

Optimal Cogeneration Technology Selection for Residential and Commercial Buildings

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ABSTRACT

The energy requirements for most residential and commercial buildings show both annual or seasonal, and daily variations. In addition, depending on the electrical rate schedule and location, there can be time-of-use variation in the prices a customer pays for electricity. Such facts make it harder to select (a) the best-fit equipment for the host building and (b) the best operating strategy for the selected equipment. This article proposes a mixed integer programming (MILP) model to help decide the optimal make up of a prospect cogeneration system as applied to a residential complex located in Zaragoza, Spain. The model considers the possibility of whether to use or not a set of proposed alternative technologies within a previously defined superstructure. Such superstructure is defined through binary variables and takes into account the optimal operation of all feasible combinations of technologies throughout a typical meteorological year. The model's objective function is to minimize the total annual cost, which includes the cost of invested capital, subject to technical, economic and legal constraints.

INTRODUCTION

The energy consumption in residential and commercial buildings in developed countries continues to grow. Thus, central plants to provide energy services (utilities) for new and existing urban complexes and larger buildings present a significant opportunity for cogeneration systems. The advantages include greater overall energy efficiency, improved

quality of energy supply and, above all, lower cost for the building utility services. From a system performance perspective, there are three essential factors which favor installing integrated energy supply systems: (i) the correct combination of certain types of technologies reduces the primary energy input and the fuel bill between 30 to 60%; (ii) natural gas utilization as fuel allows the introduction of new technologies such as gas engines, low temperature and condensing boilers, gas engine driven chillers and gas fired absorption chillers; and (iii) the installation of engine generators and energy efficient gas-fired refrigeration technologies reduce electrical demand during peak cooling times. Next, from a market economics view point, electrical deregulation has in general contributed to an increase of electricity prices during the periods of higher electrical demand during cooling seasons.

The commercial availability of a large variety of energy conversion technologies and the need to integrate them in the most energy efficient way make the process of selecting the best combination of such technologies a difficult and tedious task (Serra et al, 2009). In addition, for a given site, there are often several technically feasible combinations. In the industrial sector, this problem has been dealt with successfully (Biegler et al, 1997) using MILP techniques; with the advantage that most industrial facilities show less variation in energy demand than their residential or commercial counterparts. The mathematical foundation of applied MILP can be found in Nemhauser and Wolsey (1999). Horii and Yokoyama et al (1987, 1994, 2002) and Lozano et al (2001, 2009, 2010) have applied such techniques to cogeneration systems design for (a) the selection of the number and size of equipment to be installed and (b) to find the optimal way of operating the equipment.

This article proposes an optimization model for the synthesis of energy supply systems in buildings, based on the comparison of the economic annual balances for all feasible plant configurations contained in a superstructure. The model was applied to the design of a cogeneration system for a residential complex in Zaragoza, Spain. The effects of financial market conditions in the optimal structure of the system are analyzed.

ENERGY SYSTEM MATH MODEL

The basis for this research is the superstructure shown in Figure 1 and the fundamental math model implied by Table 1. Figure 1 depicts

