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Combined energy hub optimisation and demand side management for buildings

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ABSTRACT

The deployment of innovative energy management (EM) approaches based on systematic modelling and optimisation techniques has received an increasing amount of attention in the last decade. This has been often prompted by more stringent energy policy objectives aiming at reducing carbon emissions, phasing out nuclear plants and promoting overall energy efficiency, while containing both capital and operating costs. In this respect the energy hub concept has proven to be a popular approach for operating technologies and units comprising diversified energy carriers, small-scale production units, storage devices and converter systems. Additionally, developments in communication network and control infrastructure afford the possibility, at least in principle, to actively steer and adjust the load on the demand side of the energy balance, leading to the formulation of demand side management (DSM) techniques. This paper proposes an EM solution that combines the features and advantages of both of the aforementioned approaches, i.e. the energy hub framework and DSM methods. The key idea is to combine the supply-side characteristics of energy hubs with the demand side flexibility yielded by the deployment of DSM schemes. This combined approach is validated on an existing building complex by formalizing its energy supply system as an integrated hub and by modelling its heating demand based on thermodynamic principles. Numerical results based on this experimental setup are presented, illustrating that the combined approach can lead to overall savings typically exceeding 10% compared to a baseline scenario where no EM solution is applied, i.e. where only a rule-based heuristic is employed to control the available energy assets, and underscoring the advantages brought by a systematically integrated modelling and optimisation approach. The proposed solution is thus of interest for a broad host of installations in the residential and commercial domain, and for the latter a specific real-world example has been explicitly considered and analysed. The obtained results are encouraging and warrant further analysis and investigation.

1. Introduction

Global trends in energy policies have fostered the development and adoption of novel technologies, control paradigms and management techniques for improving general system performance and attaining long-term objectives set forth in terms of environmental targets and economic constraints. Future energy systems will therefore increasingly combine the features borne by typically large, dispatchable and conventional energy sources with those of relatively small and intermittent renewables. Running the overall system in the most effective way has thus become an issue of increasing importance, since it features units with both complementary and conflicting characteristics. This is furthermore relevant not only at a grid level but also on the scale of industrial, commercial and even residential installations. Such issues are additionally complicated by the fact energy networks for different carriers (e.g. electricity and gas) will foreseeably be more closely interconnected in the future due to the presence of novel conversion units, and storage devices will also be commonly deployed and operated.

The problem of how to deal with such an assorted set of components, technologies and boundary conditions is often referred to as the energy dispatch problem in the literature, and novel formulations have been derived over the course of the last decade in order to adapt it to the requirements of distributed generation units. One such solution was proposed in terms of the concept of energy hub modelling [1], which leverages the potential of a specific, constrained set of energy assets – referred to as a hub

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– to provide the optimal energy dispatch for a given demand. It takes information related to the price and availability of external energy carriers, the forecast of expected renewable energy contribution, the physical characteristics of conversion units and storage devices present on-site and the load prediction as input to solve the problem of determining the optimal energy procurement and technology utilization.

In parallel, recent research work has also focussed on removing the assumption that the load is given and fixed and on investigating viable demand side management (DSM) approaches that dynamically adjust the load, within given bounds, in order to fulfil or improve a specified performance requirement. These methods yield additional flexibility and introduce new degrees of freedoms in novel energy management approaches, since the load had otherwise been assumed to be passive and static in classic formulations.

A number of approaches for the formulation and solution of optimisation problems have been proposed in the literature, such as related to the dimensioning and operation strategy selection [2–6], planning of distributed and micro-grid energy systems [7–13], MILP based evaluation and scheduling of energy units [14–19], and energy management and planning tools [20–22]. One of the first models for the optimisation of non-renewable energy sources demand, emissions and operating costs for a given municipal system was proposed in [2]. In [3] a tool was described for the sizing and operational optimisation of system units, which was applied in [4] for electricity and heat production in a Swedish municipal utility.

Contrary to the proposed solution which is aiming at real-time optimization of facility operation, a number of approaches were published so far dealing with an off-line evaluation of optimal design and planning of distributed energy systems. One of such approaches aiming at dimensioning and operation strategy selection for tri-generation plants considering various operation parameters and energy tariffs was proposed in [5] and [6]. Also, several approaches for the optimal design and planning of distributed energy systems were proposed, such as for commercial buildings [7], large scale energy supply systems [8] and multiple energy carrier systems [9,10]. In addition, a linear programming cost minimisation model for high-level system design and the corresponding unit commitment of generators and storage within a micro-grid was developed in [11].

