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Techno-economic and environmental modelling and optimization of flexible distributed multi-generation options

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ABSTRACT

It is arguable how much flexibility and efficiency from coupling different energy vectors through available technologies is exploited in current energy systems. In particular, in spite of the growing interest for the multi-energy concept, there are very few models capable of clearly explaining the benefits that can be derived from integration of complementary technologies such as cogeneration, electric heat pumps and thermal storage. In this light, this paper introduces a comprehensive analysis framework and a relevant unified and synthetic Mixed-Integer Linear Programming optimization model suitable for evaluating the techno-economic and environmental characteristics of different Distributed Multi-Generation (DMG) options. Each option's operational performance and flexibility to respond to electricity market signals are analysed in detail and assessed against the needed investment costs in different contexts. Numerical case studies focus on highlighting the flexibility benefits that can be gained in economic terms from multi-energy system integration in district heating (DH) applications. Detailed sensitivity analyses of different DMG configurations also clearly show what economic as well as environmental performance (at both global and local levels) can be expected in current and future scenarios when coupling different energy vectors and complementary technologies in a multi-energy context.

1. Introduction

In the light of the increasing interest for multi-energy systems, where multiple energy vectors optimally interact with each other [1], district energy systems are likely to play a more and more important role in delivering a sustainable energy future, particularly with the projected number of people living in cities constantly increasing. In this outlook, multi-generation options for combined production of different energy vectors [2–4] are an effective solution to increase energy efficiency, particularly in urban areas and in district energy systems. The simplest multi-generation concept is combined heat and power (CHP), producing usable heat and electricity from a certain input fuel. Advantages of combined heat and power plants, with respect to the conventional separate production (SP) of electricity and heat, are well known [5,6]. In Ref. [7] the author elaborates on basic efficiency concepts determined by the European Directive for the promotion of cogeneration, providing guidelines on defining primary energy savings of CHP units which are eligible for financial benefits. Economic and environmental advantages of CHP units for district heating (DH) systems are analysed in Refs. [8] and [9]. Electric heat pumps (EHP), also considered as an efficient and economic alternative to existing boilers, have a capability to decarbonise the heating sector but are dependent on concurrent decarbonisation of electricity generation. In addition, large integration of EHP means significant increase of electricity load in the grid. This will eventually require further investments in the electric grid infrastructure [10].

Conventional small to medium scale CHP units are negligibly flexible in responding to electricity market prices as they have a primary task of covering demand (of heat or in limited cases of electricity), and in order to be able to cope with more volatile energy prices they need to be more flexible. This is where the importance of coupling with thermal energy storage (TES) is recognized, most noticeably in Denmark where this strategy was initially supported by three level feed-in tariff; today even smaller distributed units are allowed to participate in the electricity day-ahead market [11]. Several other countries have introduced incentives for wide spread integration of DH CHP systems such as Germany [12]. Sweden has instead decided to focus its heating

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Nomenclature

Acronyms and indices

AEF average emission factor
CCGT combined cycle gas turbine
CO carbon monoxide
CO_2 carbon dioxide
CHP combined heat and power
DH district heating
DMG distributed multi-generation
EDS electricity distribution system
EHP electric heat pump
LSP local separate production
MILP mixed-integer linear programming
MSG minimum stable generation
NO_x nitrogen oxides
PPES polygeneration primary energy saving
PCO_2ER polygeneration CO_2 emission reduction
SP separate production
D demand
e electricity
th thermal
aux auxiliary
s thermal energy storage
t time step
1, 2, 3, 4, 5, 6, 7 index of distributed multi-generation option