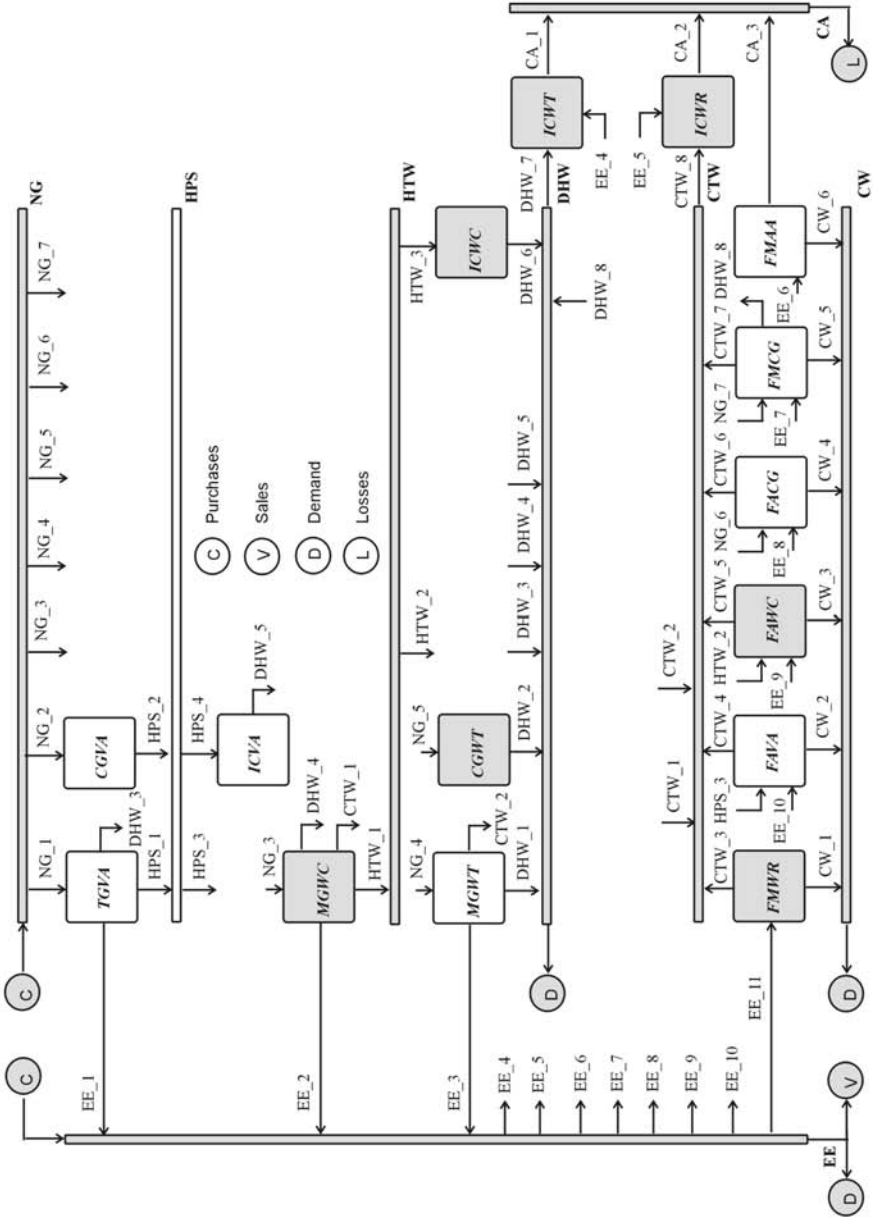


Figure 1. Superstructure of the Energy Supply System

the superstructure of the energy supply system considered in this study, showing the proposed technologies that can be selected, the energy utilities that can be present, and the interactions between technologies and utilities.

The algebraic model in Table 1 is expressed in terms of the *technical coefficient of production* or *TCP*, which are defined as follows. The rows indicate potential energy conversion technologies and the columns primary and/or demanded energy utilities (such as electrical energy EE, natural gas NG, domestic hot water DHW for sanitary and heating services, and chilled water CW for air conditioning). We also consider other energy utilities that may be needed to produce the previously defined demanded utilities. These include high pressure steam HPS and high temperature hot water HTW. In addition, cooling tower water CTW and air cooling AC are utilities used to dissipate heat to the environment. The TCP highlighted (boldface) **1** shows the flow that defines the capacity of the technology. A positive technical coefficient indicates a produced utility and a negative one a consumed utility. For instance, using a MGWC technology (see technology definitions at the bottom of Table 1) we have electrical energy (EE) as its main output, and its TCP is $+1$. Next, to produce x MW of electricity (EE), MGWC needs to consume $2.6x$ MW of natural gas (NG), recover $1x$ MW of high temperature hot water (HTW) and $0.1x$ MW of domestic hot water (DHW), and reject $0.1x$ MW of heat to the environment through the cooling tower water (CTW).

DEMAND AND ECONOMIC DATA

The annual demand data are characterized by using the energy consumption of a typical day for each of 12 months of the year. Each day is divided in 12 two-hour periods. This results in a total of 144 periods, each with a set of different heating, cooling and power demands. Table 2 shows the demands for a residential complex building in Zaragoza for three significant months: December (heating \uparrow), April (no heating and no cooling) and August (cooling \uparrow). The data for the rest of the months are available from the authors.

