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Optimal Design of Energy Supply Systems for Housing Complexes Using Multiple Cogeneration Technologies

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This paper presents a multi-objective optimisation approach for designing residential cogeneration systems based on a new superstructure that allows satisfying the demands of hot water and electricity minimising costs and environmental impact. The optimisation involves the selection of technologies, size of required units and operating regimen of equipment. A residential complex in Mexico was considered as case study. The results show that the implementation of the proposed optimisation method yields significant economic and environmental benefits due to the simultaneous reduction in the total annual cost and overall greenhouse gas emissions.

1. Introduction

Cogeneration (CHP) is the simultaneous production of electrical and thermal energy from a single energy stream (Tahouni at al., 2012). In CHP systems, the efficiency of energy conversion increases to over 80 % as compared to an average of 35 % for conventional generation systems (see Figure 1). It can result in lower costs and the reduction of the greenhouse gas emissions (GHGE) when compared with the conventional methods (Karabegovic, 2014). A CHP system is designed with the purpose of satisfying the demands of electricity and hot water for sanitary use (HWS) (Chicco and Mancarella, 2009). This kind of distributed energy systems can also serve as backup or peaking systems and provide energy to remote areas without grid coverage (Liu et al., 2013). Although a CHP system can be designed to operate independently from the electric grid, it is useful to establish a link with the grid to buy and sell electricity (Lozano et al., 2009).

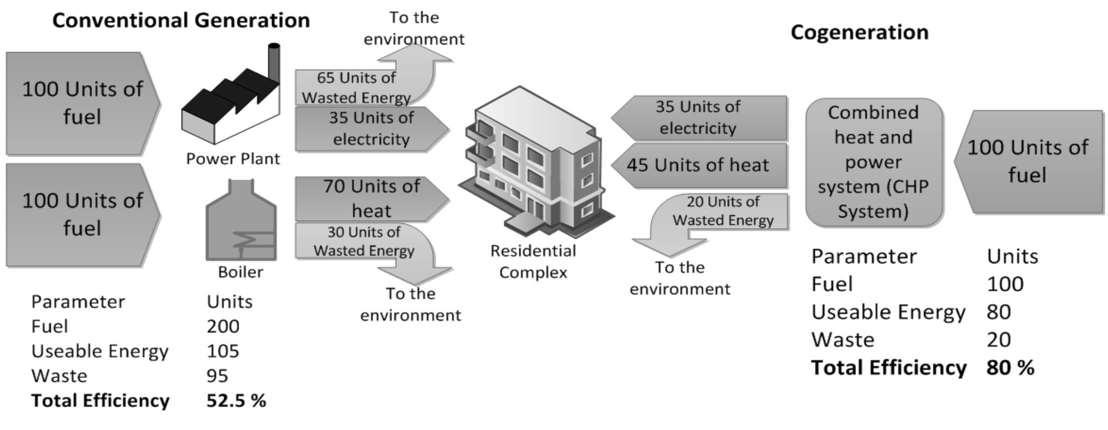

Figure 1: Comparison between traditional generation and CHP systems.

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The design problem in CHP systems for the residential sector is associated with factors such as energy consumption habits of the home user, which show seasonal and hourly variations, installation costs, operation and maintenance, GHGE and environmental conditions. These conditions affect the sizing, operating scheme and type of selected prime mover equipment. This paper proposes an optimisation model for the simultaneous integration of a CHP system accounting for economic and environmental objectives, using as independent variables the operating scheme, sizing and selection of the prime mover system, as well as the dimensioning of the thermal storage system. The model considers the inclusion of an auxiliary heating system (Boiler, B). The following units are considered to select the prime mover system: reciprocating internal combustion engine (RICE), Stirling engine (SE), fuel cell (FC) and microturbine (MTG). The scheme includes the hourly temperature throughout the day; this allows migration between different geographic scenarios with different hourly average temperatures. For this work, results for energy demands and ambient temperatures of a housing complex in Mexico are evaluated.

