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Planning tool for polygeneration design in microgrids

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Abstract

This work suggests a methodology to assist the designer during the planning phase of microgrids and eco-districts. A mixed integer linear programming model is designed to mathematically describe the different energy systems and the physical relations among them. Given the different electrical/thermal demand profiles, the micro grid's topology and a set of boundary conditions, the model can identify the optimum mix of (poly-)generation units and energy storage systems, as well as the necessary district heating/cooling infrastructure. Both economic and energetic cost functions are defined to explore the problem from different perspectives. The described tool is applied to study an actual district of the NTU campus in Singapore, comprising 5 multi-purpose buildings and a district cooling network supplied by centralized electrical chillers. The planning tool was run to assess the optimal configuration that minimizes the overall cost (initial investment and O&M); the outcome results presented a layout and a mix of energy systems different from the present one. In particular, the optimal configuration results to be a district cooling system served by a mix of electrical chiller plant, trigeneration distributed energy system and sensible cold thermal energy storage.

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Keywords: Micro grid design, energy mix optimizaion, techno-economic analysis; eco-district; polygeneration

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1. Introduction

Electricity generation, transmission and distribution systems have been changing dramatically in the last 20 years. Everywhere in the world, the diffusion of renewable driven distributed generation is posing new challenges to the national grids. This trend is eventually going to threaten the entire distribution system in terms of reliability, costs and service quality. Micro grids have a critical role in this scenario. Micro grids can locally manage the combined generation of multiple useful products like power, heat and cooling energy. Being made by the integration of several energy distribution systems and storage technologies, they are complex entities to design [1-2] and manage [3-4]. The goal of obtaining the optimal design for the energy system for a micro grid has been widely analyzed both in the literature, with authors concentrating on an optimal distribution of heat pumps [5] or on interactions between different users [6]; but also in already available software tools. Most of these tools mainly focus on electricity generarion and consumption: that is the case of H.O.M.E.R (Hybrid Optimization Model for Electric Renewable) [7] and Sandia Labs MDT (Microgrid Design Toolkit) [8]. The planning tool presented in this paper aims at designing polygeneration systems considering all the energy networks usually involved in a microgrid and eco-district: other than electricity, thermal (district heating) and cooling (district cooling) energy.

1.1. Novelty and Goals

The goal for this work was then to obtain a framework for the design of microgrids which could take into account the different kinds of energy vectors aligned with the microgrid needs, therefore consisting in electrical and thermal demand; where the latter is made up of both heating and cooling. A model was built, simulating the operation of a microgrid for a year in which both electrical and cooling/heating demand had to be satisfied; the demand can be centralized or dislocated in multiple sites. The outputs of the simulation are the optimal mix of energy systems to install and the associated costs, including the ones for district cooling/heating networks.

2. Methodology and mathematical model

2.1. Test Case Description

The case study of this work is part of the campus of the Nanyang Technological University (NTU) in Singapore. The part of the campus under study, consists of five sites and presents a peak demand for cooling of around 21.5 MW_c. At the present time, each building has its chiller plant room in order to meet its own cooling demand. Table 1 shows the actual configuration of the electric chillers in the five sites of the NTU campus under study.

Campus Site	Boiler (kW)	CHP/Genset (kW_e)	Absorption Chiller cooling capacity (kW_c)	Electrical Chiller cooling capacity (kW_c)	Electric Storage (kWh_e)	Thermal Storage capacity (kWh_c)
U1	-	-	-	3600	-	-
U2	-	-	-	8000	-	-
U3	-	-	-	1600	-	-
U4	-	-	-	3300	-	-
U5	-	-	-	7000	-	-
Total				**23500**		

Table 1. Actual configuration of the cooling power installed on each site

The campus has been modeled as a series of 5 sites, where each one represents a User with its own power/cooling demand; on each site there is the possibility to install different kinds of energy systems such as Boilers, CHP units, Electrical and Absorption Chillers and thermal storages. The sizes to take into consideration for each energy system have been selected accordingly to the energy demands to be satisfied. Also, the possibility of mutually exchanging energy among the five sites by means of a district cooling network has been allowed, thus allowing the share of a generation equipment among the different sites, in order to improve the efficiency of its usage. The goal was to understand if the existing solution is the optimal one or if it could be further improved by means of a unique district cooling network served by high efficiency electric chiller or even by polygeneration system such as combined cooling heat and power (CCHP). Finally, the possibility of buying and selling energy from/to the national grid at a fixed price has been allowed. The optimization procedure has been implemented and carried out in an AIMMS model in order to determine the optimal set of energy systems to purchase; AIMMS [9] is a software environment for the modeling of optimization problems.