The technology investment cost is given in Table 1 expressed as a linear function of capacity installed. Non-energy operating costs are only considered for cooling towers. The price of natural gas is $ccNG = \$0.015/kWh$. The prices for purchased and sold back electricity dur-

Table 1. Technical Coefficients of Production and Technology Data Matrix

	Technical Coefficients of Production								CY	cx	co
	NG	HPS	HTW	DHW	CTW	AC	CW	EE	10 ³ \$	\$/kW	\$/kWh
TGVA	-3.3	+1.4	—	+0.3	—	—	—	+I	700	700	0
MGWC	-2.6	—	+1.1	+0.1	+0.1	—	—	+I	200	600	0
MGWT	-2.6	—	—	+1.2	+0.1	—	—	+I	200	600	0
CGVA	-1.2	+I	—	—	—	—	—	—	30	40	0
CGWT	-1.1	—	—	+I	—	—	—	—	20	30	0
FMWR	—	—	—	—	+1.17	—	+I	-0.17	30	50	0
FMAA	—	—	—	—	—	+1.25	+I	-0.25	20	80	0
FMCG	-0.5	—	—	+0.2	+1.25	—	+I	-0.001	60	120	0
FACG	-0.85	—	—	—	+1.7	—	+I	-0.01	60	100	0
FAVA	—	-0.7	—	—	+1.7	—	+I	-0.005	50	100	0
FAWC	—	—	-1.6	—	+2.6	—	+I	-0.01	40	120	0
ICVA	—	-1	—	+I	—	—	—	—	5	5	0
ICWC	—	—	1	+I	—	—	—	—	5	5	0
ICWT	—	—	—	-I	—	+1	—	-0.03	5	25	0
ICWR	—	—	—	—	-I	+1	—	-0.02	10	20	0.001

Nomenclature:

TGVA: Gas Turbine + Heat recovery boiler for HPS and DHW

MGWC: Gas Engines + Heat recovery for HTW and DHW

MGWT: Gas Engine + Heat recovery for DHW

CGVA: Steam boiler

CGWT: DHW boiler or heater

FMWR: Electrically driven chiller with water cooled condenser

FMAA: Electrically driven chiller with air cooled condenser

FMCG: Gas engine driven chiller

FACG: Natural gas fired double-effect absorption chiller

FAVA: Steam heated double-effect absorption chiller

FAWC: Hot temperature water heated single-effect absorption chiller

ICVA: Heat exchanger, HPS → DHW

ICWC: Heat exchanger, HTW → DHW

ICWT: Air cooled radiator to reject DHW surplus heat

ICWR: Cooling tower to reject condensing water heat

ing flat-demand hours are $ccEE = \$0.050$ and $cvEE = \$0.045$ per kWh, respectively. Such prices are multiplied by 1.7 during peak-demand hours (Oct-Mar: 18:00-22:00, Apr-Sep: 10:00-14:00); and by 0.57 during low-demand hours (Jan-Dec: 00:00-08:00). Note flat-demand hours are all those which are not peak or low demand hours. These data are only approximate.

MILP MODEL FOR TECHNOLOGY SELECTION

The underlying MILP model is shown in the next frame. To solve it, we have used the mathematical programming software LINGO (2010).

The Energy Balance equation has been generally defined as follows: C represents purchases (NG, EE), D demand (DHW, CW, EE), L losses to the surroundings (CA) and V sales (EE). There is an additional condition (whenever gas engines or turbines are installed) that the equivalent electrical efficiency be larger than a minimum (55% for gas engines and 59% for gas turbines). See the definition of equivalent electrical efficiency and related efficiencies in Lozano et al (2010) and Lozano and Ramos (2010).

