



# Integrated design and control of multigeneration systems for building complexes



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## ABSTRACT

Building complexes have demands of electricity, cooling capacity for air conditioning, and sanitary hot water. These demands can be met efficiently using multigeneration systems. The design of a multigeneration system involves three integrated layers of decisions that include technology selection, equipment sizing and operational (control) policy design. In this work we cast this integrated design problem as a multi-objective mixed-integer nonlinear programming problem. The optimization formulation considers internal combustion engines, fuel cells, microturbines, Stirling engines, solar water heaters, and absorption chillers as technology options. The formulation also considers the sizing of a storage tank for hot water. Optimal operating policies are considered using daily scenarios of ambient temperature, solar radiation, fuel costs, electricity prices, and energy demands over an entire year. We compute compromise solutions that trade-off total annual costs, greenhouse gas emissions, and water consumptions. The method is demonstrated using real data for a Building complex with 420 households located on the Pacific Coast of Mexico. Our approach finds technologies that provide an optimal compromise between cost, emissions, and water consumption. In particular, we have found designs that reduce water consumption by 75% and emissions by 74% compared to the cost minimization case while increasing total cost by only 10%.

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## 1. Introduction

Building complexes present high demands of electricity, heating, and cooling services. These demands can be covered using sustainable generation and storage technologies [1]. Combined Cooling, Heat and Power (CCHP) systems, which are commonly called multigeneration systems [2], are promising technologies to provide multiple utilities for building complexes, and offer several benefits including high utilization efficiencies and the potential to integrate sustainable primary energy sources. Its implementation, compared with conventional thermoelectric plants, reduces fuel consumption [3], and consequently operational costs [4] and greenhouse gas emissions [5]. Also, due to the size, capacity and operational flexibility of the CCHP units, other technologies for alternative energy can be included as auxiliary equipment

according with local conditions and available resources [6]. These benefits ultimately lead to reduced environmental impact and can foster deployment of decentralized resources at a system level to increase flexibility [7]. The design and control of multigeneration systems for residential use is complicated by several factors. Building electricity and thermal loads follow different and complex daily patterns that are dictated by social behavior and weather. Consequently, these factors cannot be forecasted and coordinated precisely [8] and play a critical role in choosing appropriate CCHP configurations [9]. Local variations of energy market conditions also affect the selection of CCHP configurations. In particular, the interaction with the local power grid influences operational policies and equipment sizing [10]. CCHP design is also complicated by the need to consider multiple conflicting metrics and the need to account for dynamics of storage units [11].

CCHP design studies reported in the literature focus on different aspects of the problem. Most studies do not fully capture variations of demand, weather and market conditions, and thus might miss extreme conditions and/or correlations. In particular, many studies

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use typical day behavior [12], average demands [13], single demand forecasts [14], or sensitivity analysis [15]. Energy integration techniques have also been developed to design CCHP systems [16]. These techniques have focused on economic and energy production issues. Pirkandi et al. [17] presented an analysis considering the exergetic efficiency and the net power output as performance metrics. Askari et al. [18] developed a cost-based analysis for a multigeneration system based on solar technologies. Ebrahimi and Keshavarz [19] addressed the problem of sizing the CCHP system considering the net present value and risk of the investment based on the energy market volatility. Piacentino et al. [20] presented a model for sizing a multigeneration system considering the minimization of net present cost. The selection of optimal CCHP configurations was addressed by Omu et al. [21] using a mixed-integer linear programming (MILP) formulation.

Multigeneration systems have significantly higher efficiencies compared to traditional power plants (efficiencies increase from 45 to 75%). The environmental impact of multigeneration systems, however, is still an important issue [22]. Recently, environmental impact has been considered as an objective in designing CCHP systems. Keirstead et al. [23] studied the impact of the location of CCHP systems on air quality and noise in urban areas. Sadegheih [24] incorporated costs of emissions in CCHP systems. Zhang et al. [25] presented a method based on the life cycle assessment. Wol-sink [26] assessed water consumption of different power generation technologies. Kablouti [27] incorporated water cost as a metric of environmental impact. Using water cost as an environmental metric is, in fact, a common assumption used in the design of energy systems [28]. An important limitation of this approach is that it might not properly value water resources [29].

Multi-objective optimization approaches that account for economic and environmental impacts have also been reported. These studies have focused on determining optimal operational strategies [30], determining the equipment size and operational strategies [31], selecting auxiliary equipment [32], and comparing CCHP systems with conventional power generation systems [33]. The uncertainty of energy demands, ambient conditions, and energy market conditions has also been addressed. These studies focus on supply allocation [34], development of optimal generation schedules [35] and operation of storage systems [36].

This paper presents a comprehensive optimization formulation for determining the optimal design of a CCHP system to provide electricity and thermal utilities for building complexes. The approach selects the prime mover technology and the sizing of auxiliary equipment and of the thermal storage system. For the prime mover we consider several alternatives that include internal combustion engines (ICE), fuel cells (FC), microturbines (MT) and Stirling engines (SE). We also consider a solar water heater as thermal auxiliary equipment and absorption chillers for meeting the cooling load. The formulation also determines power exchanges with the grid of the local utility company and computes optimal operating policies for the storage system. We model the equipment efficiency at partial load and we consider a detailed dynamical model for the thermal storage system. This results in a large-scale and nonconvex mixed-integer nonlinear programming (MINLP) formulation. We implement the optimization problems in GAMS and use the global optimization solver BARON to solve them [37]. Optimal operating policies are considered using daily scenarios based on real data for ambient temperature, solar radiation, fuel costs, electricity prices, and user demands. This approach is preferred over using seasonal historical averages, which may lead to undersized equipment with respect to extreme conditions [38]. We compute Pareto optimal compromise solutions that trade-off total annual costs, greenhouse gas emissions, and water use. The proposed method is demonstrated for a building complex of 420

households located in the Pacific Coast of Mexico. Our approach finds that a solid oxide fuel cell provides an optimal compromise between cost, emissions, and water consumption.

## 2. Problem statement

The problem addressed in this paper is schematically described in Fig. 1, and it can be stated as follows: given the thermal demand profiles associated to hot water for sanitary use (HWS) and cooling load for air conditioning, as well as the power demands of a building complex, the environmental temperature, solar radiation and the prices for fuel and electrical rates, determine the CCHP configuration and daily operational policy that meet the energy demands that simultaneously minimize the total annualized cost, greenhouse gas emissions (GHGE) associated with fuel use, and water consumption. Design decisions include sizing and selection of the prime mover, sizing of the thermal storage system as well as the sizing of an auxiliary thermal system, which consists of a solar collector (SC) to provide the extra hot water needed. Operational policy decisions include the operation of the CCHP unit, level and temperature of the storage, as well as electricity purchases and sales with the local utility company (see Fig. 1).

## 3. Proposed approach

We formulate a superstructure (see Fig. 2), which is a representation of the flowsheet that includes all the configurations of practical interest. The mathematical model of the proposed superstructure is implemented in the algebraic modeling language GAMS [37]. The superstructure model is tied to the grid of the local electrical company and comprises four integrated CCHP technologies (i.e., internal combustion engine-ICE, Stirling engine-SE, microturbine-MTG and fuel cell-FC), an auxiliary solar water heater (SC), an absorption chiller (AC), and a thermal storage tank (ST). The CCHP technologies are used to meet the electricity, chilled water, and hot water demands of the building complex. The produced electricity is sent to the building complex, and the excess of produced electricity is then sent to the grid of the electric company (i.e., when the CCHP system produces surplus energy, this is sold to the local electric company). When the CCHP system produces less electricity than the one required by the building complex, the shortfall is purchased from the local utility company. An insulated tank is used to store hot water generated from the CCHP system in the proposed superstructure, which helps to mitigate the lack of coordination between the hot water and electricity demands. We also consider auxiliary equipment (i.e. a solar collector, SC) for providing extra hot water. The hot water stream obtained from the storage system is mixed with cold water to reach the temperature needed for domestic use and thus large amounts of water can be used if the system is improperly operated. The cold water is generated from an absorption chiller (AC) using excess heat from the CCHP technologies. The optimization formulation must determine the type and size of the CCHP system, the size of the thermal storage tank, the needed auxiliary heating system, and the chiller to meet the hot water and air conditioning demands, as well as the interactions with the local electric company. The formulation trades-off the total annual cost, greenhouse gas emissions, and water consumption.