2.2. Mathematical Formulation

For the sake of reduction of the computational time an approach relying only on linear relations was undertaken; therefore a MILP (Mixed Integer Linear Programming) algorithm was chosen and all the equations expressing constitutive relations of the systems, problem constraints and objectives were also expressed as linear. For the same reason while being the simulation intended to represent the scenario for a whole year; only the worst (in terms of User demand) week of every month has been taken into account. Thus given the fact that the simulation has been carried out with a timestep of one hour the size of the time parameter has been reduced from the original 8760 to 2016 hours. The modelling approach chosen extends the one presented by Ameri et al. [10] to consider also energy storage systems, while rethinking a portion of the constraint formulation.
Each energy system and component of the microgrid networks (pipelines) were modeled only via linear equations; also their existence was modeled by linear equations using binary variables. As an example any of energy system has set in its equations two relations expressing both its existence and, if existing (i.e. if the planning tool chose it) its operativity to be above a certain threshold. An example of these equations is the following:

$$\mathrm{X_{comp}(sz,u,h)} \leq \mathrm{Y_{comp}(sz,u)} \tag{1}$$

$$\mathrm{Q_{comp}(sz,u,h)} \geq \mathrm{lim_{comp}} * \mathrm{X_{comp}(sz,u,h)} \tag{2}$$

Where Y is the binary variable representing the existence of the component, X is the binary variable representing its operativity, lim is its minimum operative energy output and Q its actual output at the hour h in the site u and for the equipment of size sz. By computing the optimal energy mix for each timestep h the algorithm obtains the set of binary variables Y, representing the selection of energy systems that are to be installed. Then the capital cost is calculated multiplying each of the Ys which are set to 1 for their respective price.
The optimization tool also takes into account the costs which are dependent on the analysis timespan; such as maintenance, operation costs and purchased energy.

2.3. Objective Function

In this paper, the objective function used for the analysis was the minimization of the total cost of the system. The total life cycle cost includes the initial investment cost of each system and takes into account its depreciation over the expected lifespan; the costs related to the operativity and maintenance and the value of the purchased energy were also taken into account.

3. Results

This section presents the results of the optimization strategy, corresponding to the minimum total cost function described in Section 2.3. At the end of the procedure the optimal mix of energy systems with relative size was returned. In the model, the price of the electricity exchanged with the national grid was kept constant: 0.05 €/kWh for electricity selling and 0.15 €/kWh for electricity purchasing. Natural gas cost was assumed equal to 0.044 €/kWh. Table 2 shows the mix of energy systems resulting from the optimization process.

Campus Site	Boiler (kW)	CHP/Genset (kW_e)	Absorption Chiller cooling capacity (kW_c)	Electrical Chiller cooling capacity (kW_c)	Electric Storage (kWh_e)	Thermal Storage capacity (kWh_c)
U1	-	-	-	4853	-	-
U2	-	5200	1238 + 2170	1033+1795+2426+4853	-	-
U3	-	-	-	-	-	-
U4	-	-	-	-	-	3000
U5	-	-	-	1795+2426	-	-
Total	**-**	**5200**	**3408**	**19181**	**-**	**3000**

Table 2. Selection of energy systems installed in each site of the campus with an economical optimization

With respect to the present configuration, consisting in five building each served by a chiller plant, the optimization tool suggests that the optimal configuration would consist of one district cooling network served by a mix of chiller plants, trigeneration units (CHP unit + absorption chillers) and sensible cold thermal energy storage (CTES). Moreover, not all the buildings have a chiller plant. On the contrary most of the cooling capacity is gathered at the site that has the highest cooling demand, that is User 2; Users 3 and 4 do not have chiller plant but they exchange cooling energy with others sites by means of the district cooling network. According to the optimized solution, User 4 does not have a chiller plant but it has installed a 3000 kWh CTES. This choice can be explained by the fact that is economically advantageous for the the trigeneration unit to produce as more electricity as possible even if the cooling demand is lower than the one produced by the absorption chillers: the excess of cooling is then usefully recovered by the CTES. The choice of the trigeneration unit highlights the role of distributed generation and of self production of the electricity. In the optimized solution, trigeneration unit provides the baseload for the NTU campus, considering that its power production is almost completely self consumed by the electrical chillers.