2. Problem statement

The problem can be defined as follows (see Figure 2) and it is stated as a multi-objective optimization problem (Sharma et al., 2014). Given are the thermal consumptions associated to HWS and the power demands of a housing complex and the average hourly temperature; the problem then consists in determining the operating scheme, sizing and selection of the prime mover and sizing of the thermal storage system, as well as the auxiliary system, such that the total annual cost (TAC) and the GHGE are minimised. This work proposes a superstructure (Figure 3) that operates synchronously with the grid. The proposed superstructure is basically formed by four integrated technologies (RICE, SE, MTG and FC), an auxiliary water heater and a thermal storage system (i.e. a thermally insulated tank, ST).

3. Model Formulation

The model formulation is based on the superstructure shown in Figure 3, which is a mixed integer nonlinear programming problem (MINLP). It is defined in an hourly basis for a demand of a typical day.
The electricity demand is satisfied by the sum of the purchased electricity from the grid and the electric energy produced and sent to the housing complex by the CHP equipment. The electricity produced by each CHP unit can be distributed according to the needs as energy sent to the housing complex and the energy sold to the grid as surplus production.

$$W_t^{D} = W_t^{purchase} + W_t^{RICE-H} + W_t^{MTG-H} + W_t^{FC-H} + W_t^{SE-H}, \forall t \in T \quad (1)$$

$$W_t = W_t^{-H} + W_t^{-sale}, \forall t \in T, \quad (2)$$

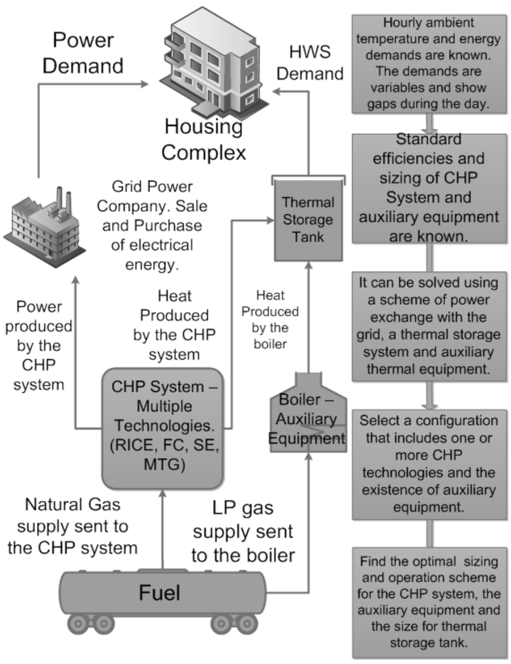


Figure 2. Problem statement.

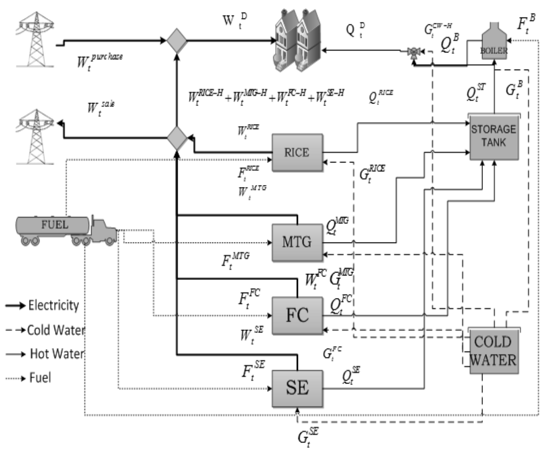


Figure 3. Superstructure for residential CHP systems.