The proposed model formulation is based on the superstructure shown in Fig. 2, which is a mixed-integer nonlinear programming problem (MINLP). Binary variables are used for determining the existence of the technologies. The behavior of the storage tank and the conditions of partial load are defined by nonlinear expressions. We use the global optimization solver BARON for finding the optimal configuration of the system and the operational policy. The

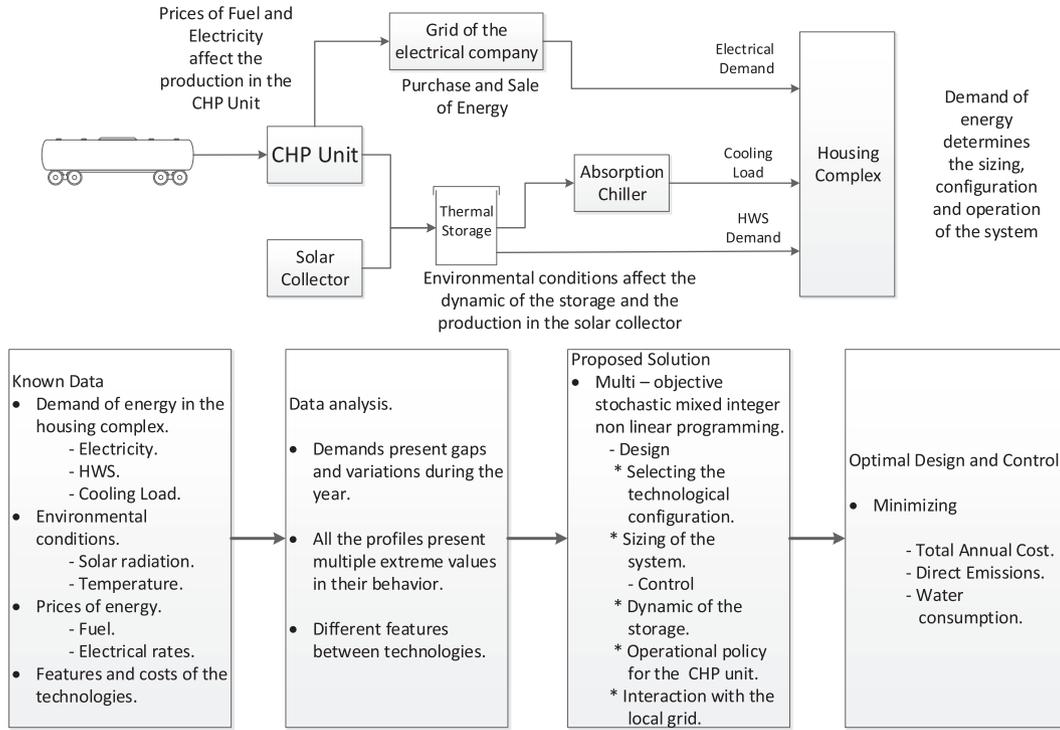


Fig. 1. Problem statement.

proposed mathematical model is explained in the next section.

### 3.1. Supply of electric energy

The electricity demand of the building complex in each time period ( $t$ ) of the day ( $d$ ) ( $W_{d,t}^D$ ) is satisfied by the sum of the energy purchased to the grid ( $W_{d,t}^{purchase}$ ) and energy produced by the CCHP system ( $W_{d,t}^{CHP}$ ) considering each technology separately ( $W_{d,t}^{ICE-H}$ ,  $W_{d,t}^{FC-H}$ ,  $W_{d,t}^{MT-H}$ ,  $W_{d,t}^{SE-H}$ ).

$$W_{d,t}^D = W_{d,t}^{purchase} + W_{d,t}^{ICE-H} + W_{d,t}^{MT-H} + W_{d,t}^{SE-H} + W_{d,t}^{FC-H}, \quad \forall d \in D, \forall t \in T \quad (1)$$

### 3.2. Energy balance of electricity of the CCHP system

The CCHP units are represented using the next set:

$$CHP - Tech = \{ICE, FC, MT, SE\} \quad (2)$$

The electricity produced by each CCHP unit over each time period ( $W_{d,t}^g$ ) can be calculated as the sum of the dispatch of energy for the building complex ( $W_{d,t}^{g-H}$ ) and the energy sold to the grid as surplus production ( $W_{d,t}^{g-GRID}$ ), which is stated as follows:

$$W_{d,t}^g = W_{d,t}^{g-H} + W_{d,t}^{g-GRID}, \quad \forall t \in T, \forall d \in D, \forall g \in CHP - Tech \quad (3)$$

This interaction with the utility company allows obtaining incomes from the sale of power to an external client and also to smooth the gaps between the demands for electricity and heat [39].

### 3.3. Thermal storage system

A common problem in the control and design of CCHP systems is the synchronization of the system with energy demands that follow different patterns (electricity and hot water). Because of this, a

thermal storage device is needed. In the storage tank the levels of stored water and the temperature are dynamic conditions [40]. They are determined by the inlets of hot water, which are provided by the CCHP system and the solar collector, and the outlets, which are defined by the water sent to the building complex, the absorption chiller and the convective losses. Equation (4) considers the operative and initial conditions of the proposed superstructure, and it is a discretized expression for the mass balances of the storage of hot water. The level of hot water stored in the tank over the time period  $t$  and day  $d$  ( $V_{d,t}^{ST}$ ) is the result of the addition of hot water stored over the time period  $t - 1$  plus the water sent to the tank from the CCHP system and the solar collector ( $G_{d,t}^{ICE}, G_{d,t}^{MT}, G_{d,t}^{FC}, G_{d,t}^{SE}, G_{d,t}^{SC}$ ) minus the water sent to meet the demand of the costumers ( $G_{d,t}^{ST}$ ) and the hot water sent to the chiller ( $G_{d,t}^{ST-AC}$ ).

$$\rho^{water} (V_{d,t}^{ST} - V_{d,t-1}^{ST}) = G_{d,t}^{ICE} + G_{d,t}^{MT} + G_{d,t}^{FC} + G_{d,t}^{SE} + G_{d,t}^{SC} - G_{d,t}^{ST} - G_{d,t}^{ST-AC}, \quad \forall t \in T, \forall d \in D, t > 1 \quad (4)$$

Similarly, the energy balance in the thermal storage tank is stated using the heat capacities and temperatures for the involved streams. It is important to note that the water temperature inside the thermal storage tank is a decision variable ( $T_{d,t}^{ST}$ ), and the energy balance is applied to all time periods:

$$\rho^{water} C_p^{water-ST} (V_{d,t}^{ST} T_{d,t}^{ST} - V_{d,t-1}^{ST} T_{d,t-1}^{ST}) = G_{d,t}^{ICE} C_p^{ICE-T^{ICE}} + G_{d,t}^{MT} C_p^{MT-T^{MT}} + G_{d,t}^{FC} C_p^{FC-T^{FC}} + G_{d,t}^{SE} C_p^{SE-T^{SE}} + G_{d,t}^{SC} C_p^{SC-T^{SC}} - G_{d,t}^{ST} C_p^{ST-T^{ST}} - G_{d,t}^{ST-AC} C_p^{ST-AC-T^{ST-AC}} - Q_{d,t}^{loss} \quad \forall t \in T, \forall d \in D, t > 1 \quad (5)$$

