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Heterogeneous resource management in energy hubs with self-consumption: Contributions and application example

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HIGHLIGHTS

- New formulations enhance the modeling of certain characteristics or processes.
- Integration into the electricity market and solar self-consumption management.
- Real-world case study for the test-bed plant representative of an industrial cluster.

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ABSTRACT

The energy hub concept and modeling methodology are widely employed tools for solving resource conversion and storage scheduling problems. For instance, industrial clusters might benefit from determining the suitable time to operate their facilities and to sell electricity to the public power grid, according to legal, economic or environmental factors. In this paper, novel elements are introduced in order to more accurately represent real plants and to reduce the amount of decision variables. The major innovation is to consider devices consuming a resource which is not related to the quantity of output produced, by attaching binary decision variables to certain energy hub outputs. Secondly, a path vector is defined to take into account the flows of resources within the system instead of employing a variable for each branch between the components. The third innovation consists of an additional vector to express the amount of output resources sold from the energy hub, including constraints for those resources which are exported and imported through the same medium. An extended energy hub model is first proposed and then applied to a real plant example, including multiple and heterogeneous resources and performing a comparison between days with different demands, weather conditions and electricity prices. The results obtained in the selected scenarios demonstrate a logical operation scheduling, and therefore validate the proposed approach.

1. Introduction

Over the last few years, energy policies aimed at increasing efficiencies in production, transportation, consumption and storage processes have led to approaches based on decentralizing these processes and combining different kinds of energy to benefit from the use of available local resources and infrastructure in a synergistic way. Consequently, renewable energies are expected to play a key role given their relevance in distributed generation either for power networks [1] or combined energy systems [2]. However, because of their intermittent nature, many require storage systems and management strategies that decouple generation from demand in order to be economically viable [3].

On the one hand, recent concepts such as distributed multi-generation (DMG) [4] and multi-energy systems (MES) [5] have come to set a general research framework to manage systems that include various energy carriers and integrating them in demand response programs [6]. Within the so-called MES, the energy hub approach is widely used as a simplified model for the interactions inside diverse complexity systems relating to their input-output structure. A formal definition of the energy hub concept was given for the first time by Geidl et al. [7] in 2007: a unit where multiple energy carriers can be converted, conditioned, and stored. At the same time, its usage was exemplified in a resource dispatch problem [8]. Since then, many authors have applied this concept to different problems, such as resource management, introducing robust optimization algorithms [9], methodologies to

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enhance the representation of operational constraints [10] or to facilitate the automatic modeling of arbitrary energy hub configurations [11], and load management strategies [12]. In addition, the energy hub modeling framework has been implemented in microgrid management problems [13], including its integration into vehicle to grid systems [14]. The concept is also used in problems related to economic dispatch [15] or optimal device configuration in systems with [16] or without [17] storage elements. A recent review on common resources and converters in energy hub models [18] shows that most works focus on electricity and thermal heating technologies, paying less attention to other material resources (such as solid fuels, water, carbon dioxide or hydrogen); this makes them interesting from the research point of view. Since energy hub models can be used for both energy and material flows, the term “resource” will be used to refer to them from now on.

One existing obstacle is that legal frameworks for MES networks are still under development and each resource supply and distribution network usually operates under its own rules. Electricity power systems have one of the most extensive legal frameworks, which has set the fundamental basis for smart grid development [19]; this has been thanks to recent advancements in information and communication technologies, as well as those in automation and electronics. For instance, in the Spanish context, some works have already dealt with microgrid management and its integration into the electricity market as a system agent (both as a direct consumer and producer) [20]. Regarding indirect consumers, who are not considered market agents and therefore do not participate in the electricity market, the most recent law regulating self-consumption [21] was approved in 2015, establishing two sorts of self-consumers (depending on the facility features and the contract holder), as described below. Thus, in spite of the legal differences between countries, self-consumption and renewable-based systems become an interesting consideration for small industries [22] and for commercial [23] or residential buildings [24], because of their potential economic and environmental benefits [25].

