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A life cycle multi-objective economic and environmental assessment of distributed generation in buildings

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ABSTRACT

Distributed generation, namely cogeneration and solar technologies, is expected to play an important role in the future energy supply mix in buildings. This calls for a methodological framework to assess the economic and environmental performance of the building sector when such technologies are employed. A life-cycle model has been developed, combining distributed generation and conventional sources to calculate the cost and environmental impacts of meeting the building energy demand over a defined planning period. Three type of cogeneration technologies, solar photovoltaic and thermal, as well as conventional boilers along with the Portuguese electricity generation mix comprise the energy systems modeled. Pareto optimal frontiers are derived, showing the trade-offs between different types of impacts (non-renewable cumulative energy demand, greenhouse gas emissions, acidification, eutrophication) and cost to meet the energy demand of a commercial building. Our analysis shows that according to the objective to employ distributed generation (reducing cost or environmental impacts), a specific design and operational strategy for the energy systems shall be adopted. The strategies to minimize each type of impact and the associated cost trade-offs by exploring the solutions located on the Pareto optimal frontiers are discussed.

1. Introduction

Energy use in the building sector accounts for more than 40 percent of the EU energy consumption [25]. The generation of energy at the point of consumption, employing Distributed Generation (DG) technologies, is pointed out as a key option for promoting energy efficiency and use of renewable sources in building sector [48]. Combined Heat and Power (CHP) technologies and solar technologies, namely Photovoltaic (PV) and Solar Thermal (ST), represent promising onsite generation alternatives and several strategies, including the introduction of financial incentives, have been implemented to further increase the share of DG in the building sector energy mix [46]. A comprehensive view on distributed multi generation by Chicco and Mancarella [11] also underlines this point.

The introduction of different types of DG calls for a framework to assess the building economic and environmental performance when such technologies are employed. Some studies have assessed DG technologies considering efficiency and economic perspectives, by using techniques other than optimization. Xuan et al. [54] examined the application of a gas-fuelled reciprocating Combined Heat and Power (CHP) in a commercial building in China. Wu and Rosen [53] employed an energy equilibrium model to compare conventional and NG cogeneration-based district energy systems for heating, cooling and electrical services. Marantan et al. [33] demonstrated the potential of tri-generation NG CHP application in commercial buildings. The importance of cogeneration systems for sustainable energy use was underlined in Çakir et al. [8]. Gunes [22] examined the application of fuel cell-based Total Energy System (TES) for residential buildings. Dentice d'Accadia et al. [15] dealt with the application of a small scale fuel cell cogeneration (electrical power <15 kW) to light commercial application users. Another study on fuel cells [17] offered a methodology for assessing the performance of two types of fuel cells in terms of primary energy demand and CO_2 emissions. Bhattacharyya and Quoc Thang [5] found that economic feasibility of medium and large scale cogeneration systems is vulnerable to changes in buy-back rate of electricity and investment costs. Mone et al. [36] investigated the underlying factors in economic feasibility of CHP systems using commercially available gas