The convective loss ( $Q_{d,t}^{loss}$ ) is a function of the ambient

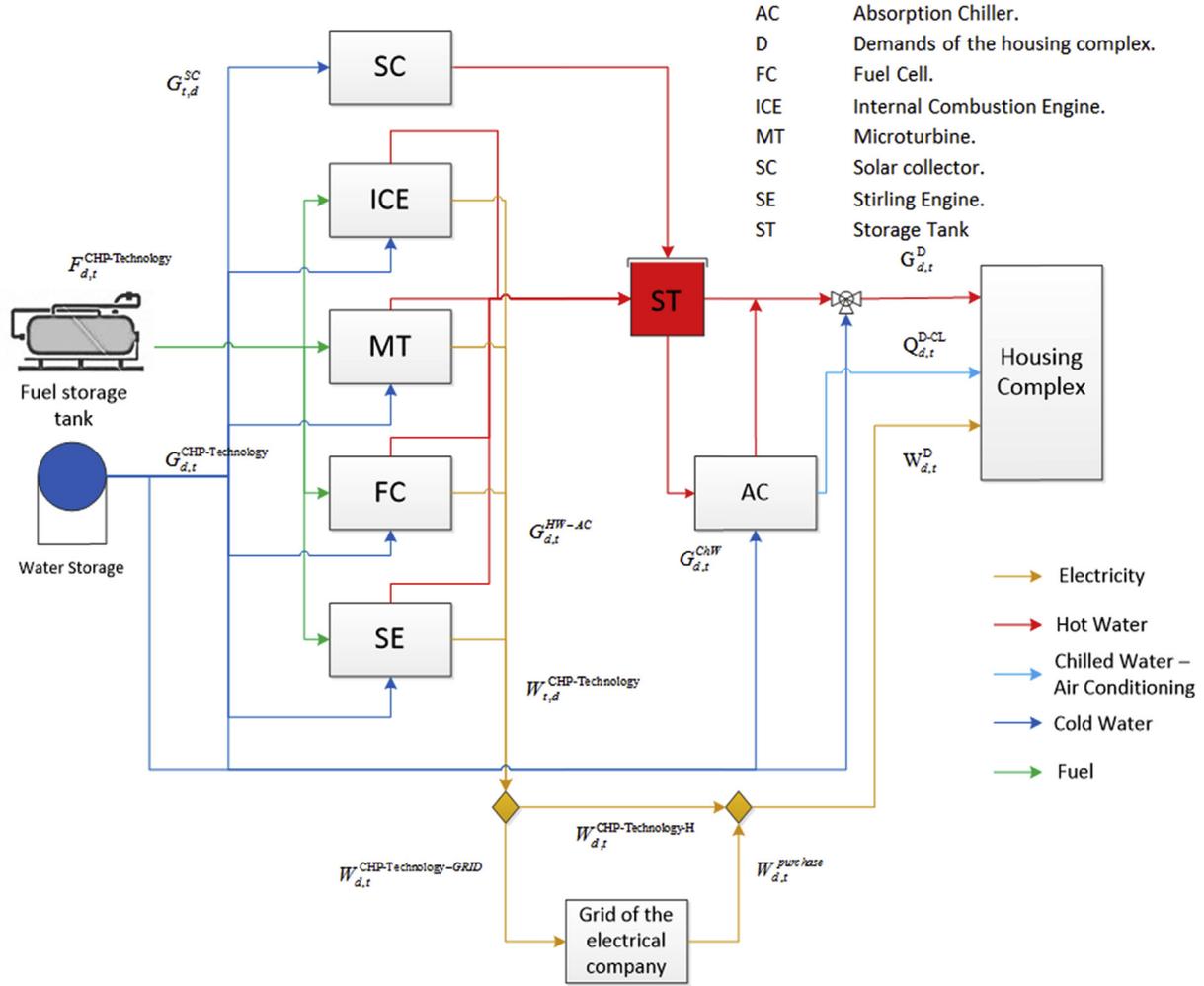


Fig. 2. Proposed superstructure.

temperature ( $T_{d,t}^{\text{amb}}$ ) (which varies through the day and are input data) and the area of the storage tank ( $A^{ST}$ ). The area and volume ( $V^{MAX-ST}$ ) of the storage tank are decision variables.  $U$  is the overall heat transfer coefficient for the storage tank, which is a constant in the optimization formulation determined from the type of construction. Thus, the convective losses are calculated as follows:

$$Q_{d,t}^{\text{loss}} = UA^{ST} (T_{d,t}^{ST} - T_{d,t}^{\text{amb}}), \forall t, \forall d \quad (6)$$

$$A^{ST} = 6(V^{MAX-ST})^{2/3} \quad (7)$$

Thermal storage has been set above 70 °C to prevent the biological growth of *Legionella* [41]:

$$T_{d,t}^{ST} \geq 70^\circ\text{C} \quad (8)$$

The thermal storage tanks are closed containers and the vent pipes are installed for preventing accumulations of pressure. Due to the operating conditions of domestic thermal storage tanks, pressure build up and water losses due to evaporation are negligible [40].

This work considers convective losses in the storage tank and does not capture losses in the hot water distribution network.

Such a setting is significantly more complex because one must capture geometric features of pipelines, transport equations, and pumping effects [42]. We leave this topic as part of future work.

#### 3.4. Balance for hot water supply

The hot water required for sanitary use is determined by the hourly demand of users ( $G_{d,t}^D$ ). It is covered by water from the thermal storage tank ( $G_{d,t}^{ST}$ ). This water is regulated by cold water ( $G_{d,t}^{CW-H}$ ), which is at ambient temperature ( $T_{d,t}^{\text{amb}}$ ). The supply temperature, for comfort and safety issues, is sent at 50 °C [43]. The hot water balance is stated as follows:

$$G_{d,t}^D = G_{d,t}^{ST} + G_{d,t}^{CW-H}, \forall t \in T, \forall d \in D \quad (9)$$

$$G_{d,t}^D Cp_{d,t}^D T^D = G_{d,t}^{ST} Cp_{d,t}^{W-ST} T_{d,t}^{ST} + G_{d,t}^{CW} Cp_{d,t}^{CW} T_{d,t}^{\text{amb}}, \forall t \in T, \forall d \in D \quad (10)$$

#### 3.5. Balance for the CCHP system

The main parameters that define the operation of the CHP system are the thermal ( $\eta^Q$ ) and electrical ( $\eta^W$ ) efficiencies. Both represent the relationship between the products, either electricity

( $W$ ) and heat ( $Q$ ), and fuel required to produce them ( $F$ ) in energy units. The partial load ( $PL$ ) represents the ratio between electricity production in a given period and the production capacity of the unit under full load ( $W^{MAX}$ ). We assume that no unit can operate below a certain value of partial load ( $PL^{\ell-MIN}$ ) because of their design conditions [38]. This condition is constrained in relationships (13) and (14), which affects the design efficiency of the CCHP unit ( $\eta_0^{W^\ell}$ ). The variation of the efficiency in the CHP unit, due to the partial load, is captured by Equation (15) [44]. The heat transfer for each CCHP unit is defined by Equation (16) for the different technologies. In these equations,  $y^\ell$  is a binary variable used to determine the existence or not of a given CCHP unit (this can be ICE, MT, FC and SE).

$$\eta_t^{W^\ell} = \frac{W_t^\ell}{F_t^\ell}, \forall t \in T, \forall \ell \in \text{CHP} - \text{Tech} \quad (11)$$

$$\eta_t^{Q^\ell} = \frac{Q_t^\ell}{F_t^\ell}, \forall t \in T, \forall \ell \in \text{CHP} - \text{Tech} \quad (12)$$

$$PL_t^\ell = \frac{W_t^\ell}{W_t^{MAX-\ell}}, \forall t \in T, \forall \ell \in \text{CHP} - \text{Tech} \quad (13)$$

$$PL^{1-MIN} y^\ell \leq PL_t^\ell \leq PL^{1-MAX} y^\ell, \forall t \in T, \forall \ell \in \text{CHP} - \text{Tech} \quad (14)$$

$$\eta_t^{W^\ell} = \left( -0.000159(PL_t) + 0.024(PL_t) + 0.1904 \right) \eta_0^{W^\ell}, \forall t \in T, \forall \ell \in \text{CHP} - \text{Tech} \quad (15)$$

$$Q_t^\ell = G_{d,t}^\ell C_p^\ell \left( T^\ell - T_{d,t}^{amb} \right), \forall t \in T, \forall d \in D, \forall \ell \in \text{CHP} - \text{Tech} \quad (16)$$

### 3.6. Balance for the solar collector

A solar collector is used as an auxiliary unit to satisfy the domestic heat demand in the building complex. In Equation (17),  $\alpha_{d,t}$  is the solar heat produced accounting for the radiation and climatic conditions. In addition,  $A^{SC}$  is the collector size. The efficiency of the solar collector is variable during the day ( $\eta_{t,d}^{SC}$ ) and it depends on the environmental conditions, especially because of convective losses [45]. This factor is considered in Equations (18) and (19). The output of water from the solar collector ( $Q_{d,t}^{SC}$ ) is presented in Equation (20).

$$Q_{d,t}^{SC-A} = \alpha_{d,t} A^{SC}, \forall t \in T, \forall d \in D \quad (17)$$

$$Q_{t,d}^{SC} = \eta_{t,d}^{SC} Q_{d,t}^{SC-A}, \forall t \in T, \forall d \in D \quad (18)$$

$$\eta_{d,t}^{SC} = \eta_0^{SC} - UA^{SC} \frac{T_{d,t}^{SC} - T_{d,t}^{amb}}{Q_{d,t}^{SC-A}}, \forall t \in T, \forall d \in D \quad (19)$$

$$Q_{d,t}^{SC} = G_{d,t}^{SC} C_p^{SC} \left( T_{d,t}^{SC} - T_{d,t}^{amb} \right), \forall t \in T, \forall d \in D \quad (20)$$

### 3.7. Balance for the absorption chiller

The chilled water demands ( $Q_{d,t}^{D-CL}$ ) are met using an absorption

chiller [46]. This element of the superstructure is modeled using an energy balance and the coefficient of performance ( $COP^{AC}$ ). The heat duty for the absorption chiller is obtained from the thermal storage (see Equation (22)).

$$Q_{d,t}^{D-CL} = COP^{AC} Q_{d,t}^{AC} \quad (21)$$

$$Q_{d,t}^{AC} = G_{d,t}^{ST-AC} C_p^{ST-AC} \left( T^{ST-AC} - T^{W-AC} \right), \forall t \in T, \forall d \in D \quad (22)$$

$$Q_{d,t}^{D-CL} = G_{d,t}^{ChW} C_p^{ChW} \left( T_{d,t}^{amb} - T^{ChW} \right), \forall t \in T, \forall d \in D \quad (23)$$

### 3.8. Sizing the elements of the system

The size of the system is determined by the size of the central units of the CCHP system (i.e., ICE, MT, FC and/or SE), the thermal storage tank (ST), the solar collector (SC) and the absorption chiller (AC), which are determined as follows.