In view of the above, this paper attempts to address the gap in previous formulations for representing systems of diverse nature and complexity by presenting a widely applicable generic modeling framework. With regard to the formulations made by Parisio et al. [9] and Evins et al. [10], the approach proposed in [12] is a good starting point to include flexible loads (energy hub outputs) although the constraints proposed result in a non-linear formulation of the problem. Similarly, the methodology recently proposed in [11] simplifies the implementation of models, yet it augments the number of decision variables and therefore the size of the matrices which represent the system. Owing to the scarcity of works centered on certain material resources [18], an industrial cluster integrating them will serve as an energy hub example. To provide a real and captivating application for the developed approach, (without loss of generality), the legal situation in Spain concerning type 2 self-consumers is considered, in which sales to the grid are allowed at the pool price and both the self-consumed energy and that sold to the grid are taxed. Consequently, the main contributions can be summarized in the list below:

1. Complementing previous models in order to include the possibility of representing more accurately certain processes, such as selling output resources and adding loads related to the operating state (on/off) of certain devices, which ensures more economical results; and to reduce the number of decision variables for modeling complex energy hubs, which entails reducing the computation effort.
2. Providing an energy hub modeling example, with multiple material and energetic resources, which includes unusual inputs (such as seawater and biomass), outputs (CO_2 enrichment for a greenhouse [26]), and converters (a solar-powered desalination plant and an absorption chiller).
3. Testing the proposed approach’s validity using simulation on two different cases for systems with self-consumption, in which operational scheduling is determined considering variations in the electricity price throughout the day.

The remainder of this paper is organized as follows. Section 2 contains a detailed formulation of a general energy hub, distinguishing between conversion and storage models. Section 3 summarizes the Spanish self-consumption regulations, daily and intraday electricity markets and briefly describes the test-bed plant representative of an industrial cluster. In Section 3.4 and 3.5, the results from various simulation scenarios of the presented energy hub are shown and discussed. Finally, Section 4 highlights the concluding remarks and proposes future lines of research.

2. Extended energy hub model

In broad terms, energy hub models are obtained from energy and mass balances between different input and output resource flows. These flows are represented mathematically through variables which constitute the respective input and output vector elements. First formulations [8] defined the so-called coupling matrix in order to establish the relationship between them. Additional introduced terms are required when storage elements appear, so there is usually a distinction between the conversion and storage model [9]. The systems represented are supposed to contain their devices close enough to assume that resource losses only occur in conversion and storage processes. In order to formulate a linear model, the use of dispatch factors [8] must be avoided; thus Parisio et al. [9] suggested introducing as many variables as there are conversion devices, rearranging the input vector and the coupling matrix in a new equation which relates them to the output vector. A similar approach was adopted by Evins et al. [10] which combined an input-output equation with the one proposed by Parisio et al. [9].

Considering the most common elements in previous approaches (represented in black in Fig. 1), the conversion and storage model of a general energy hub is formulated which comprises N_i inputs, N_o outputs, and N_d Single-Input and Single-Output (SISO) conversion devices. The equation represents the system in discrete time using a uniform sample time $T = t(k+1)-t(k)$, where k constitutes any time instant. All the novel elements introduced have been highlighted in blue in Fig. 1 and justified below.

2.1. Additional formulations for the conversion model

Firstly, in contrast to the model in [9] a path vector $\boldsymbol{P}=[P_1 \ \cdots \ P_{N_p}]^T$ is defined. It contains a variable for each possible path between inputs and outputs (N_p in total), and therefore its size depends

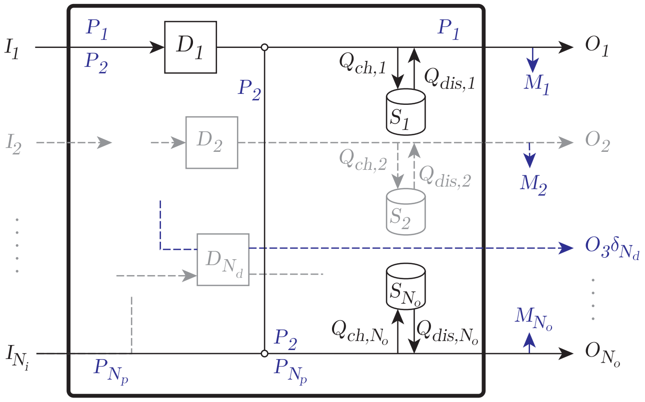

Fig. 1. Schematic diagram of a general energy hub with storage at the output ports. The novel elements introduced in this paper are highlighted in blue: binary variables attached to certain outputs, paths between the inputs and outputs, and output resource sales. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)