$$\begin{aligned} Cost(US\$)/kW = & 4*10^{-10}*(x-1130)^3 \\ & +10^{-5}*(x-1130)^2 \\ & - 0.0818 * (x-1130) \\ & + 603.2 \end{aligned} \qquad (10)$$

Where: X is the ISO base rating of the unit and:

IC	Investment cost (polynomial function in unit capacity, shown in equ. # 10)
TNS	Total net savings
$LF_{c.\ load}$	Load factor of connected load
LF_{cog}	Load factor of the cogen. Unit
R_{cog}	Rated capacity of cogen. Unit
RH_{cog}	Recoverable heat from the cogen. Unit
TE_{dryer}	Thermal energy demand of the dryer
T/E_{plant}	Thermal to electric ratio of the plant
T/E_{cog}	Thermal to electric ratio of the cogen. Unit
TE_{cog}	Thermal energy: of the cogen. unit
TE_{plant}	Thermal energy: load of the plant
$TE_{supp.}$	Thermal energy: the supplementary firing.
EEC_{cog}	Elec. energy cost form the cogen. unit
EEC_{ut}	Elec. energy cost from the utility
EE_{cog}	Electric energy supplied by the cogen.
EE_{plant}	Electric energy of the plant load
$EE_{exchange}$	Electric energy from the cogen. Unit to the utility or from the utility to the plant.
$EEC_{cog\text{-}plant}$	Elec. Energy cost between the cogen unit and the plant.
$EEC_{ut\text{-}plant}$	Elec. Energy cost between the utility and the plant.
$EEC_{grid\text{-}ut}$	Elec. Energy cost between the public grid and the utility.
$EEC_{grid\text{-}ut}$	Elec. Energy cost between the public grid and the utility.
$EEC_{cog\text{-}ut}$	Elec. Energy cost between the cogen. unit and the utility.

Both the thermodynamic model and the techno-economical scheme are correlated to the optimization objective function. The thermodynamic model takes into consideration; change in gas composition, variation in specific heats and combustion equilibrium. It provides the output electric power of the unit, exhaust gas temperature and heat rate at different site and electric loading conditions. The model input parameters include; inlet temperature, relative humidity, altitude, inlet and outlet pressure losses, compressor and turbine efficiencies, pressure ratio, combustion chamber pressure loss, turbine inlet temperature, exhaust flow rate, mechanical and generator efficiencies, air to fuel ratio and unit electric loading. Also fuel chemical composition is provided. The thermodynamic model output has been verified against data provided by the manufacturers of the gas turbine units. Agreement has been found between the thermodynamic model and data provided. The techno-economical scheme calculates the savings related to electric and thermal energies, as well as their corresponding financial savings. The inputs to the techno-economical scheme are shown in table 1.

Table 1 The Input values to the techno -economical evaluation

NG lower heating value	37,000 kJ/m^3
Fuel cost	0.141 LE/m^3
Demand charge	87.6 LE/kW
Electrical energy cost	0.1535 LE/kWh
Annual unit availability	94%
Cost of O & M	0.034 LE/kWh

Customs duties & taxes	20% of CIF price
Installation cost (isolated mode)	600,000 LE
Installation cost (parallel mode)	1,150,000 LE
Installation supplies	20% of unit price
Currency exchange rate	3.5 L.E./US$

Optimum Sizing and Operational Scenario for the Cogeneration Unit

The optimal IRP formulation did consider two approaches; the standalone (isolated) and the parallel operation with the utility.

Stand alone approach (isolated). Based on the electric and recoverable thermal demands in the plant, a matrix for different stand-alone alternatives has been developed; table 2 shows this matrix. A database for all available suitable gas turbine units has been developed; it is based on a survey of gas turbine manufacturers in the world (1,6). The database includes 9 gas turbine units together with their detailed technical specifications. Table 3 shows a summary for the specifications of these units. Considering the nine alternatives in table 2 and the nine gas turbine units in table 3; 81 combinations are possible. To select the optimum alternative out of these; the developed optimal formulation has been used.