#### 3.8.1. CCHP central units

The dimensioning of the CCHP units ( $W^{MAX-\ell}$ ) is determined by the highest capacity available in the market ( $W^{UB-\ell}$ ) and the highest load required for operating the system during any time period ( $W_{d,t}^\ell$ ). The existence of the units is defined by the binary variable  $y^\ell$  as follows:

$$W^{MAX-\ell} \leq W^{UB-\ell} y^\ell, \forall \ell \in \text{CHP} - \text{Tech} \quad (24)$$

$$W^{MAX-\ell} \leq W_{d,t}^\ell, \forall \ell \in \text{CHP} - \text{Tech} \quad (25)$$

#### 3.8.2. Thermal storage tank

The sizing ( $V^{MAX-ST}$ ) of the thermal storage tank (ST) is defined by two factors. The first one is the maximum water stored during all the operation periods ( $V_{d,t}^{ST}$ ) and the second one is the maximum available capacity in the market ( $V^{UB-ST}$ ). The existence of this storage in the optimal solution is defined by the binary variable  $y^{ST}$ :

$$V^{MAX-ST} \geq V_{d,t}^{ST}, \forall t, \forall d \quad (26)$$

$$V^{MAX-ST} \leq V^{UB-ST} y^{ST} \quad (27)$$

#### 3.8.3. Solar collector

The existence and sizing of the solar collector are determined by the associated binary variable ( $y^{SC}$ ) and the operating area ( $A^{SC}$ ). The operating area required for all the time periods is bounded by the maximum area available for the solar collector ( $A^{UB-SC}$ ):

$$A^{SC} \leq A^{UB-SC} y^{SC} \quad (28)$$

#### 3.8.4. Chiller

The sizing of the chiller is defined by the maximum cooling load and the maximum available capacity in the market:

$$Q^{MAX-AC} \geq Q_{d,t}^{D-CL}, \forall d, \forall t \quad (29)$$

$$Q^{MAX-AC} \leq Q^{UB-AC} y^{AC} \quad (30)$$

### 3.9. Capital costs

The total capital cost ( $CostCap^T$ ) corresponds to the purchase of equipment including installation costs and it involves the capital costs for the CCHP Technologies ( $CostCap^\ell$ ), the solar collector ( $CostCap^{SC}$ ), the chiller ( $CostCap^{AC}$ ) and the ST ( $CostCap^{ST}$ ). The total capital cost is computed as follows:

$$CostCap^T = CostCap^{ICE} + CostCap^{MT} + CostCap^{FC} + CostCap^{SE} + CostCap^{SC} + CostCap^{AC} + CostCap^{ST} \quad (31)$$

The capital cost for each CCHP technology is based on the size of the equipment, which is determined accounting for a fixed part ( $FC^\ell$ ) and a variable part ( $VC^\ell$ ) that is multiplied by the size of the equipment ( $W^{MAX-\ell}$ ) elevated at the exponent  $\beta^\ell$ , which represents the scaling factor to account for the economies of scale (see Table 1):

$$CostCap^\ell = k_F \left( FC^\ell y^\ell + VC^\ell \left( W^{MAX-\ell} \right)^{\beta^\ell} \right), \forall \ell \in \text{CHP} - \text{Tech} \quad (32)$$

Similarly, for the solar collector and thermal storage tank, the capital cost functions are determined by fixed costs, variable costs associated with the sizing and economy of scale factor as follows:

$$CostCap^{SC} = k_F \left( FC^{SC} y^{SC} + VC^{SC} \left[ A^{SC} \right]^{\beta^{SC}} \right) \quad (33)$$

$$CostCap^{ST} = k_F \left( FC^{ST} y^{ST} + VC^{ST} \left[ S^{MAX-ST} \right]^{\beta^{ST}} \right) \quad (34)$$

$$CostCap^{AC} = k_F \left( FC^{AC} y^{AC} + VC^{AC} \left[ Q^{MAX-AC} \right]^{\beta^{AC}} \right) \quad (35)$$

Here,  $k_F$  is a factor used to annualize the investment. This annualization factor accounts for the time value of the money, the life of the project (15 years in the case study), and the interest rate (10% in this case study) [47].

### 3.10. Fuel cost

The fuel cost ( $CostOp^{Fuel}$ ) is the economic value of the total fuel

consumed during each time period through the operation of the CCHP system, which is represented as follows:

$$CostOp^{Fuel} = CostOp^{Fuel-ICE} + CostOp^{Fuel-MT} + CostOp^{Fuel-FC} + CostOp^{Fuel-SE} \quad (36)$$

The fuel costs for the CCHP system and the boiler are equal to the amount of fuel consumed by the CCHP system ( $F_{d,t}^\ell$ ) multiplied by the unit fuel costs (UCF $^\ell$ ) for the CCHP system. We highlight that the unit fuel costs are based on the prices of the local energy market.

$$CostOp^{Fuel-\ell} = UCF^\ell \sum_{d=1}^D \sum_{t=1}^T F_{d,t}^\ell \quad (37)$$

### 3.11. Cost for the operation and maintenance

The costs for the operation and maintenance of the different units ( $CostOM^T$ ) are calculated based on the unit cost associated to the total production of the equipment ( $W_{d,t}^\ell, G_{d,t}^{SC}, Q_{d,t}^{D-CL}$ ) as follows:

$$CostOM^\ell = UCOM^\ell \sum_{d=1}^D \sum_{t=1}^T W_{d,t}^\ell \quad (38)$$

$$CostOM^{SC} = UCOM^{SC} \sum_{d=1}^D \sum_{t=1}^T G_{d,t}^{SC} \quad (39)$$

$$CostOM^{AC} = UCOM^{AC} \sum_{d=1}^D \sum_{t=1}^T Q_{d,t}^{D-CL} \quad (40)$$

$$CostOM^T = CostOM^{ICE} + CostOM^{MT} + CostOM^{FC} + CostOM^{SE} + CostOM^{SC} + CostOM^{AC} \quad (41)$$

### 3.12. Costs of power purchase

The cost of the purchased power ( $CostPower^{GRID}$ ) involves the purchase of electricity at peak periods ( $W_{d,t}^{purchase}$ ) (i.e., at time periods during the day when the production of electric energy from the CCHP unit is insufficient to fulfill the demands) and the unit cost of energy (UCP $_t$ ). It is worth noting that UCP may change

**Table 1**  
Techno-economic parameters for the considered CCHP technologies and auxiliary equipment [45,55–57].

Parameter	ICE	MTG	FC	SE	SC	AC	Thermal storage tank
Electrical efficiency ( $\eta^W$ - %)	37.25	26	38	30			
Thermal efficiency ( $\eta^Q$ - %)	47.5	47.5	50	60	75	1.75 <sup>b</sup>	
Maximum size ( $W^{UB}$ , $G^{UB}$ and $S^{UB}$ - kW, m <sup>2</sup> (SC) and m <sup>3</sup> )	15800	12500	2000	1500	1500 <sup>a</sup>	1740	200
Minimum partial load (PL <sup>MIN</sup> - %)	35	60	50	42.5			
Unitary fuel cost (UFC - \$/kWh)	0.02	0.02	0.02	0.02			
Fixed cost (FC - \$)	100	100	100	100	30	10	120
Variable cost (VC - \$)	400	450	2500	450	50	100	125
Scale factor ( $\beta$ )	1	1	1	1	1	1	1
Annualization factor ( $k_F$ )	0.23	0.23	0.23	0.23	0.23	0.23	0.23
Maintenance cost (UCOM - \$/kWh)	0.015	0.065	0.015	0.015	0.001	0.012	
Outlet temperature (°C)	90	90	90	90	70	5	

<sup>a</sup> Area available for solar collector.