A problem in the design of CHP systems is synchronising the operation of the system with the energy demands, electricity and HWS, this way an appropriate thermal storage device is needed. The energy balance in the thermal ST is stated considering the thermal properties of the involved streams. The convective loss is determined by the area of the ST which defined by the volume of the ST.

$$S_t^{water} = S_{t-1}^{water} + G_t^{RICE} + G_t^{MTG} + G_t^{FC} + G_t^{SE} - G_t^{ST}, \forall t \in T \quad (3)$$

$$S_t^{water}\mathrm{Cp}_t^{\text{W-ST}}T_t^{ST} = S_{t-1}^{water}\mathrm{Cp}_{t-1}^{\text{W-ST}}T_{t-1}^{ST} + G_t^{RICE}\mathrm{Cp}_t^{\text{RICE}}\mathrm{T}_t^{\text{RICE}} + G_t^{MTG}\mathrm{Cp}_t^{\text{MTG}}\mathrm{T}_t^{\text{MTG}} + G_t^{FC}\mathrm{Cp}_t^{FC}\mathrm{T}_t^{\text{FC}} + G_t^{SE}\mathrm{Cp}_t^{SE}\mathrm{T}_t^{\text{SE}} - G_t^{ST}\mathrm{Cp}_t^{\text{ST}}T_t^{ST} - Q_t^{loss}, \quad (4)$$

$$\forall t \in T$$

$$Q_t^{loss} = \mathrm{U}A\left(T_t^{ST} - \mathrm{T}_t^{\text{amb}}\right), \forall t \quad (5)$$

$$A = \frac{1}{6}\left(S^{MAX-ST}\right)^{2/3} \quad (6)$$

The HWS required in the housing complex is determined by the hourly demand of users, which is covered by water from the ST, water from the B and regulated by cold water which is at the ambient temperature. The supply temperature of HWS is fixed in 50 °C.

$$\mathrm{G}_t^{\mathrm{D}} = G_t^{ST} + G_t^{B} + G_t^{CW-H}, \forall t \in T \quad (7)$$

$$\mathrm{G}_t^{\mathrm{D}}\mathrm{Cp}_t^{\mathrm{D}}\mathrm{T}_t^{\mathrm{D}} = G_t^{ST}\mathrm{Cp}_t^{\text{W-ST}}T_t^{ST} + G_t^{B}\mathrm{Cp}_t^{\text{W-B}}\mathrm{T}_t^{\mathrm{B}} + G_t^{CW-H}\mathrm{Cp}_t^{\mathrm{CW}}\mathrm{T}_t^{\text{amb}}, \forall t \in T \quad (8)$$

The parameters that define the operation of the CHP equipment are the thermal Eq(10) and electrical Eq(11) efficiencies. The partial load (PL), see Eq(12), represents the ratio between electricity production in a given period and the production capacity of the unit under full load. None unit can operate below a value of PL because of their design conditions. These conditions are defined for each CHP technology as follows:

$$\eta^{\mathrm{W}} = \frac{W_t}{F_t}, \forall t \in T \quad (9)$$

$$\eta^{\mathrm{Q}} = \frac{Q_t}{F_t}, \forall t \in T \quad (10)$$

$$PL_t = \frac{W_t}{W^{MAX}}, \forall t \in T \quad (11)$$

$$\mathrm{PL}^{\mathrm{MIN}}y \le PL_t \le \mathrm{PL}^{\mathrm{MAX}}y \quad (12)$$

$$Q_t = G_t\mathrm{Cp}_t\left(\mathrm{T}_t - \mathrm{T}_t^{\text{amb}}\right), \forall t \in T \quad (13)$$

The boiler (B) is the auxiliary unit, Eq(14) states the energy balance to cover the heat demand.

$$\eta^{\mathrm{B}}F_t^{B} = G_t^{B}\mathrm{Cp}_t^{B}\left(\mathrm{T}_t^{\mathrm{B}} - \mathrm{T}_t^{\text{amb}}\right), \forall t \in T \quad (14)$$

The operating costs of the proposed system are defined by the annual consumption of fuel and water multiplied by the unit cost of the resource used by each technology.