Minimize $CA[\$/y] = fa[y^{-1}] \sum_i CI_i[\$] + \sum_k NH_k[h/y] CH_k[\$/h]$

Where: *CA*: Total annual cost
 fa: Capital amortization factor
 CI_i: Cost of investment or first cost of technology i
 NH_k: Number of hours in period k
 CH_k: Cost of plant operation in each period k

Subject to

- The power Π installed for technology i: $P_i^{\min} y_i \leq \Pi_i [kW] \leq P_i^{\max} y_i$ with $y_i \in \{0,1\}$
- The investment cost for technology i: $CI_i = CY_i[\$] y_i + cx_i[\$/kW] \Pi_i$
- For each period k:
 - Production limit for technology i: $P_{i,k} \leq \Pi_i$ (*P produced* \leq *Π installed*)
 - Operating cost for technology i: $CO_{i,k}[\$/h] = co_i[\$/kWh] P_{i,k}$
 - Flow - Product relationship for each utility j: $F_{i,j,k} = TCP_{i,j} P_{i,k}$
 - Energy balance for each utility j: $C_{j,k} + \sum_i F_{i,j,k} - D_{j,k} - L_{j,k} - V_{j,k} = 0$

Cost account (purchases C, rejection L, sales V and operating cost CO):

$$CH_k = \sum_j cc_j[\$/kWh] C_{j,k} - cl_j[\$/kWh] L_{j,k} - cv_j[\$/kWh] V_{j,k} + \sum_i CO_{i,k}$$

ANALYSIS OF RESULTS

One of the most remarkable findings of this research is the dependency between the optimal plant configuration and the capital recovery factor fa . Logically, a lower cost of capital favors more efficient technologies which tend to have higher installed costs. We obtained the following optimal solutions with the MILP model described above.

With $fa = 0.2 \text{ y}^{-1}$ the optimal solution corresponds to install gas fired hot water boilers ($\Pi_{CGWT} = 2780 \text{ kW}$) and mechanical chillers ($\Pi_{FMWR} = 2320 \text{ kW}$), as shown in the next diagram (Figure 2).

With $fa = 0.15 \text{ y}^{-1}$ we must add gas fired engines with DHW heat recovery ($\Pi_{MGWT} = 610 \text{ kW}$, $\Pi_{CGWT} = 2050 \text{ kW}$, and $\Pi_{FMWR} = 2320 \text{ kW}$), as shown in the next diagram (Figure 3).

And **with $fa = 0.1 \text{ y}^{-1}$** the engines are upgraded to generate high temperature hot water; thus hot-water heated absorption chillers become feasible ($\Pi_{MGWC} = 1470 \text{ kW}$, $\Pi_{CGWT} = 1010 \text{ kW}$, $\Pi_{FMWR} = 1340 \text{ kW}$, and $\Pi_{FAWC} = 980 \text{ kW}$), as shown in the next diagram (Figure 4).

In all cases we require heat exchangers and/or cooling towers to dissipate energy to the environment (with $fa = 0.1 \text{ y}^{-1}$: $\Pi_{ICWC} = 1620 \text{ kW}$, $\Pi_{ICWR} = 4260 \text{ kW}$, and $\Pi_{ICWT} = 1590 \text{ kW}$).

The following steps of the study will lead us to select the number of and size of the equipment for each technology to be installed. A complete and simple example of all these steps is given by Lozano et al (2001, 2009, 2010).