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turbines. Ullah et al. [51] evaluated the application of a single tubular Solid Oxide Fuel Cell (SOFC) with an electrolyte of Yttria-Stabilized Zirconia ceramic powder. Ranjbar et al. [41] reported the energy and exergy assessments of a trigeneration system based on a SOFC. Raj et al. [40] investigated the effect of temperature, stoichiometry and the degree of humidification on the performance of a planar solid oxide fuel cell. Brandoni et al. [7] assessed the impact of micro-generation technologies on the mid- and long-term sustainability of urban areas. A dynamic energy analysis of a residential building-integrated cogeneration system under different boundary conditions was presented in Rosato et al. [45]. Regardless of the purpose to install DG (e.g. reducing cost or environmental impacts), factors such as characteristics of different types of DG, dynamic energy costs, different types of building energy demand and their variation, varying solar resources, and national policy frameworks to promote each type of DG should be taken into account to decide on the design and operating strategy of DG. Optimization models applied to DG systems typically consider only cogeneration systems, focusing on economic and technical aspects. For instance, Alanne et al. [3] discussed the techno-economic optimization of Stirling engine micro-cogeneration systems in residential buildings. Casisi et al. [10] studied the effect of different economic support policies on the optimal synthesis and operation of a renewable-based distributed energy supply system for an industrial area. Calise et al. [9] dealt with the design and simulation of a prototype of a small-scale solar CHP system based on evacuated flat-plate solar collectors and organic Rankine cycle. Abdelhady et al. [1] discussed the design of a small scale stand-alone solar thermal co-generation plant for an isolated region in Egypt. Akikur et al. [2], analyzed the performance of a cogeneration SOFC system combined with solar energy. Kabalci et al. [28] proposed a smart monitoring system for renewable based distributed energy systems. Bortolini et al. [6] evaluated the technical and economic design of a combined PV and battery energy storage system. Arcuri et al. [4] proposed a combination of heat pumps, absorption chillers and cogeneration systems, discussing the optimal operation strategy of the energy systems maximizing annual short- and long-term economic returns. Cho et al. [12] developed a model to minimize the total cost of energy usage for a building based on energy efficiency constraints for each component. Dorer and Weber [18] assessed the emission performance of residential micro-cogeneration systems with dynamic whole-building simulation programs. Hawkes and Leach [23] developed an equivalent annual cost minimization model to determine the driving factors behind the investment in fuel cell CHP technologies. A sensitivity analysis showed that the results were sensitive to capital cost, energy import/export prices, plant lifetime, and the temporal precision selected for the study [24]. İnan et al. [26] examined the effect of exchange rate on the cogeneration systems fixed and variable costs in Turkey. The performance assessment of various building cogeneration through energy and exergy efficiencies was discussed in Kanoglu and Dincer [29]. Kong et al. [30] developed an energy optimization model for gas turbine cogeneration systems. Mavrotas et al. [34] discussed an optimization framework for energy supply systems in commercial buildings by considering the demand uncertainty. Monteiro et al. [37] developed a model for planning micro-CHP plants in agreement with the Portuguese energy legal framework. Pan et al. [39] presented a real-time optimum operation strategy to improve the efficiency of the cogeneration systems, integrating turbine generator and cooling tower. Yokoyama et al. [55] discussed the optimal design of a gas engine cogeneration system for electricity and hot water supply, using a branch and bound method. In this regard, relatively few recent studies have looked at the combination of renewable and CHP. Such studies include Akikur et al. [2], who examined the performance analysis of a cogeneration system using solar energy and SOFC technology. Ismail et al. [27] discussed the sizing optimization of a system consisting of PV panels, CHP and storage, using genetic algorithms. Rezvan et al. [44] developed a robust optimization model to determine the optimum capacity of DG for buildings in the case of demand uncertainty. Moreover, despite environmental impacts associated with the building sector is a key issue, only some studies incorporate environmental aspects into the design and operation of DG. Ren & Gao [42] developed a single-objective model for the integrated plan and evaluation of DG systems. The model was extended to a multi-objective model in Ren et al. [43], minimizing energy costs and operating CO_2 emissions. Lu et al. [31] presented a multi-objective optimization based for energy management of a district site in China. A systematic optimization procedure to select and size a cogeneration plant fuelled by natural gas, evacuated tube solar collectors, and gasified biomass is discussed in Rubio-Maya et al. [46]. Torchio [50] compared a district heating CHP and a distributed generation CHP in terms of energy and economic criteria, as well as CO_2 and NO_x emissions. Wang et al. [52] proposed a multi-objective optimization for combined cooling, heating and power system driven by solar energy. Such studies mainly assess operating CO_2 (or $NO_{\underline{x}}$ or SO_2), and do not adopt Life-Cycle (LC) approaches, whereas any comparison among energy supply options must employ a LC approach [32]. An exception is Osman et al. [38] who looked at both costs andtwo types of environmental impacts (greenhouse gases, tropospheric ozone depletion), taking into account only CHP technologies.

The incorporation of environmental aspects into the analysis calls for multi-objective models and techniques in which decisions should be made exploiting the trade-offs between the conflicting axes of evaluation of the merits of distinct solutions, which are made operational by multiple objective functions to be optimized. A model to minimize the Life-Cycle Costs (LCC) of meeting the energy demand (power, heating, cooling) of a commercial building by integrating DG and conventional energy sources was presented in Safaei et al. [47]. Here, the model is extended into a multi-objective linear programming (MOLP) model by introducing four additional environmental impacts as objective functions along with cost. To calculate the environmental impacts of different energy solutions, a Life-Cycle Assessment (LCA) was conducted considering the impacts related to construction and operation of energy systems, as well as the upstream processes related to their fuel input, i.e. NG for CHPs. MOLP techniques are employed to unveil and exploit the trade-off between the competing objectives, i.e. minimizing cost versus minimizing each type of impact category.

Section 2 provides a brief overview of the model and its inputs. In Section 3 the Pareto optimal frontiers obtained for cost vis-à-vis environmental impacts are presented. This is followed by the discussions of the results in Section 4. Finally, in Section 5 the main conclusions are drawn.

2. MOLP model

The mathematical model was presented in Safaei et al. [47] for cost optimal design and operation of DG in Portuguese commercial buildings. The model incorporates different types of CHP technologies (Micro-Turbines – MT, Internal Combustion Engines – ICE, Solid Oxide Fuel Cells – SOFC), separate production of electricity - Portuguese electricity generation mix in 2011 [20] and heat (onsite boilers), renewable sources (ST and PV), and auxiliary cooling systems (Absorption Chiller – AC, Compression Chiller – CC). The specifications of the energy systems considered and the main assumptions are described below:

- Solar PV systems: 4 kW_p (KW peak) mono-crystalline PV system with lifetime of 30 years and three 2500 W inverters.