$$CostOp^{Fuel} = \mathrm{H_D}\left(\sum_t \mathrm{UCF^B}F_t^{B} + \sum_t \mathrm{UCF^{RICE}}F_t^{RICE} + \sum_t \mathrm{UCF^{MTG}}F_t^{MTG} + \sum_t \mathrm{UCF}^{FC}F_t^{FC} + \sum_t \mathrm{UCF}^{SE}F_t^{SE}\right) \quad (15)$$

$$CostOp^{CW} = \mathrm{H_D}\left(\sum_t \mathrm{UCCW^H}G_t^{CW-H} + \sum_t \mathrm{UCCW^B}G_t^{B} + \sum_t \mathrm{UCCW^{RICE}}G_t^{RICE} + \sum_t \mathrm{UCCW^{MTG}}G_t^{MTG} + \sum_t \mathrm{UCCW}^{FC}G_t^{FC} + \sum_t \mathrm{UCCW}^{SE}G_t^{SE}\right) \quad (16)$$

Although the proposed superstructure indicates the presence of all units, the existence of the units is defined by the binary variables (y) that indicate which technologies are needed in the optimal solution. The sizing is defined by the maximum available unit capacity in the market and the maximum value reached by the system operating at full load, which is modelled for B by Eq(17), for ST by Eq(18) and for each CHP technology by Eq(19). These values determine the capital cost.

$$G^{MAX-B} \le \mathrm{G}^{\text{UB-B}}y^{B} \quad (17)$$

$$S^{MAX-ST} \le \mathrm{S}^{\text{UB-ST}}y^{ST} \quad (18)$$

$$W^{MAX} \le \mathrm{W}^{\mathrm{UB}}y \quad (19)$$

The cost of power purchase is the economic value of the energy taken from the electrical company grid. The sale of electric power to the grid of the electrical company is an income from an external client to the system that consists of the total electricity production of each unit sold to the grid. The electric power sold is multiplied by the unit price for the electricity and the operating time per year. The sale of energy to users of the housing complex is determined by the sum of the electric power and thermal energy produced by the CHP system multiplied by the corresponding unit prices.

$$W_t^{sale} = W_t^{MTG-sale} + W_t^{RICE-sale} + W_t^{FC-sale} + W_t^{SE-sale} \quad (20)$$

$$SalePower = \mathrm{H_D}\left[\sum_t \mathrm{VCS^W} W_t^{sale}\right] \tag{21}$$

$$Powersale^{CHP-H} = \mathrm{H_D}\mathrm{UCP^W}\left(\sum_t W_t^{RICE-H} + \sum_t W_t^{MTG-H} + + \sum_t W_t^{FC-H} + \sum_t W_t^{SE-H}\right) \tag{22}$$

$$Heat^{Sale-H} = \mathrm{H_D}\mathrm{UCP^H}\left(\sum_t Q_t^{RICE} + \sum_t Q_t^{MTG} + \sum_t Q_t^{FC} + \sum_t Q_t^{SE} + \eta^{\mathrm{B}}\sum_t F^B\right) \tag{23}$$

The economic objective (TAC) function consists of capital costs, maintenance, operation and purchase - sale of electricity to the grid and energy sales to the housing complex. The environmental objective function is determined by the sum of the GHGE produced by the CHP system, the grid and the boiler.

$$TAC = CostCap^T + CostOp^T + CostO\,\&\,M^T + CostPowerPurch - Powersale^T - Heat^{Sale-H} \tag{24}$$

$$GHGE^T = GHGE^B + GHGE^{CFE} + GHGE^{CHP} \tag{25}$$

4. Case study

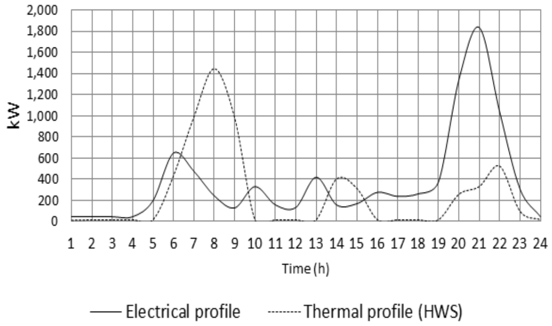
A residential zone located near to a mountainous zone which consists of 1,440 homes was considered as case study. Figures 4 and 5 show the profiles for demanded energy and hourly averaged annual temperature associated to the locations using the considered system. The considered technical and operating parameters in the case studies are presented in Table 1.