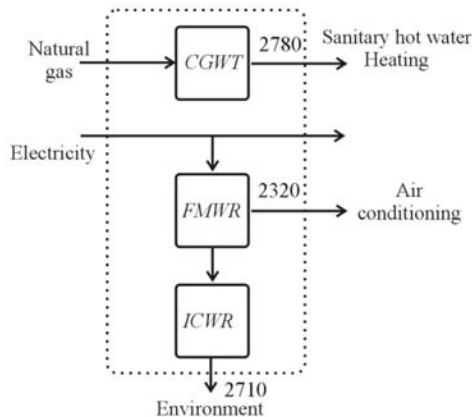


Figure 2. Gas Fired Hot Water Boilers and Mechanical Chillers

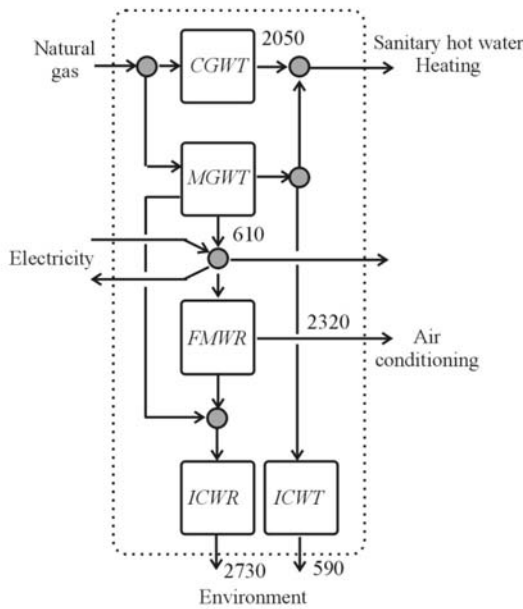


Figure 3. Gas Fired Engines with Heat Recovery

Table 2 shows the hour by hour operation of three representative months of the plant configuration obtained with a capital recovery factor $fa = 0.1 \text{ y}^{-1}$. The operating strategies for such months are given next.

In December, the Gas Engine (MGWC) is subject to part loads in the electrical power off –peak or valley hours, adjusting the heat output to the heat demand. During on peak and flat hours, the engine works at top or high loads, respectively. Thus, any excess heat is wasted. And a gas boiler (CGWT) makes up any heat shortage from the engine.

In April, the operation highlights are similar to the December ones. However, since space heating demand is lower, the engine operates at part load and the boiler is off.

In August the gas engine (MGWC) operates at part load during off-peak or valley hours, adjusting the heat output to the sanitary hot water demand. During on peak and flat hours, the engine works at top or high loads, respectively. The cogenerated heat is used in an absorption chiller (FAWC). If there is not enough absorption cooling capacity a mechanical chiller is run (FMWR).

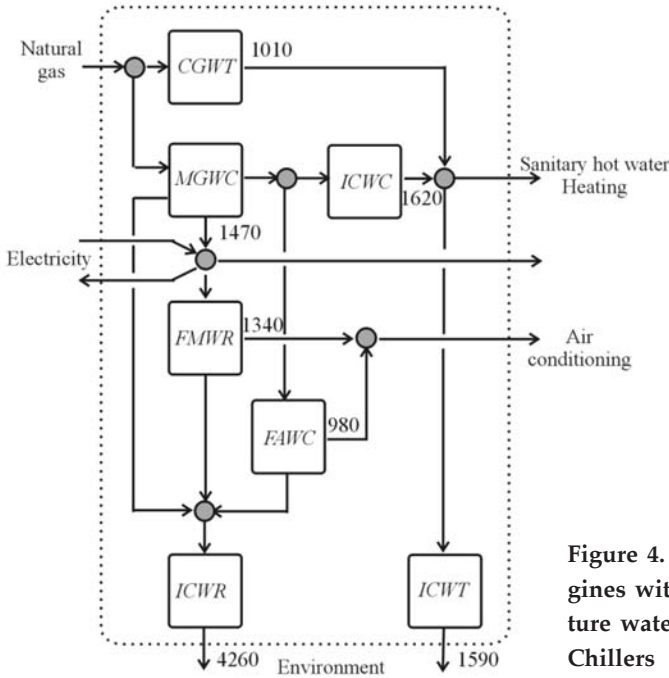


Figure 4. Gas Fired Engines with high temperature water for Absorption Chillers

Table 2. Demands, purchases, sales and production for three months ($f_a = 0,1 \text{ y}^{-1}$)