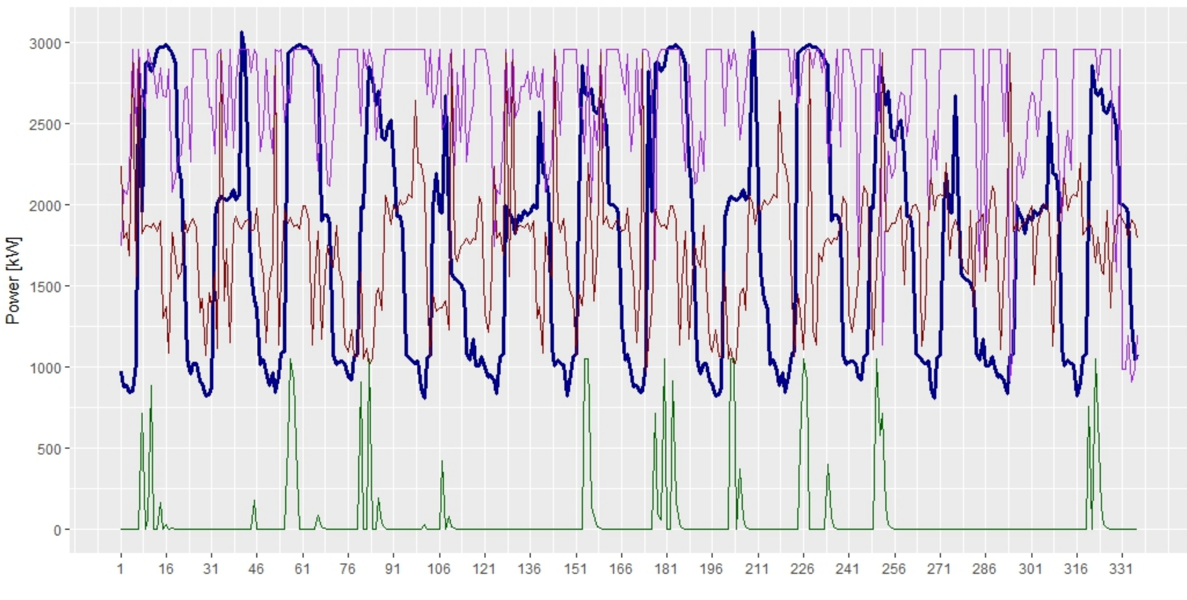

Figure 1. Supply of the cooling demand (in blue) for User 4: power flowing from district cooling network in purple (flow from user 2) and red (flow from user 3); energy provided by the CTES.

Figure 1 shows the mix of supply sources used to meet the cooling demand of User 4 during a period of 14 days. In particular, Figure 1 shows that the cooling demand of User 4, that does not have its own chiller plant, is completely met by the district cooling network, in particular, by Users 2 and 3. Actually, it is worth noticing that also User 3 does not have a chiller plant; the meaning of the red line din figure 1 is that the cooling capacity is provided by a physical pipe coming from User 3. Finally, Figure 1 shows that the cooling energy coming from Users 2 and 3, highly exceeds the cooling demand of User 4: this excess of energy is partially used to charge the CTES whereas most part “just” passed thorugh User 4 in its way to User 5 (this flows is not shown in Figure 1) via another physical pipe.

4. Conclusions and future work

4. This paper presents a planning tool for microgrid able to holistically take into account electricity, thermal and cooling demand. These demands can be distributed in different sites so that district heating/cooling networks can be assessed as part of the output of the analysis. The tool is based on a MILP (Mixed Integer Linear Programming) algorithm. In this work, the planning tool was applied to part of the NTU campus, comprising the cooling energy demand of 5 buildings. The output of the analysis was used to compare the present solution and the optimal one. The optimization goal was the minimization of the total cost over the expected lifespan, including both capital and O&M costs. The optimization tool suggests that the optimal configuration would consist of one district cooling network served by a mix of chiller plants, a trigeneration units (CHP unit + absorption chillers) and a sensible cold thermal energy storage (CTES). Not all the buildings have their own chiller plant. On the contrary most of the cooling generation capacity is gathered at the site that has the highest cooling demand.

The planning tool proves to be a good starting point for the techno-economic design of a microgrid, or an eco-districts, served by polygeneration systems. Future developments of this work could include the extension of the technologies taken into account and a more elaborate analysis of the requests on the demand side: such as heating power, hot sanitary water demand.

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