Table 2 Matrix for thermal to electric ratios of different stand alone alternatives

	Feeder # 1	Feeder # 2	Feeders 1+2
Large Dryer	5.1	5.9	2.7
Small Dryer	2.5	2.9	1.3
Total dryers load	7.5	8.8	4.0

Table 3 Suitable turbine for different stand alone alternatives

Model	ISO Base Rating (kW)	Air Flow Rate (kg/hr)	Thermal to Electric Ratio
A	2,650	54,720	2.0
B	2,824	64,653	3.1
C	2,898	53,224	2.5
D	3,050	55,510	2.2
E	3,130	63,184	2.1
F	2,950	45,714	2.4
G	5,647	70,204	1.6
H	5,560	70,694	1.7
I	6,040	119,184	1.5

Considering all the aforementioned data as well as the site conditions it was found that unit “H” stratifies the optimum conditions. These are 27,125,758 kWh, 3,045,223 LE and 3.9 years for the annual energy supply by the co-generation unit, net annual savings and simple pay back period respectively. The unit carries the combined loads of the two feeders and provide hot exhaust gases at 533°C to the large dryer. Since the unit thermal to electric ratio is 1.7 while the thermal to electric ratio of this alternative is 2.7, supplementary firing will be needed to compensate for the reduction in the recovered heat as the unit tracks the electrical load. The existing burner attached to the spray dryer will provide supplementary firing. The unit will run at its peak for around 750 hours per year. According to the unit technical data, it can run safely at its peak load for 2000 hours per year.

Parallel operation with the utility. Three electric energy exchange alternatives are examined, these are: only exporting, exporting/importing and only Importing. The price of the electricity sold by the generation company to the distribution company under concern is 0.103 LE/kWh (7). This price is a flat rate one. The distribution company profit is due to the marginal difference between the purchasing price form the generating company and form the cogeneration unit. Also the amount of profit is a function in the quantity of electric energy purchased.

Since this parallel operation approach is more flexible regarding the capacities of the gas turbines, the previously developed gas turbine database has been expanded by adding another seven gas turbine units (1,6). Table 4 shows the technical specifications of these additional units.

TABLE 4 Turbines for the different alternatives to operate in parallel with the utility

Model	ISO Base Rating (kW)	Air Flow Rate(kg/hr)	Thermal to Electric Ratio
J	6,249	99,592	1.7
K	1,600	25,142	2.4
L	1,850	53,714	3.9
M	1,812	34,612	2.9
N	3,746	55,510	1.8
O	3,650	56,000	2.0
P	3,655	56,000	2.0

Applying the optimal IRP formulation considering all the aforementioned data as well as the site conditions it was found that unit “H” satisfies the optimum conditions. It provides a continuous base load below the peak demand and above the plant average demand.

The annual electricity generated by the unit is 42,081,638 kWh out of these 11,838,354 kWh will be exported to the utility. On the other hand 428,103 kWh will be imported from the utility to the plant. The net annual savings are 3,438,051 LE to the plant. The utility will generate an annual profit of 392,828 LE considering a selling price of 0.07 LE/kWh from the plant to the utility. This reflects a simple pay back period of 3.6 years to the plant.

The environmental impact assessment. EIA of the IRP gas turbine-cogeneration parallel application will result in the following annual net pollutant reductions, these are:

Pollutant	Annual reduction (tons/year)
CO_2	12,582.00
CO	3.38
SO_2	384.20
Nox	41.60
HC	35.20

These pollutant reductions are due to:

i) Using natural gas for the cogeneration unit rather than liquid fuel that is used at utility generating stations (likely fuel # 6). NG has less CO_2 emissions by 40% than liquid fuel. Sulfur content in NG is almost nil. NG mixes better with combustion air leading to reductions in CO and HC emissions.

ii) Combustion in gas turbine is carried at lean conditions leading to a reduction in NOx, CO and HC emissions.

iii) Utilization of waste heat in the spray dryer result in emissions reductions equivalent to those emitted when NG is burned in the dryers.

CONCLUSIONS

High potentials for cogeneration application are available in ceramics industry. The suitable type of cogeneration systems for this industry is the gas turbine with direct heat recovery in spray dryers. An optimization technique has been developed and used successfully during this study. The developed IRP optimal formulation guarantees minimum SPB which satisfies maximum coverage of the plant electric and thermal demands form the cogeneration unit, highest energy utilization efficiency for the cogeneration unit, maximum energy cost savings to the plant and maximum profit to the electric utility as a result of electric energy exchange. Two approaches have been assessed through out this study. These approaches included; the standalone (isolated) and the parallel operation with the utility. The parallel operation approach, which relies on the Exporting/Importing scenario, is the most financially attractive approach. The most suitable unit for this application is a unit with a rated output less than the plant peak demand and higher than the plant average demand. This unit can export electricity to the utility at a competitive price while keeping an attractive rate of return to the ceramics plant. Accordingly, due to its obvious benefits, the utility is encouraged to look into adopting the parallel operation with the plants that have a potential for cogeneration via Exporting/Importing contracts. Finally the EIA showed substantial reduction in polluting emissions due to the IRP optimum approach.

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ACKNOWLEDGMENTS

The support of the United States Agency for International Development (USAID) under contract agreement #263-0140.3 through the ECEP project is acknowledged. The authors would also like to acknowledge the Ceramics company, the Electricity Distribution company for their full cooperation.