<sup>b</sup> COP for the AC.

every hour of the day according to the policies of the local power company.

$$\text{CostPower}^{GRID} = \sum_{d=1}^D \sum_{t=1}^T \text{UCP}_t W_{d,t}^{\text{purchase}} \quad (42)$$

### 3.13. Electricity sales

The sale of electricity ( $\text{Powersale}^T$ ) is carried out in different directions, the direct energy sent to the building complex ( $W_{d,t}^{\ell-H}$ ) and the one sent to the grid of the local electric company ( $W_{d,t}^{\ell-GRID}$ ). It should be noted that all the clients buy energy at the lowest unit price in the market (VCP).

$$\text{Powersale}^T = \text{VCP} \sum_{d=1}^D \sum_{t=1}^T (W_{d,t}^{\ell-H} + W_{d,t}^{\ell-GRID}), \forall \ell \in \text{CHP} - \text{Tech} \quad (43)$$

### 3.14. Heat sales

The heat sales ( $\text{Heatsale}^H$ ), as hot water or chilled water sent to the different costumers, represent an income. This is calculated based on the heat produced in the CCHP system and the solar collector ( $Q_{d,t}^{\ell}$ ,  $Q_{d,t}^{SC}$ ) and the heat unit price of the local energy market (UCH):

$$\text{Heatsale}^H = \text{UCH} \sum_{t=1}^T \sum_{d=1}^D (Q_{d,t}^{ICE} + Q_{d,t}^{MT} + Q_{d,t}^{FC} + Q_{d,t}^{SE} + Q_{d,t}^{SC}) \quad (44)$$

### 3.15. Greenhouse gas emissions

Despite their high efficiency, CCHP systems consume fossil fuels that involve the generation of greenhouse gases, the most important being  $\text{CO}_2$  [48]. Based on the proposed superstructure, the emissions have two sources. The first one corresponds to the direct emissions associated with the consumed fuel in the CCHP unit ( $F_{d,t}^{\ell}$ ) and the second one corresponds to the emissions generated by the local electrical company ( $W_{d,t}^{\text{purchase}}$ ). In all the cases, a factor of generation per unit of consumption is used ( $\text{GHGF}^{\text{CHP}}$ ,  $\text{GHGF}^{GRID}$ ). In the case of the fuel, the emissions depend on the quality and characteristics of the used fuel. In the case of those generated by the grid, these depend on the generation characteristics associated to the local electrical company.

$$\text{GHGE}^{\text{CHP}} = \text{GHGF}^{\text{CHP}} \sum_{d=1}^D \sum_{t=1}^T (F_{d,t}^{ICE} + F_{d,t}^{MT} + F_{d,t}^{FC} + F_{d,t}^{SE}) \quad (45)$$

$$\text{GHGE}^{GRID} = \text{GHGF}^{GRID} \sum_{d=1}^D \sum_{t=1}^T W_{d,t}^{\text{purchase}} \quad (46)$$

### 3.16. Objective functions

The objective functions that determine the optimal design of the system are the minimization of total annual cost (TAC), the

minimization of direct greenhouse gas emissions (GHGE) associated with the consumption of fuels, and the minimization of water consumption (SW).

#### 3.16.1. Total annual cost (TAC)

The total annual cost is determined by the sum of annualized capital costs ( $\text{CostCap}^T$ ), purchased power from the local electric company ( $\text{CostPower}^{GRID}$ ), operating cost of fuel ( $\text{CostPower}^{GRID}$ ) and maintenance costs ( $\text{CostOM}^T$ ). The sources of revenue are sales of electrical power ( $\text{PowerSale}^T$ ), heat ( $\text{HeatSale}^H$ ), and cooling utilities. Therefore, the TAC is determined as follows:

$$\text{TAC} = \text{CostCap}^T + \text{CostOp}^{\text{Fuel}} + \text{CostOM}^T + \text{CostPower}^{GRID} - \text{PowerSale}^T - \text{HeatSale}^H \quad (47)$$

#### 3.16.2. Greenhouse gas emissions

The generated greenhouse gas emissions ( $\text{GHGE}^T$ ) are calculated based on the generation of  $\text{CO}_2$  of each of the elements of the grid of the power company ( $\text{GHGE}^{GRID}$ ) and the CCHP system ( $\text{GHGE}^{\text{CHP}}$ ). The total emissions are determined as follow:

$$\text{GHGE}^T = \text{GHGE}^{\text{CHP}} + \text{GHGE}^{GRID} \quad (48)$$

#### 3.16.3. Supply of water

The supply of water (SW) is the sum of the water needed to run the CCHP units ( $G_{t,d}^{\ell}$ ), the solar collector ( $G_{t,d}^{SC}$ ), the water used to regulate the temperature of hot water supplied to the Building complex ( $G_{t,d}^{CW-H}$ ) and the chilled water used to provide cooling supply ( $G_{t,d}^{ChW}$ ). In this case, the total water consumption of the system is give as follows:

$$\text{SW} = \sum_{d=1}^D \sum_{t=1}^T (G_{t,d}^{ICE} + G_{t,d}^{MT} + G_{t,d}^{FC} + G_{t,d}^{SE} + G_{t,d}^{SC} + G_{t,d}^{CW-H} + G_{t,d}^{ChW}) \quad (49)$$

### 3.17. Optimization method

The optimization formulation is a multi-objective mixed-integer nonlinear programming problem that seeks to simultaneously minimize TAC,  $\text{GHGE}^T$ , and SW while satisfying the constraints (1)–(49). Because these three objectives are conflicting, we need to identify Pareto optimal compromise solutions. There are different methodologies for solving multi-objective problems. A common way to do it is obtaining the entire Pareto surface [49]. In this work, we use a utopia-tracking approach that allows us to obtain compromise solutions without forming the Pareto front. This is important because the computational complexity of the proposed superstructure model is high and because we have several objectives [50]. In the utopia-tracking approach we first solve single objective problems to determine the lower bounds ( $\text{TAC}^{\text{LB}}$ ,  $\text{GHGE}^{\text{TLB}}$ ,  $\text{SW}^{\text{LB}}$ ) for the objective functions. These solutions define the coordinates of the so-called utopia point, which is unreachable since the objectives are conflicting but it provides a reference. The solution of the single objective problems also defines the upper bounds ( $\text{TAC}^{\text{UB}}$ ,  $\text{GHGE}^{\text{TUB}}$ ,  $\text{SW}^{\text{UB}}$ ), which define the coordinates of the so-called nadir point. We use the coordinates of the utopia and nadir points to scale the objective functions so that their values lie in the range of

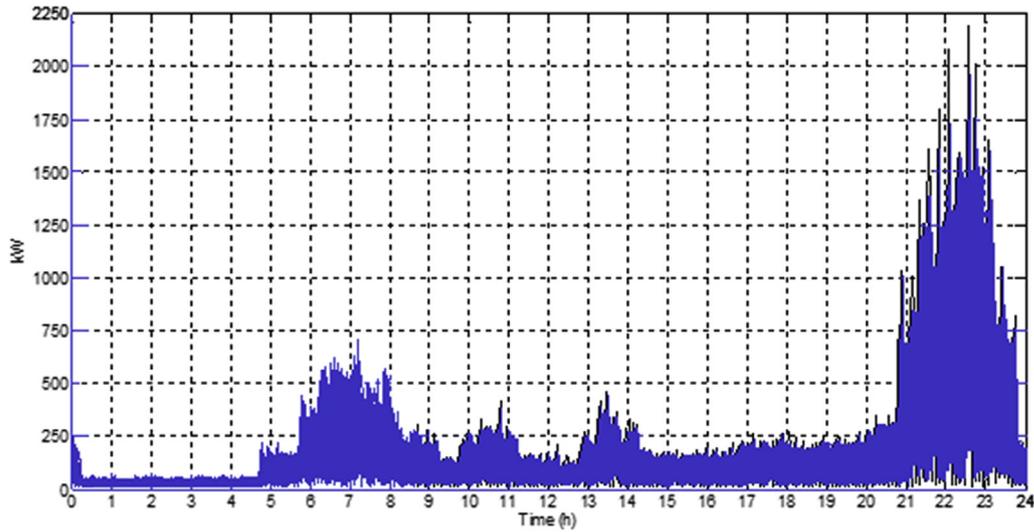


Fig. 3. Behavior of the electricity demand for one year (daily profiles are overlapped).

zero and one. We then seek to find a Pareto solution that is closest to the utopia point. This is done by solving the problem:

$$\min \left( \left| \frac{TAC - TAC^{LB}}{TAC^{UB} - TAC^{LB}} \right| + \left| \frac{GHGE^T - GHGE^{T-LB}}{GHGE^{T-UB} - GHGE^{T-LB}} \right| + \left| \frac{SW - SW^{LB}}{SW^{UB} - SW^{LB}} \right| \right) \quad (50)$$

One of the advantages of the utopia-tracking approach is that we can compute compromise solutions without forming the Pareto front.