In [12] a cost optimal design of ice-storage cooling system in commercial building was determined under various electricity tariff schemes. In [13] optimal scheduling was investigated for a microgrid laboratory system by targeting the minimisation of active power losses. In [14] an MILP (mixed integer linear programming) model was developed which minimises overall annual energy costs by selecting the units to install and determining their operating schedules. Another integrated MILP based approach for the design, operation and evaluation of distributed energy systems was presented in [15] and applied in [16] for optimal system design at the neighbourhood level. An MILP model was also applied for the optimal operation of a virtual power plant composed of intermittent renewable sources and storage units in [17] and [18]. Moreover, in [19], four approaches for modelling the thermal energy storage units with mixed-integer linear programs were introduced. A flexible decision support tool for energy management and environmental planning of regional-scale systems was presented in [20] and [21], and a general mathematical formulation of a multi-commodity energy network flow model was described in [22]. At the same time, a number of approaches investigating demand side optimisation were analysed in the literature as well [23–28]. For instance, a decision support information system which assists dealing with various load management scenarios based on a neural networks methodology was proposed in [23]. In [24] a decentralised control scheme that coordinates the actions of the end users was presented. A multi-objective genetic algorithm approach to implementing the DSM in an automated warehouse was investigated in [25]. Furthermore, a modified genetic algorithm was used in [26] to optimize the scheduling of direct load control strategies. An autonomous and distributed demand side energy management system based on game theory was proposed in [27]. Finally, a novel autonomous demand response system that tries to achieve both optimality and fairness with respect to the involved participants was designed in [28]. In [29], a fuzzy logic approach utilizing wireless sensors and smart grid incentives for load reduction in residential HVAC systems was presented. Additionally, an integration of renewable energy sources and EVs with proper home demand side management was evaluated through different scenarios in [30].

The approach proposed in this paper aims at providing a holistic solution integrating both energy supply side optimisation and demand side management to attain an improved degree of operation of the facility within the given constraints. Such an approach, i.e. integrating both supply and demand side management, has in general received somewhat less attention in the literature. For instance, contrary to the approach proposed in this paper which aims at real-time optimization at building level, the authors of [31] described a solution for off-line minimization of capital and operation costs for local utilities through CHP, heat storage and electricity load management. In addition, solution in [31] introduced an irregular coarse-grained time division, excluding the possibility for higher resolution control. In [32] and [33], EH model was used in combination with the possibility of performing DSM for investment evaluation of utility infrastructure and district energy distribution infrastructure, respectively. Unlike the proposed approach, which was demonstrated in a real-world scenario, solution in [32] was validated by Monte Carlo simulations whereby the tariffing prices were defined as random variables, while [33] evaluated different potential heating system configurations. For determining DSM constrains, more precisely of the heat load management, both [32] and [33] used a parametrized model of heated space but in a simplified form comparing to the proposed approach which delivered more accurate estimation. Furthermore, in [34] an integrated DSM program for multiple EHs was proposed as a non-cooperative game within a cloud-based infrastructure. Contrary to the proposed approach which actively takes into account the possibility of influencing the non-critical demand, integrated DSM program was demonstrated for EHs with critical loads hence optimizing only the supply for multiple EHs. Each EH was incentivized to participate the program which required the exploitation of different supply energy carriers, thus affecting the overall energy supply price value. The authors of [35] applied the EH concept for optimization of energy flows in simulated interconnected networks, but without taking into account the DSM actions. Finally, in [36] the authors evaluated the energy hub upon typical infrastructure of residential household by simulating different case studies, while the proposed solution was evaluated completely upon measured energy data and real pricing tariffs.

With respect to the foregoing references, i.e. [31–36], the present work employs a conceptually similar approach by jointly optimizing both the supply and demand side of a chosen energy system, where the latter is represented by an existing building complex equipped with operational on-site hardware and measuring devices. The heating dynamics of the building are explicitly modelled and employed to derive a suitable DSM constraint formulation in terms of admissible thermodynamic requirements. A predictive optimal control algorithm is employed to minimize operating costs, and by using data and measurements from real-life operating conditions it is shown that simultaneously acting on both supply and demand can lead to a more advantageous operating profile over the selected temporal horizon. The overarching objective of the