5. Results

The set of Pareto solutions that compensate the economic and environmental objectives are shown in Figure 6. It should be noticed that the solutions above the curve are suboptimal solutions, whereas the solutions below this curve are infeasible solutions. This way, any point of this Figure 6 corresponds to an optimal solution. The operative scheme for each technology and scenario is shown in Figure 7. Although the ideal is the use of scenarios with unique technology, as obtained for scenarios A, B and E, they present an operational scheme with quite marked variations throughout the day. Schemes based on a combination of technologies, such as those obtained in solutions C and D, show a more stable behaviour. Schemes C and D have stable performance with better results, from the economic and environmental points of view, and long term system performance because the operating changes impact the efficiency of the system (Ghadimi et al., 2014).

Table 1: Technical parameters.

Parameter	RICE	MTG	FC	SE	Boiler	Thermal storage tank
Electrical efficiency (η^W - %)	37.25	26	38	30		
Thermal efficiency (η^Q - %)	47.5	47.5	50	60	70	
Maximum size (W^{UB}, G^{UB} and S^{UB} – kW, L/h and m^3)	15,800	12,500	2,000	1,500	15,000	200
Minimum partial load (PL^{MIN} - %)	35	80	50	42.5		
Water temperature at the outlet (T - °C)	100	100	100	100	70	
Unitary fuel cost (UFC - $/kWh)	0.02	0.02	0.02	0.02	0.04	
Unitary cost of cold water (UCCW - $/L)	0.001	0.001	0.001	0.001	0.001	
Fixed cost (FC - $)	100	100	100	100	100	120
Variable cost (VC - $)	400	450	2500	450	70	125
Scale factor (β)	1	1	1	1	1	1
Annualisation factor (k_F)	0.23	0.23	0.23	0.23	0.23	0.23
Maintenance cost (UCOM - $/kWh)	0.015	0.065	0.015	0.015	0.156	



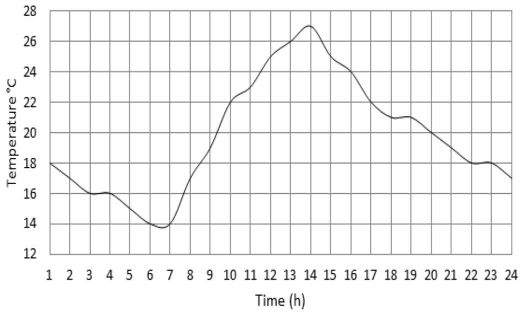
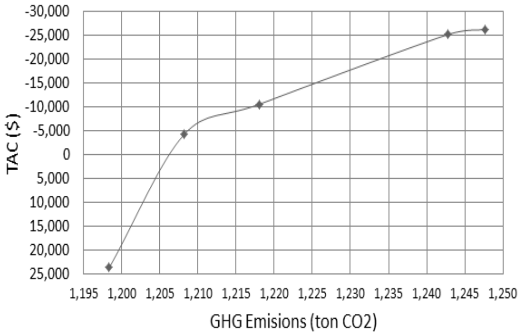


Figure 4. Energy demand profiles of housing complex.

Figure 5. Average hourly ambient temperature.