4. Case study

A case study based on *real data* is presented for a building

complex in the Pacific coast of Mexico. This complex is comprised of 420 homes with an average of 5 inhabitants per home (2400 total). The electricity demands are shown in Fig. 3, the thermal demands are shown in Fig. 4, and the cooling demands are shown in Fig. 5. These represent the behavior of these variables during one year and we overlap the daily profiles. In the case of the electricity and cooling demands the measured periods are of five minutes (288 data points for 365 days); for the hot water the measurement periods are of an hour. There are different ways for determining the energy demands for domestic users. These can be obtained by direct measures [51] or by a survey [52]. The demands of hot water are different in the different regions. The demand profile of hot water for sanitary uses is defined by cultural, economic, and ambient factors [54]. In some studies the profiles of hot water include also the hot water use for district heating or the absorption chiller consumption [53]. In our case the hot water

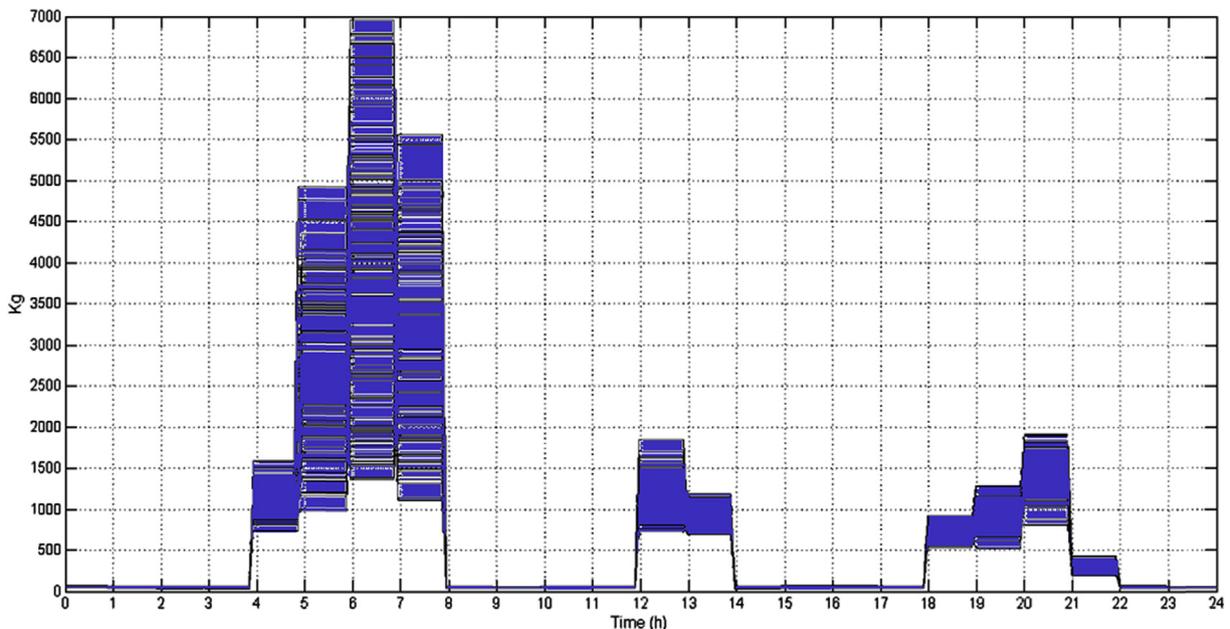


Fig. 4. Behavior of hot water demand for one year.

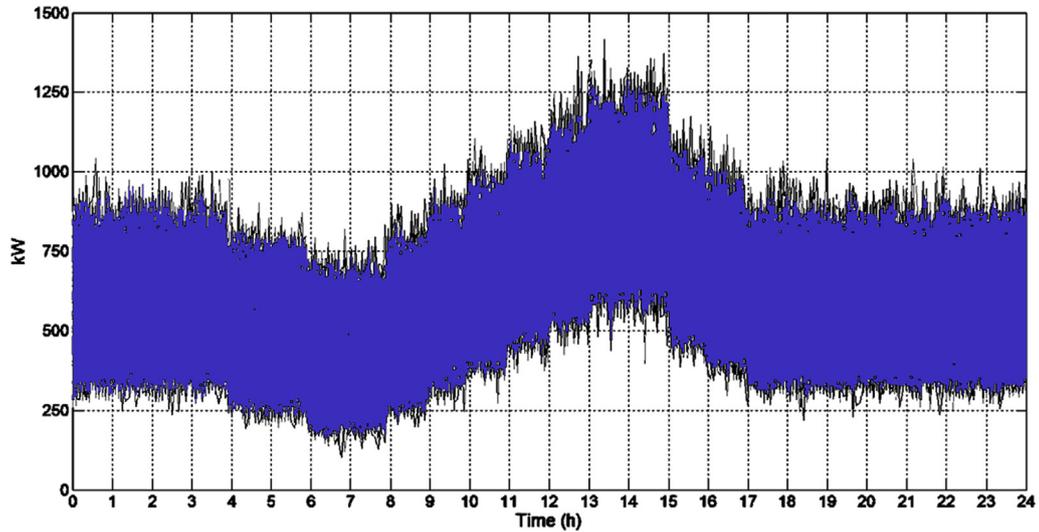


Fig. 5. Behavior of cooling demand for one year.

demand profile (Fig. 4) represents the sanitary hot water. In this region high consumption periods are observed in the morning where hot water demand is used to take showers. At noon and night, it is used for other housing activities. The low consumption periods are defined by the periods when most inhabitants are at work or sleeping.

Figs. 6 and 7 present real data profiles for solar radiation and ambient temperature, respectively in this region. The solar radiation presents a very consistent behavior during the year despite the overlapping of the daily profiles. The considered technical and operating parameters in the case study are presented in Table 1 [55]. The environmental objective is to minimize the total GHGE over the year. The unit factors for this metric are shown in Table 2 [56]. We assume that all the units consume natural gas [57]. Table 2 also shows the economic data for the local heating energy market obtained from Mexico's Energy Council [58].

Fig. 8 shows the hourly electricity pricing scheme for the local utility company [59]. It is important to note that we assumed that the electricity generated by the CCHP system is sold to the utility company at the lowest price. This consideration allows a competitive price compared with the end user. In the Mexican energy market the sales of electricity are not allowed in a strict sense. At the moment, the surpluses of electricity are compensated using net metering schemes [60]. In other words, the sold electricity is discounted from the payments to the utility company.

## 5. Results

The multi-objective optimization formulation was coded on the algebraic modeling language GAMS [37]. The model consists of 2, 844, 771 continuous variables, 6 binary variables, and 3, 370, 791 constraints. Nonlinear features include bi- and tri-linearities along

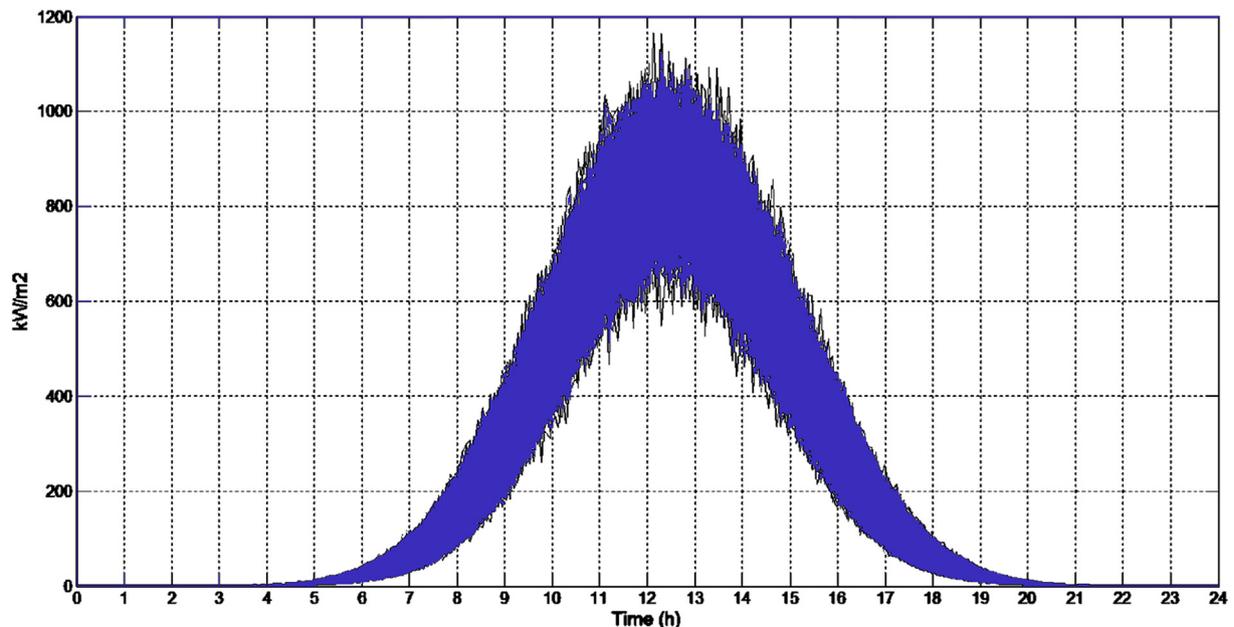


Fig. 6. Solar radiation during one year.