Period	D_{DHW}	D_{CW}	D_{EE}	C_{NG}	C_{EE}	V_{EE}	P_{MGWC}	P_{CGWT}	P_{FMWR}	P_{FAWC}	P_{ICWC}
December											
0 → 2	60	-	120	130	70	0	50	0	-	-	55
2 → 4	640	-	100	1387	0	432	533	0	-	-	586
4 → 6	1220	-	100	2643	0	915	1017	0	-	-	1118
6 → 8	1380	-	120	2990	0	1028	1150	0	-	-	1265
8 → 10	2440	-	180	4570	0	1290	1473	672	-	-	1621
10 → 12	1320	-	260	3831	0	1197	1473	0	-	-	1621
12 → 14	800	-	240	3831	0	1201	1473	0	-	-	1621
14 → 16	700	-	180	3831	0	1258	1473	0	-	-	1621
16 → 18	620	-	220	3831	0	1216	1473	0	-	-	1621
18 → 20	1040	-	240	3831	0	1209	1473	0	-	-	1621
20 → 22	1700	-	240	3831	0	1228	1473	0	-	-	1621
22 → 24	140	-	180	3744	0	1209	1440	0	-	-	1584

(Cont'd)

Table 2 (continued). Demands, purchases, sales and production for three months ($f_a = 0,1 \text{ y}^{-1}$)

April											
0 → 2	20	-	140	43	123	0	17	-	-	-	18
2 → 4	0	-	100	0	100	0	0	-	-	-	0
4 → 6	100	-	100	217	2	0	83	-	-	-	92
6 → 8	220	-	120	477	0	63	183	-	-	-	202
8 → 10	180	-	180	3831	0	1243	1473	-	-	-	1621
10 → 12	180	-	260	3831	0	1163	1473	-	-	-	1621
12 → 14	300	-	260	3831	0	1166	1473	-	-	-	1621
14 → 16	260	-	200	563	0	16	217	-	-	-	238
16 → 18	100	-	220	3657	0	1136	1407	-	-	-	1547
18 → 20	160	-	260	3787	0	1146	1457	-	-	-	1602
20 → 22	320	-	260	693	0	6	267	-	-	-	293
22 → 24	6	-	180	3571	0	1143	1373	-	-	-	1511
August											
0 → 2	20	0	100	43	84	0	17	-	0	0	18
2 → 4	0	0	80	0	80	0	0	-	0	0	0
4 → 6	80	0	60	173	0	7	67	-	0	0	73
6 → 8	180	40	100	390	0	42	150	-	40	0	165
8 → 10	140	1260	140	3831	0	1214	1473	-	280	980	53
10 → 12	140	1660	180	3831	0	1096	1473	-	680	980	53
12 → 14	240	1960	180	3831	0	1037	1473	-	1005	955	92
14 → 16	200	2320	140	3831	0	1010	1473	-	1340	980	53
16 → 18	80	1800	160	3831	0	1087	1473	-	820	980	53
18 → 20	140	520	180	2106	0	596	810	-	0	520	59
20 → 22	260	280	180	1534	0	391	590	-	0	280	201
22 → 24	60	60	140	3779	0	1259	1453	-	0	60	1503
Nomenclature:											
D_{DHW} : DHW demand for sanitary and heating services (kW)											
D_{CW} : Chilled Water demand for air conditioning (kW)											
D_{EE} : Electricity Demand (kW)											
C_{NG} : Natural Gas consumption (kW)											
C_{EE} : Electricity purchases (kW)											
V_{EE} : Electricity sales (kW)											
P_{MGWC} : Electricity production with gas engines (kW)											
P_{CGWC} : Hot water production with gas fired boilers (kW)											
P_{FMWR} : Chilled water production with mechanical chillers with water cooled condenser (kW)											
P_{FAWC} : Chilled water production with single-effect absorption chillers fired with hot water (kW)											
P_{IAWC} : Heat transferred in HTW - DHW heat exchangers (kW)											

CONCLUDING REMARKS

This article has demonstrated the implementation of a MILP model for selecting the most convenient configuration of the energy supply system for commercial and residential buildings with highly variable—seasonal and daily—heat and power demands. To illustrate the model, this authors use actual demand data from a residential complex in Zaragoza, Spain. The model is able to minimize the total annual cost subject to technical, economic and legal constraints. A remarkable finding is that the capital recovery factor (which depends on interest rate) is the most influential factor in deciding what kind of technology best fits the residential building under study. Further research is warranted to understand the impact of combining cogeneration systems with energy storage alternatives (electrical and thermal) to mitigate the demand variability of commercial and residential buildings and to continue to improve the overall energy system profitability and efficiency, on a life cycle cost basis.

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