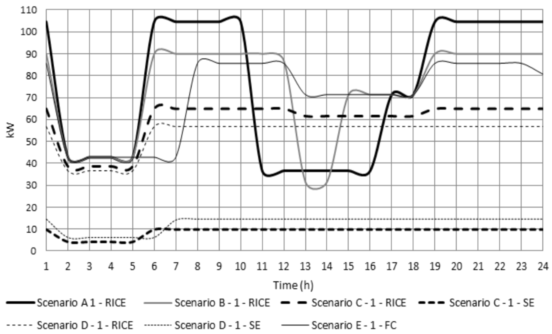


Figure 6. Pareto solutions.

Figure 7. Average hourly ambient temperature.

Table 2: Optimal solutions analysis.

	Conventional	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E
TAC ($)	506,600	- 26,187	- 25,120	- 10,560	- 4,288	23,721
GHGE (annual t CO_2)	1,644.0	1,247.7	1,242.7	1,218.1	1,208.2	1,198.3
Technologies	Boiler	RICE	RICE	RICE SE	RICE SE	FC
Technologies Sizing (kW)	9,544 L/h	105	90	65 10	57 15	86
Volume of thermal storage tank (m^3)		11.7	12.2	12.6	12.8	13.5
Annualized capital cost ($)	153,690	10,012	9,133	7,422	7,175	49,680
Annual maintenance cost ($)	133,100	9,796	9,727	9,009	8,705	9,351
Annual fuel cost ($)	48,755	35,064	34,817	33,253	32,613	32,810
Value of power sold to the grid ($ annual)	0	0	0	0	0	0
Value of power sent to homes ($ annual)	0	117,550	116,720	108,100	104,450	112,210
Value of energy bought to the grid ($ annual)	281,360	163,810	164,640	173,260	176,900	169,150
Value of heat sold to homes ($ annual)	132,880	149,900	148,840	147,980	147,830	147,640

The details of each solution obtained are shown in Table 2. The produced energy in the CHP system is directly related to the emissions from fuel consumption. From an economic point of view, scenarios B, C and D have a lower capital investment, which represents a lower initial cost to implement the system and its acquisition. The technology that achieves fewer GHG emissions is the fuel cell in this case the capital costs considerably increase the total annual cost compared with other technologies. In all cases, the solutions using CHP technologies are better than the conventional generation, both in economic (TAC) and environmental (GHGE) points of view. The scenarios A, B, C and D represent an income by implementing CHP technologies to meet the energy demand of the residential complex; this is shown in the negative value of the TAC. In all scenarios, it is observed that there is no sale of energy to the grid of the electric power company; this is due to the price parities purchase - selling to the local energy market. It should be noted that most of the integrated solutions represent economic gains, and the GHGE also are reduced with respect to the conventional solution. The solution with the minimum cost (Scenario A), which presents a financial income, is 190 % cheaper than the solution with the minimum GHGE (Scenario E), which presents an economic cost, but the emissions increase 3.96 % from Scenario E to Scenario A.

6. Conclusions

This paper has presented a new superstructure for the optimal design of domestic CHP systems involving the optimal selection of multiple technologies to satisfy electricity and hot water demands. Based on the superstructure presented, a mathematical programming formulation has been developed for the simultaneous minimisation of the TAC and the associated GHGE. A proper solution approach based on the epsilon constraint method has been implemented to show compensated solutions. The proposed model also considers the interactions with the grid of the electrical company, possibilities of implementing auxiliary thermal systems, the sizing of equipment and thermal storage system, and the operative scheme of the prime mover system. The design is done by taking into account local weather conditions, the hourly variation of the energy demand in different geographic locations with different houses and temperature variations throughout the day. Also, the results have shown that the solutions that involve the CHP are better from the economic point of view with respect to the conventional solutions, and these solutions are also competitive from the environmental point of view. The solutions that involve the combination of technologies show a more stable behaviour, and compensate in a better way the considered objectives.
No numerical complications were observed during the solution of the case studies and finally the proposed approach is general and this can be applied to different case studies.

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