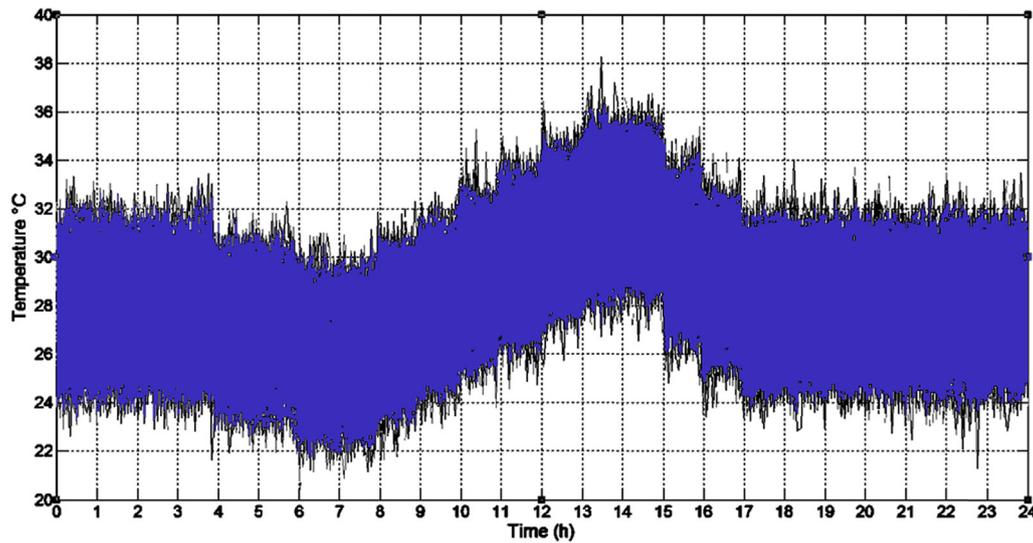


Fig. 7. Ambient temperature during one year.

**Table 2**  
Data for emissions and heat sale [58].

Parameter	CHP system	Grid local electrical company
GHGE (gr CO <sub>2</sub> /kWh of consumed fuel)	503	350
Unitary sale value of thermal energy for internal consumption (UCH - \$/kWh)	0.18	—

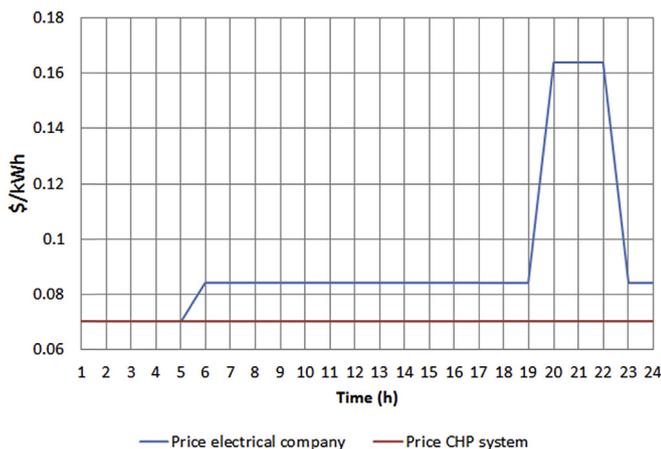


Fig. 8. Prices of electric energy through the day [47,58].

with exponential expressions. We use the global optimization solver BARON to handle the problem [61]. On average, each optimization problem (the utopia, compromise, and nadir problems) required 69,500 s (19 h) of CPU time. All computations were performed on an Intel processor running at 2.4 GHz and with 8 GB of RAM memory available. Because of the long computational times, we have found the utopia-tracking approach particularly useful [50].

The points for individual minimizations of  $TAC$ ,  $GHGE^T$ , and  $SW$  are presented in Fig. 9. In this figure we also present the location of the utopia point (UP), nadir solution (NS) and compromise solution (CS). The objective values for all these points are reported in Table 3. Also, the main results of the different optimal solutions are showed in Table 3.

An interesting finding is that water consumption varies strongly with the different solutions. We first penalized for water

consumption by considering an average water price in Mexico of 0.69 USD/m<sup>3</sup> [62]. We first notice that the solution obtained by minimizing  $TAC$  with no water consumption is \$100,336/yr while that obtained considering water cost is \$154,333/yr. This indicates that the cost of water is 34% of the  $TAC$  and this can be attributed to the large amounts of water consumed by the selected technology (ICE with a capacity of 580 kW<sub>e</sub>). In particular, the CCHP system for the  $TAC$  minimization case consumes around 78 million kg of water per year. We contrast this amount of water to that consumed with the water supply ( $SW$ ) minimization case in which 75% less water is consumed. Interestingly, the  $SW$  minimization case also selects an ICE system but with a capacity of 287 kW<sub>e</sub>, which implies that most of the electricity is bought from the utility company. The  $SW$  minimization case has a total cost of \$199,816/year if we consider the cost of water at a price of 0.69 USD/m<sup>3</sup>. This represents an increase in cost of 30% compared to the  $TAC$  minimization case. The  $GHGE$  minimization case selects a Stirling engine system with a capacity of 180 kW<sub>e</sub> and this consumes around 72% less water compared to the  $TAC$  minimization case and the total cost increases by 25%. The compromise solution (CS) selects an FC system with a capacity of 267 kW<sub>e</sub> that consumes 74.4% less water than the  $TAC$  minimization case and increases the total cost by only 10%. The result thus show that water consumption is a factor that should be carefully valued by itself.

Furthermore, the  $TAC$  minimization case increases emissions by 335% compared to the  $GHGE$  minimization case. The compromise solution only increases emissions by 12%. This illustrates that compromise solutions obtained with the utopia-tracking approach can provide solutions that represent optimal trade-offs.

We also note that none of the identified solutions incorporates the solar collector as an element of the optimal configuration. In the case of the minimum  $TAC$  and CS solutions, this is due to the fact that the solar collector can only generate hot water at 70 °C while ICE, SE, and FC technologies can generate electricity and hot water at 90–100 °C. In particular, the hot water supply temperature of the

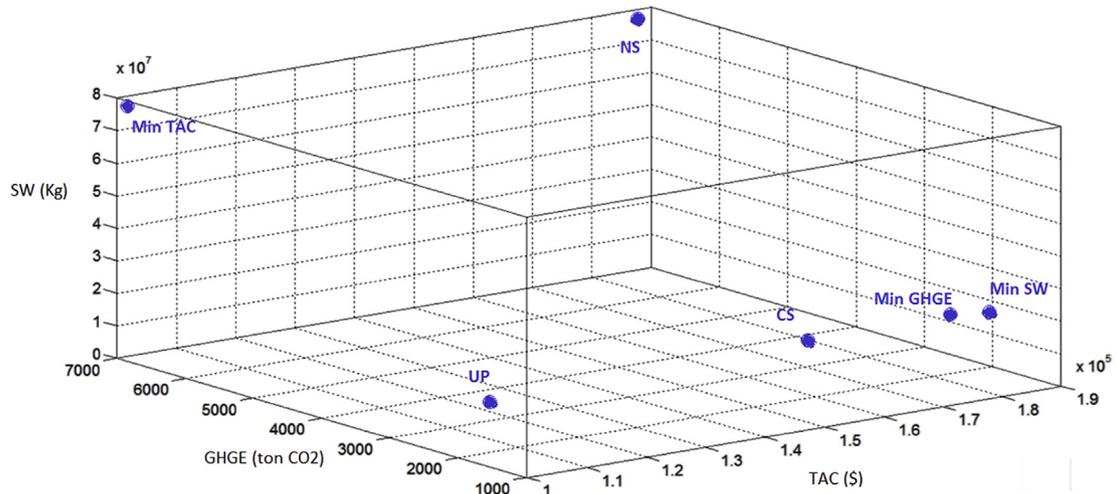


Fig. 9. Utopia, nadir, and compromise solutions for case study.