Input values

η_e electric efficiency of a CHP unit
η_{th} thermal efficiency of a CHP unit
α shifting factor
COP coefficient of performance
E_D electricity demand
H_D heat demand
E_{chp_max} maximum generation output of CHP unit
E_{chp_min} minimum stable generation of CHP unit
H_{aux_max} maximum boiler output
H_{hp_max} maximum heat generation from EHP
T_{s_max} maximum water temperature in the thermal storage tank
T_{s_min} minimum water temperature in the thermal storage tank
ramp ramp rate value of the CHP unit
C_{fuel} cost/price of input fuel (natural gas)
C_{elec_buy} cost/price of electricity bought from the grid
C_{elec_sell} cost/price of electricity sold to the grid

Decision variables

E_{chp} electricity produced by CHP unit
H_{chp} heat produced by a CHP unit
I_{chp} binary variable indicating if the CHP unit is on/off
H_s state of charge of thermal energy storage
H_{aux} heat produced by auxiliary boiler
H_{hp} heat produced by EHP
E_{hp} electricity needed by EHP for heat production
E_{hp_chp} electricity produced by CHP and used by EHP for heat production
E_{hp_g} electricity from the electric grid and used by EHP for heat production

policy on EHP systems which have already been installed in Stockholm [13]. Despite the primary focus on EHP in Sweden, city of Linköping is also supplied by CHP coupled with TES [14]. The UK is also committed to the decarbonisation of the whole energy sector and heating in particular. In this respect, different strategies have been proposed [15–17], to follow up on experience and successful implementations of the Danish/Swedish energy policies. Studies researching the optimal size of CHP coupled with TES for the case of DH in the UK are presented in Refs. [18,19]. Today only 2% of UK consumers are connected to DH systems, but estimates [20] suggest this technology could have a significant share in heat supply for 40 million forecasted UK consumers in 2030.

While benefits enabled by thermal storage are fairly clear, there is less understanding of the potential to couple CHP to EHP (and in case storage too) to gain significant flexibility to respond to system requirements and prices. These systems could have an even greater value in future electricity systems with large share of renewable energy sources when excess electricity can be harvested by shifting between energy vectors [21,22]. Some papers indeed conclude that combination of technologies could be the optimal solution in coping with volatility of net electricity load caused by increasing share of renewable energy sources [23], but this issue has not been explored systematically as yet. In particular, there are neither experiences nor comprehensive modelling framework and systematic studies on distributed multi-generation (DMG) [24,25] options, particularly the ones based on combination of CHP and EHP and whose role remains relatively unclear.

This uncertain but very dynamic context thus paves the way to the opportunity of exploring new alternative and innovative DMG options based on CHP and EHP that could be effectively deployed to increase the economic and environmental performance of future DH systems, particularly in the UK. The potential benefits these systems bring are already recognized in different countries [14,26,27], and for different district energy system applications [4,28]. The term "equivalent cogeneration plant" is for instance introduced in Ref. [29] exemplifying the benefits of cascading CHP–EHP through energy shifting factors. This concept can provide significant emission reduction [29] as well as primary energy savings, as also shown in Refs. [5,30]. The concept is further expanded to capture the flexibility benefits of multi-generation units in Refs. [31,32]. The idea of CHP–EHP where EHP uses cooled stored air from flue gases of CHP as a "free fuel" is presented in Refs. [33,34]. These papers can be considered state-of the art in terms of coupling different units and increasing flexibility by operational shifting between different energy vectors. However, there is no comprehensive market and environmental analysis of such DMG options.

On the above premises, the aim of this work is to define a comprehensive and unified techno-economic and environmental modelling and optimization framework for the operational and planning evaluation of different DMG options for DH systems. The concept of flexibility, seen here from the point of view of operational flexibility (capability to respond to price signals in close to real time), is analysed in detail for the different options. In addition, the different DMG options are also assessed from an investment perspective, also considering different price scenarios, as well as from an environmental perspective considering both local (from local pollution) and global impact (primary energy consumption and CO_2 emissions) impact and in different scenarios. In this way, a systematic and comprehensive picture of pros and cons of different DMG options in different contexts will be provided.

The rest of the paper is organized as follows. Section 2 defines different district heating DMG options and presents a unified MILP