Table 3  
Objective values for different solutions.

	Min TAC	Min GHGE <sup>T</sup>	Min SW	Compromise solution	Utopia point	Nadir solution
TAC (\$/year)	100,336	178,000	186,290	156,295	100,336	186,290
GHGE <sup>T</sup> (ton of CO <sub>2</sub> /year)	6879	1581	1727	1774	1581	6879
SW (kg/year)	78,228,000	22,186,000	19,602,600	20,018,000	19,602,600	78,228,000
CHP technologies	ICE	SE	ICE	FC		
Sizing of CHP technologies (kW <sub>e</sub> )	580	180	287	267		
Sizing ST (m <sup>3</sup> )	86	75	83	72		
Sizing of SC (m <sup>2</sup> )	0	0	0	0		
Sizing of AC (kW)	870	870	870	870		
Sales of power (\$)	336,400	52,494	70,667	157,850		
Cost of water (\$)	53,977	15,308	13,526	13,812		
TAC - Considering cost of water (\$)	154,333	193,308	199,816	170,107		

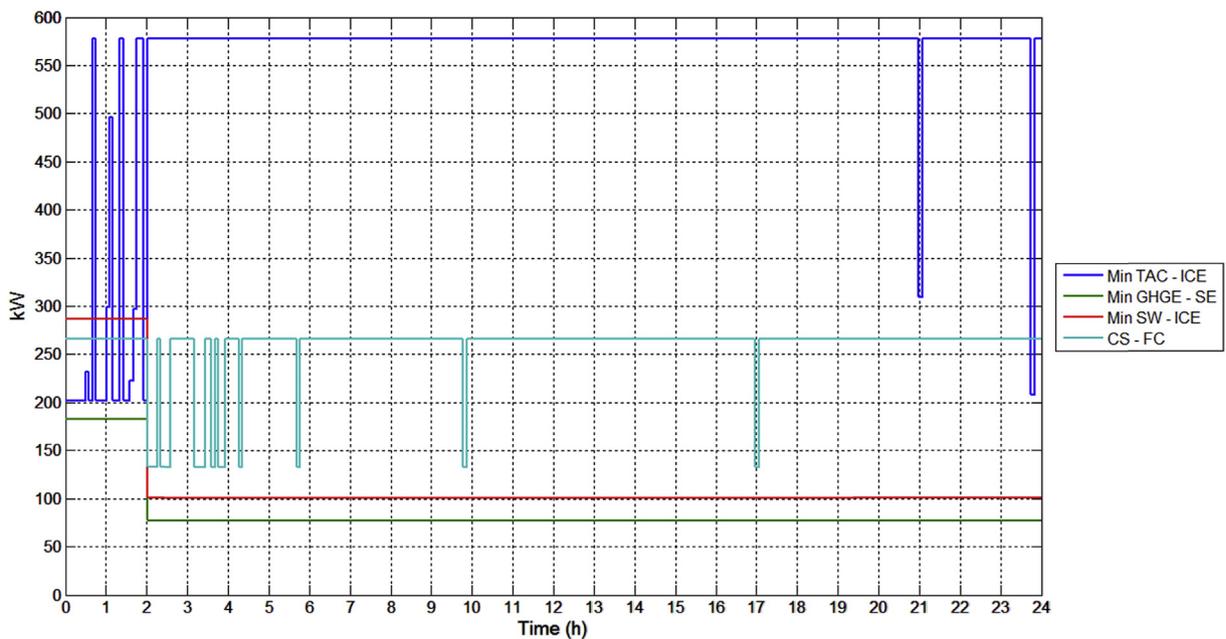


Fig. 10. Operational policies for the Pareto solutions.

solar collector forces the CHP to increase the consumption of fuel and water to meet the thermal demands, especially those associated to the operation of the AC. The decision to install a solar collector is also attributed to area installation constraints, which are common in developing countries due to the urban configuration [63].

The operational policies for the solutions are presented in Fig. 10. We note that all the policies have a strong correlation with the behavior of the thermal demand [64], defined by the HWS and the CL. In the absence of another supplier of thermal energy, the operation of the CHP unit prioritizes to meet the thermal demand [65]. This does not occur with the electrical energy demand, since there is an additional supplier (the utility company), which can cover the electrical energy demand when the CHP unit is not capable of doing it.

The solutions for the minimum TAC and CS cases show a strong tendency to operate the CCHP system at full load and thus use resources more efficiently. On the other hand, the GHGE<sup>T</sup> and SW policies show a strong tendency to work at the minimum partial load operation because it is expected to meet the energy demand using minimal resources (i.e., fuel and water). Consequently, the equipment operates at full load during periods of low demand in order to store enough thermal energy and it permits to operate the rest of the time with minimal resources.

## 6. Conclusions

This paper has presented a multi-objective optimization approach for the optimal design and control of CCHP systems for building complexes. The approach optimally selects among multiple candidate technologies to simultaneously satisfy electricity, hot water, and cooling demands. The approach also considers variations of ambient temperature, solar radiation, and energy market conditions. Our approach finds compromise solutions that optimally trade-off total annual cost, greenhouse gas emissions, and water consumption. A case study using real data from a residential complex in the Pacific coast of Mexico provides optimal CCHP configurations that provide an optimal trade-off between the considered metrics.

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## Nomenclature

### Index

<i>t</i>	Time period
<i>d</i>	Day

### Binary variables

<i>y</i>	Existence of units
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### Continuous variables

<i>A</i>	Area, m <sup>2</sup>
<i>CostCap</i>	Capital cost, \$
<i>CostOp</i>	Operating cost, \$
<i>CostOM</i>	Cost of operation and maintenance, \$
<i>CostPower</i>	Cost of electricity purchased to the grid of the local company, \$
<i>F</i>	Fuel, kWh

<i>G</i>	Flux of water, kg
<i>GHGE</i>	Greenhouse gas emissions, ton of CO <sub>2</sub> /year
<i>HeatSale</i>	Sales of heat, \$
<i>Q</i>	Heat flux, kWh
<i>PL</i>	Partial load, %
<i>PowerSale</i>	Sales of electricity, \$
<i>SW</i>	Supply of water, kg/year
<i>W</i>	Electrical flux, kWh
<i>T</i>	Temperature, °C
<i>V</i>	Volume, m <sup>3</sup>
<i>η</i>	Efficiency, %

### Parameters

<i>COP</i>	Coefficient of performance (Absorption Chiller)
<i>Cp</i>	Specific heat for water, kWh/kg °C
<i>FC</i>	Fixed cost, \$
<i>GHGF</i>	Greenhouse gas emissions factor, gr CO <sub>2</sub> /kWh
<i>KF</i>	Factor of annualization
<i>U</i>	Convective factor, kW/m <sup>2</sup> °C
<i>UCH</i>	Unit price of sales of heat, \$/kWh
<i>UCF</i>	Unit cost of fuel, \$/kWh
<i>UCOM</i>	Unit cost of maintenance, \$/kWh
<i>UCP</i>	Unit cost of power purchase, \$/kWh
<i>VC</i>	Variable cost, \$
<i>VCP</i>	Unit price of sales of energy, \$/kWh
<i>α</i>	Solar radiation, kW/m <sup>2</sup>
<i>β</i>	Scale factor
<i>ρ</i>	Water density, kg/m <sup>3</sup>

### Acronyms and superscripts

AC	Absorption chiller
CCHP	Combined cooling, heating and power
CHP	Combined heat and power
CW	Cold water
ChW	Chilled water
CL	Cooling load
CS	Compensated solution
DER	Distributed energy resources
D	Demand
FC	Fuel cell
GHGE	Greenhouse gas emissions
GRID	Grid of the local energy company
H	Building complex
ICE	Internal combustion engine
ℓ	Reference to the set of CHP-Technologies {ICE, MT, FC, SE}
loss	Convective losses
LB	Lower bound
MAX	Maximum
MIN	Minimum
MINLP	Mixed-Integer NonLinear Programming
MT	Microturbine
NS	Nadir solution
PL	Partial load
Q	Thermal heat
SC	Solar collector
SE	Stirling engine
ST	Thermal storage tank
SHW	Sanitary hot water
SW	Supply of water
T	Total
TAC	Total annual cost
UB	Upper bound
UP	Utopia point
W	Electric power

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